MARINE CONSERVATION

As Threats to Corals Grow, Hints of Resilience Emerge

Some reefs are showing a surprising ability to resist or bounce back from damage. Could such resilience help corals survive in a rapidly changing ocean?

Survivors. This coral-mangrove ecosystem in the U.S. Virgin Islands is thriving despite ocean conditions that killed nearby reefs.

CREDIT: CAROLINE ROGERS/USGS, ST. JOHN, U.S. VIRGIN ISLANDS

Eight years ago, a blistering heat wave sent local sea temperatures soaring in the eastern Caribbean, killing more than one-half of the region's coral reefs. Many have yet to recover. But in Hurricane Hole, a sheltered bay off St. John in the U.S. Virgin Islands, one vibrant coral ecosystem survived unscathed. "We've identified more than 30 coral species" that avoided the catastrophe, says Caroline Rogers, a marine biologist with the U.S. Geological Survey (USGS) in St. John. "The diversity is astounding."

Rogers has been trying to understand what made the corals in Hurricane Hole so resilient, and she has plenty of company. Around the globe, a growing corps of scientists is searching for resilient reefs and then trying to identify what enables them to resist or bounce back from severe environmental stress. They've found tantalizing hints that heat-resistance genes, the proximity of other reefs, and even the presence of plant-eating sea life that scrub corals free of weedy algae can play a role. But they're also discovering that the factors that promote resilience can vary greatly from reef to reef.

Still, coral researchers are trying to extract some general, widely applicable lessons from their studies of resilience, partly in hopes of developing smarter conservation strategies, such as better designed marine reserves. It's a task that is taking on increased urgency, as climate change threatens to wipe out corals and remake ocean ecosystems. "We in the environmental community look for points of hope," says ecologist Stephanie Wear of the Nature Conservancy in Arlington, Virginia. And in identifying possible ways to boost reef resilience, she says, "We see opportunity."

Stressful developments

Coral reefs weren't always considered fragile. When Rogers was working on her doctorate in the late 1970s, many researchers believed that reefs were intrinsically stable ecosystems, threatened mainly by local storm damage. But by the early 1980s, it was obvious that corals were in trouble. In the Caribbean, reefs took a noticeable hit after disease led to a massive die-off of spiny sea urchins, which had helped to keep reef-smothering algae in check after another group of herbivores, parrotfish, had been overexploited. In the Pacific and Indian oceans, unusually high seawater temperatures linked to the large-scale weather pattern known as El Niño caused massive "bleaching" events in 1982 and 1998 that turned reefs a ghostly, skeletal white. Bleaching happens when heat-stressed corals expel the symbiotic algae—known as zooxanthellea—which live in their tissues and supply nutrients in exchange for protection. And it is often fatal: the 1998 event killed 16% of the world's reefs overall and up to 95% in some locations, says Robert Steneck, a biologist at the University of Maine's Darling Marine Center in Walpole.

But here and there, reefs have shown the ability to resist or rebound from such shocks. In an oft-cited example, the extensive reef system off Palau, in the western Pacific, charged back within a decade after suffering extensive bleaching losses in 1998. Similarly, reefs off the Cocos Islands in the eastern Pacific, which were virtually destroyed by bleaching during the 1980s, experienced up to fivefold increases in coral cover within 20 years. These recoveries sparked widespread interest in understanding the underlying "drivers" of resilience, with an eye toward developing better reef protection plans.

Scraping by

One focus has been on understanding the role of herbivorous fish and plant-eating invertebrates such as sea urchins. Ecologists have long known that these grazers play an important role in reef health by mowing down weedy algae and clearing attractive settling spots for young corals. Now, many believe that those tasks are essential to enabling some damaged reefs to recover from ecological stress.

For example, when Steneck visited Palau's bleached reefs in 2000, he was heartened by the abundance and diversity of herbivorous fish that were still patrolling the coral skeletons. "The reefs were extremely well-grazed," he recalls. "I thought the conditions for coral recovery were great because young corals would have a chance to settle." The subsequent recovery of those reefs reinforced Steneck's belief that protecting herbivorous fish is one of the most effective means of boosting reef resilience. A number of studies appear to back his view, including experiments published in *Current Biology* in 2007 conducted on Australia's Great Barrier Reef in which researchers deliberately removed grazing fish; the corals were soon overwhelmed by algae.

