Coral reefs at a tipping point

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Healthy coral reefs play a variety of important roles, from buffering coastal communities against storms to providing fishing and tourism opportunities. But reefs are fragile ecosystems, and more than a quarter of them worldwide are in decline due to overfishing, sediment runoff, and other human-inflicted causes.

These reefs, like numerous ecosystems facing strain due to climate change and other factors, are in danger of reaching "tipping points" in which small changes could precipitate large and often abrupt shifts in an ecosystem or climate system, transformations that are difficult to reverse. If scientists could predict the impending demise of a coral reef or pinpoint the primary factors at play, they could, in principle, find better ways to protect such precious resources.

Researchers divided Hawaiian coral reefs into regimes based on the marine life present, human impacts, and other characteristics. (*Top*) A degraded reef in Waimanalo on Oahu, classified as regime 1 (high macroalgae, low fish). (*Bottom*) A reef near Kona that represents regime 5 (highest coral cover but low predator biomass). Images courtesy of (*Top*) Joseph Lecky (photographer) and (*Bottom*) Brian Neilson (Hawaii Department of Land and Natural Resources, Honolulu).

That's the idea behind the reef research of Kimberly Selkoe, at the University of California, Santa Barbara and the University of Hawaii. She has been using the science of tipping points to study Hawaiian coral reefs and identify thresholds—for factors such as fish numbers or the presence of pollutants—beyond which reefs tip over from healthy to unhealthy states. Selkoe's work relies on a careful mapping of the islands' reefs, and on data—loads of it.

"Hawaii is unique in that, as a region, our reefs are very well studied compared to others, so we harnessed these large data sources to study tipping points," she says. The project combined an unusually large dataset collected over tens of thousands of hours with sophisticated statistical analyses of the factors involved in reef decline. The ultimate aim: devise management plans that prevent reefs from going over the edge.

When Systems Tip Over

In the early 2000s, climate scientists noticed some troubling trends. Arctic ice was retreating much faster than most models had predicted, and Arctic warming was escalating by 2–3 times the global warming rate. "It became apparent that some aspects of current climate change were going a lot faster than anyone expected," says Timothy Lenton, chair in Climate Change and Earth System Science at the University of Exeter. This followed more than a decade of research showing that, during its early history, Earth had repeatedly gone through dramatic changes, says Lenton (1).

As researchers studied the processes underlying these large changes, they began to recognize the presence of climate tipping points (2–4). Collecting data about the stability of ecosystems such as coral reefs could help improve complex global climate models, Lenton says. "The trick is to relate the general behavior in our models to the actual process-based feedbacks in the real system," he says. "It's quite a difficult bridge to make, but it's an interesting and challenging one."

To study the Hawaiian reef tipping points, Selkoe and her collaborators used a treasure trove of data collected over many years by researchers from the National Oceanic and Atmospheric Administration (NOAA) and University of Hawaii, including Alan Friedlander, director of the university's Fisheries Ecology Research Laboratory.

Friedlander has spent thousands of hours diving in the Hawaiian reefs to estimate fish size and abundance, as well

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as the amount and type of coral, algae, and other marine life. "It's kind of old-school, just getting in there and getting wet and counting stuff," says Friedlander. "After you've seen a couple of thousand reefs, you start to get a picture of what's good, what's bad, and what's affecting these systems."

The researchers combined their biological data with survey data from NOAA covering lots of physical factors, including sea surface temperature and wave power, as well as with data on the human drivers affecting reef health, such as sediment runoffs and development. "Putting this all together is probably unprecedented in the scale and the amount of data that we have," says Friedlander.

The researchers constructed detailed models of five different types of "reef regimes," based on the type and amount of marine life present, as well as physical settings and human impacts. For example, one regime tends to occur near human population centers and has very low numbers of fish and coral and high levels of macroalgae. "It's what we normally think of as a degraded reef," says Selkoe. Another regime has low coral cover and macroalgae, but lots of grazing fish, whereas three others have more fish and coral but differ in the level and types of marine organisms. The researchers are analyzing the relationships between the regimes to identify the factors leading to tipping points, in which a site shifts from one regime to another as the intensity of various biological, environmental, or human drivers increases or decreases.

"It's really powerful to see these very distinct, dramatic shifts in the ecology of the reef when the driver levels change," says Selkoe, adding that human communities see the impacts on tourism, fishing, and other cultural practices.

Managing Trade-Offs

Selkoe and her colleagues aim to have their research inform the actions of natural and aquatic resource managers and policy makers (5). A recent study found that management strategies that considered tipping points were more effective in achieving conservation and management goals than strategies that did not (6).

Identifying the early warning signs of tipping points can help managers prioritize monitoring and interventions. "You don't need to necessarily have intensive regulation and spending, until you're close to a tipping point," says Selkoe.

Plus, interactions between different stressors, as well as the presence of positive and negative feedback processes in these ecosystems, means that the effects are not linear—stressors don't incrementally make things worse. Instead, there may be little effect until the system suddenly tips, with dramatic and undesirable consequences. So when regulating, for example, fishing and pollution, managers must be particularly mindful of the maximum thresholds beyond which the system tips over.

Sediment runoff often has adverse impacts on coral reefs. Scientists are trying to help control land-based pollution at this West Maui watershed, which includes dense urban development and a resort area. Image courtesy of Kirsten Oleson (University of Hawaii at Manoa, Honolulu).

For example, managers might have demands from one group that wants ample fishing and another concerned with conserving fish stocks. A seemingly reasonable compromise would be to maintain fish counts halfway between the two demands. "But the system might not be stable at that number, because there's inherent feedbacks in a system that keep it in one state or the other," Selkoe explains. "You can't just keep it at a level of stress that's putting it right on the edge."

To identify management options that minimize costs and conflicts, Kirsten Oleson, an assistant professor of ecological economics at the University of Hawaii, developed a way to perform trade-off analyses. As part of a trial in West Maui, Oleson estimated how fixing agricultural roads in the watersheds would reduce the amount of reef-damaging sediment flowing into the ocean. Most of these dirt roads are on mountain slopes, and the researchers calculated the cost of repairing them with gravel or adding small channels called "waterbars" to redirect water and sediment and reduce erosion and runoff. Some solutions provide significant sediment reduction for relatively little management cost, she says. "The managers were intrigued and really excited about it."

Oleson is working on additional management actions and considering other factors, such as nutrient inflows, that affect the reefs. The researchers are planning to release more analyses over the next year to help managers prioritize protection of sites, create effective monitoring strategies, and set meaningful management targets. "In particular, we will pinpoint the threshold levels of key drivers that cause tipping points," says Selkoe, "so that these thresholds can be avoided."

1 Alley RB (2000) Ice-core evidence of abrupt climate changes. *Proc Natl Acad Sci USA* 97(4):1331–1334.

2 Lenton TM, et al. (2008) Tipping elements in the Earth's climate system. *Proc Natl Acad Sci USA* 105(6):1786–1793.

3 Lenton TM (2011) Early warning of climate tipping points. *Nat Clim Chang* 1(4):201–209.

4 Boulton CA, Lenton TM (2015) Slowing down of North Pacific climate variability and its implications for abrupt ecosystem change. *Proc Natl Acad Sci USA* 112(37):11496–11501.

5 Selkoe KA, et al. (2015) Principles for managing marine ecosystems prone to tipping points. *Ecosyst Health Sustainability* 1(5):1–18.

6 Kelly RP, et al. (2015) Embracing thresholds for better environmental management. *Philos Trans R Soc Lond B Biol Sci* 370(1659):20130276.