At the same time, in other parts of the

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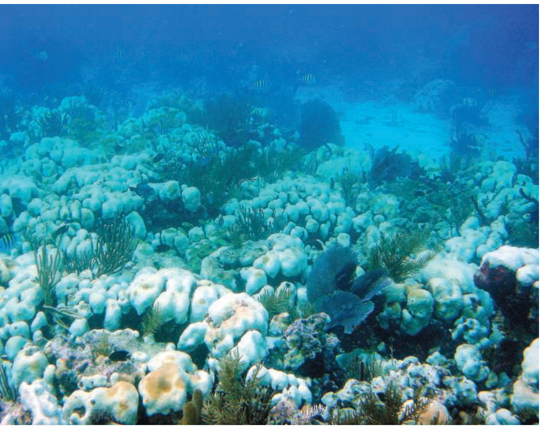
world, the importance of grazer abundance is less obvious. Researchers have found no clear relationship, for instance, between the number of reef herbivores and how much macroalgae covers reefs off the coast of New Caledonia, in the Southwest Pacific, a team led by Laure Carassou, a postdoctoral research fellow at Rhodes University in South Africa, reports in a forthcoming *PLOS ONE* paper. Even on reefs where herbivorous fish numbers had been severely depressed by overfishing—such as in the Coral Triangle, the vast marine system that stretches from the Southwest Pacific to the western tip of Indonesia—algae cover tends to be low, notes co-author Michel Kulbicki, a reef ecologist with the Research Institute for Development in Banyuls, France. Such results suggest something is still eating the algae, and that conservation plans may need to target those species—rather than all herbivores—to boost resilience.



Different fates. Corals in Palau (*top*) have recovered from severe bleaching, while many reefs in the Caribbean (*bottom*) have not.

CREDITS (TOP TO BOTTOM): ROBERT STENECK/UNIVERSITY OF MAINE; CAROLINE ROGERS/USGS, ST. JOHN, U.S. VIRGIN ISLANDS

Making connections

Researchers are finding similar complexities as they explore the role of "connectivity," or how ocean currents and oceanographic corridors enable organisms, especially juvenile fish and corals, to move from one reef to another. In general, connectivity has been seen as crucial to maintaining reef resilience, because it can enable a damaged reef to receive a steady supply of fresh recruits from even distant reefs that are still healthy. That's why conservation planners often seek to design marine reserves so that they protect both the nursery sources and the final homes of reef organisms. The problem with that approach, studies suggest, is that some damaged reefs may not be able to count on immigrants to make up for coral losses. Many coral larvae appear to travel no more than 300 meters before settling down, notes Maine's Steneck, and there is growing evidence that many reefs "self-seed," or produce their own recruits. That reproduction strategy presents a challenge to coral conservationists, because self-seeding reefs are thought to be less resilient than more connected reefs. For example, isolated reefs in the eastern Pacific—which rely on self-seeding by geographic necessity—recover more slowly from disturbances than better connected reefs to the western Pacific, according to biologist Nicholas Graham of James Cook University, Townsville, in Australia.

Hot topic

To get at the biochemical foundations of resilience, researchers have also been delving into coral physiology and genetics, particularly to understand how some reefs have avoided bleaching. In a sheltered reef pool off the coast of an island in Samoa, for instance, researchers in 2008 discovered corals that thrive in unusually warm water that regularly reaches 37°C, some 7° above the warmest summer temperature of nearby seas. That's remarkable because corals typically bleach at just one degree above the local summer maximum, notes marine biologist Stephen Palumbi of Stanford University in Palo Alto, California.

As part of their study of these atypical corals, Palumbi's team examined which genes switched on when confronted with heat stress. In all, the tests identified 61 stress-resistance genes, including those that code for heat-shock proteins, antioxidant enzymes, and immune regulators, the team reported in January in the *Proceedings of the National Academy of Sciences*. The next step, researchers say, is to see how many other corals might carry similar genes that could confer resilience.

Some good candidates might come from places where seawater temperatures already vary greatly, providing a kind of evolutionary "tough love" that could prepare corals to deal with warming seas, says zoologist Tim McClanahan of the New York City–based Wildlife Conservation Society. Off the west coast of Madagascar, for instance, reefs are sheltered from a major cooling current that flows from the east, allowing them to thrive in waters that are often as warm as those encountered during El Niño events.

The hardy corals in St. John's Hurricane Hole may have also benefited from heat-tolerance genes, since the water there is often warmer than it is around nearby offshore reefs, says USGS's Rogers. But they also may have been helped by shading from nearby mangrove trees, she says, given that exposure to ultraviolet light is known to exacerbate the effects of warmer waters on coral bleaching. (Studies by ecologist Peter Mumby of the University of Queensland in Australia suggest that coral reefs surrounding the Society Islands, in the western Pacific, escaped the 1998 bleaching event because they were protected by cloud cover.)

Lessons learned?

In a bid to draw some broad, practical lessons from these growing but scattered examples of resilience, McClanahan recently asked 50 colleagues to help him develop a list of the top factors that might predict which reefs can resist and recover from bleaching and other threats. He asked each scientist to rank 31 resilience drivers and give the top scores to those they felt had the most scientific evidence. The result, published online last August in *PLOS ONE*, was a list of 11 highly ranked drivers. The researchers said a reef could have better recovery prospects, for instance, if it had a high level of coral recruitment and a low level of macroalgae. And reefs might be able to resist bleaching if they were already home to varieties of zooxanthellae or corals known to tolerate warmer waters; corals from the genus *Porites*, for instance, don't bleach as readily as other species.

Mclanahan's study is prompting some government agencies that are responsible for managing corals—such as the U.S. National Oceanic and Atmospheric Administration (NOAA)—to try to characterize reefs by their resilience potential. The idea is to ultimately come up with site-specific protection plans that take into account a reef's strengths and seek to shore up weaknesses. For example, research suggests that sediment and nutrient pollution can diminish a coral's tolerance to heat, elevating bleaching risks. By addressing those land-based threats, managers could shore up a reef's resilience to warming seas, explains

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NOAA marine scientist Britt Parker in Silver Spring, Maryland.

There are numerous hurdles, however, to putting resilience-based plans into practice. One is that managers often lack key pieces of knowledge, such as exactly where young corals and fish come from on a given reef. So if they are trying to design a new preserve, that means they may not know which other reefs to include to ensure adequate connectivity. To get around such problems, conservation planners sometimes use proxies—such as data on currents or the knowledge of local people about fish populations—to help identify the right areas to protect. One risk in that approach, however, is that it can lead to proposed reserves that are so big that they stoke opposition from anglers, divers, and others who might lose access. Such conflicts might be reduced, Wear says, if researchers were able to develop inexpensive, noninvasive ways to establish reef connectivity (such as easy genetic tests) and fine-tune reserve designs.

Gone for good? Researchers are trying to understand what allows bleached corals, such as these off St. Croix in 2005, to recover.

A better understanding of resilience could help planners develop more targeted conservation strategies that don't threaten local livelihoods, Steneck agrees. For example, if studies show that the presence of herbivorous fish are essential to a reef's health, but carnivorous fish play a lesser role, officials could consider customized fishing limits. The Caribbean island of Bonaire, for instance, outlaws spearfishing and trap fishing, which can target herbivorous reef fish, but allows bait-and-hook fishing for carnivores. And in Palau, officials have banned the export of herbivorous parrotfish, but allow killing of the fish for local consumption. "The reef off Palau is huge, but the local [human] population is small, so there are plenty of parrotfish to graze the reef and sustain local needs," Steneck explains. "But no reef population could withstand fishing pressure for export markets."

Long-term challenges

Even if managers are successful in injecting resilience-based measures into conservation plans, however, it is not clear that they can protect reefs from the twin long-term challenges posed by rapid climate change: rising water temperatures and ocean acidification, a pH change spurred by the sea's absorption of atmospheric carbon dioxide. The discovery of heat-tolerant corals is giving some researchers hope that some species will adapt to warmer seas. In addition to the Heat-resistant Palau corals, researchers have identified reef-building corals at the northern end of Australia's Great Barrier Reef that tolerate warmer water temperatures than those found 1500 miles to the south. But to survive, reefs may also have to migrate to cooler waters—and that's a doubtful proposition, says Ove Hoegh-Guldberg, director of the Global Change Institute at the University of Queensland. Reefs would have to move by 15 kilometers per year, with their complicated ecosystems intact, to stay within the temperatures to which they're acclimated, he reported in an August 2012 study published in *Nature Climate Change*.

Keys to Reef Resilience

In general, researchers say that reefs with high fish and coral diversity and low human impacts are most likely to resist or recover from environmental stress. Other factors include:

Resistance

- Presence of heat-tolerant coral and symbiont species
- High water temperature variability, which can promote heat tolerance

Recovery

- High levels of coral recruitment to replenish denuded locations
- Suitable substrate for coral settlement and survival

Another sobering unknown is whether corals can keep pace with acidifying seas, which can dissolve the calcium skeletons of corals and interfere with the development of eggs and larvae. Coral calcification will no longer keep pace with physical reef erosion once atmospheric carbon dioxide levels top 450 parts per million, according to Hoegh-Guldberg. With levels now at 395 ppm, and rising at a rate of 2 ppm a year, that tipping point could be less than 30 years away, he notes.

Researchers have found hints that some corals and reef organisms have genetic resilience to acidification. Both Palumbi and Hoegh-Guldberg say that they have collected data showing that corals respond to acidification by changing gene expression, as they do when exposed to warmer seas. "But identifying a genetic response is a long way from showing that a coral can adapt—and that coral reefs can survive—the extremely rapid pace at which we are changing the environment," Hoegh-Guldberg says.

With conditions changing so quickly, Hoegh-Guldberg and other scientist have suggested that the world's reefs might be saved only with more radical measures to enhance resilience: by breeding heat-resistant corals and using them to build new reefs, for instance dumping minerals into the sea to neutralize acidity; or even shading reefs with vast sheets of buoyant cloth. But such measures are probably impractical, given the vast extent of reefs.

In the meantime, resilience studies are reinforcing the need for multifaceted conservation strategies that look for both short- and long-term gains. "In some ways, what we are learning about coral resilience is simply bringing us back to where we started," USGS's Rogers says. "Managing human activities at the local level—while still hoping that global efforts to control greenhouse gas emissions will become more effective."

–CHARLES SCHMIDT

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