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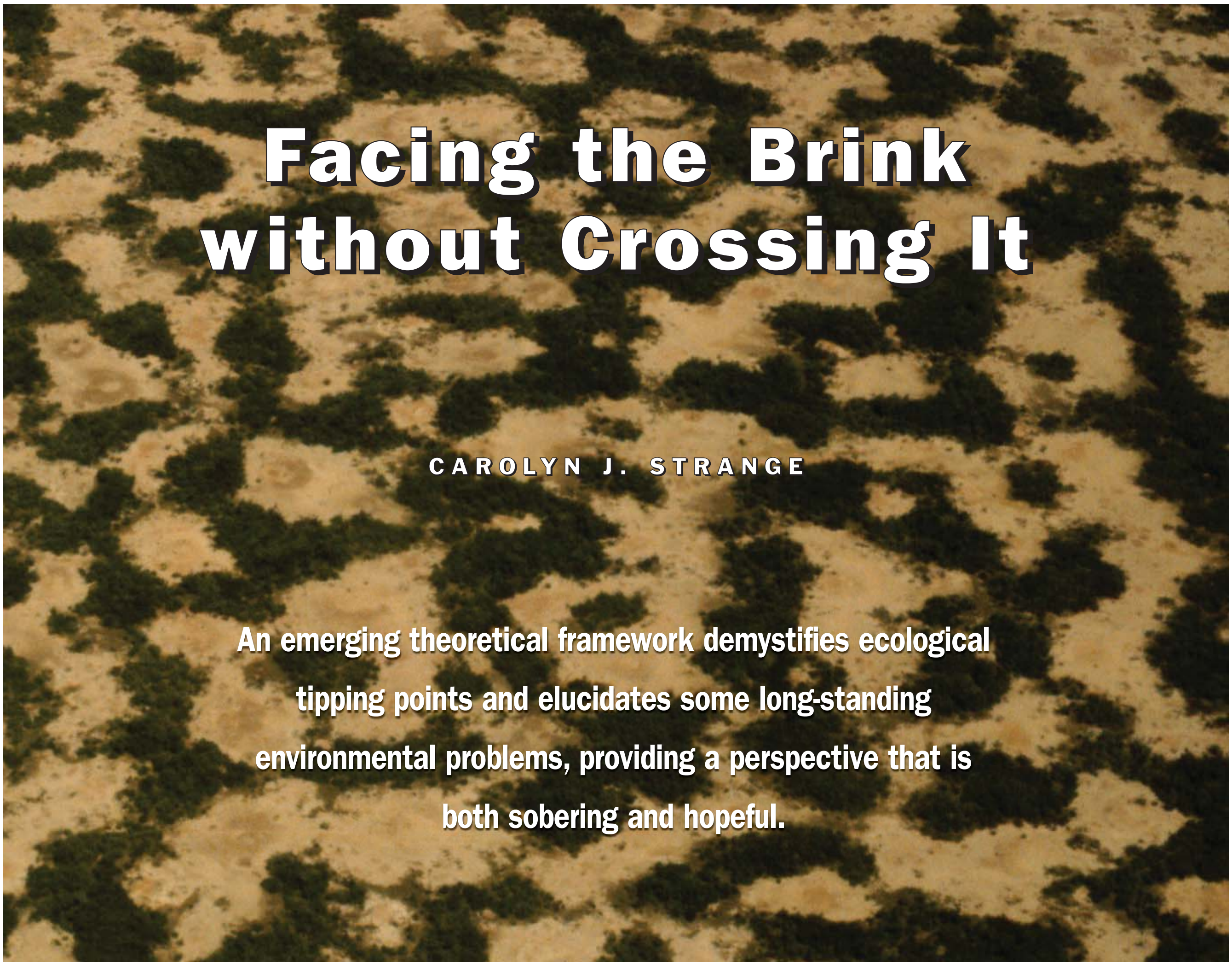


Facing the Brink without Crossing It

CAROLYN J. STRANGE

An emerging theoretical framework demystifies ecological tipping points and elucidates some long-standing environmental problems, providing a perspective that is both sobering and hopeful.

*Vegetation in Niger self-organizes into patterns, demonstrating a characteristic of complex adaptive systems in which structures at larger scales emerge from processes operating at smaller scales. Understanding and modeling the processes on the ground may enable scientists to interpret signs such as this labyrinth pattern in terms of the ecosystem's resilience and its likelihood of tipping toward desertification. Photograph: Max Rietkerk (*American Naturalist *160: 524–530), © 2002 University of Chicago.*

Clear lakes turn cloudy. Colorful, teaming coral reefs vanish under shrouds of brown seaweed. Productive pastures unravel into shrublands or deserts, perhaps displaying intriguing vegetation patterns along the way. Such dramatic, relatively abrupt shifts from one type of ecological community to another are impossible to ignore. The systems endure for a while, apparently tolerating changing circumstances, then suddenly collapse, shifting to alternate assemblages of organisms guided by new rules and different processes. Prior system behavior no longer predicts future responses. All too often, the new state is degraded, offering a diminished bundle of ecosystem services, yet it stubbornly persists despite heroic efforts to reverse it.

A growing body of broadly interdisciplinary research is explaining the processes that underlie these troubling tipping points and ensuing regime shifts, applying sophisticated mathematics and breathing new life into a deceptively simple old idea. This emerging way of thinking has the potential to improve resource management, help explain why some restoration projects struggle or fail, highlight new opportunities for restoration, and even warn of impending shifts, such as desertification.

This new approach is grounded on understanding organisms, ecosystems, and societies as complex adaptive systems, in which patterns and structures at higher levels emerge from self-organizing processes acting at lower levels. The many linkages, interconnections, and feedbacks in such systems make responses to disturbances and interventions inherently unpredictable. Complex adaptive systems can also exist in alternative states, or regimes. They behave nonlinearly, so small changes in conditions can produce big effects in a system, especially as it nears a threshold. Surprise and uncontrollability are hallmarks.

Resilience, a concept C. S. Holling introduced in 1973, also plays a central role in this new paradigm of alternate regimes and tipping points. Resilience is the capacity of a system to absorb disturbance, to reorganize and change while retaining essentially the same identity, structure, function, and feedbacks. As resilience decreases, smaller shocks can have bigger effects, knocking the system across a tipping point. Resilience is not how fast a system bounces back—called "engineering resilience," which is more about stability and doesn't consider thresholds—but the ability to get back at all.

Theory and observation came together in the 1990s when researchers studying shallow lakes began to document and explain dramatic shifts convincingly. "Lakes are modular," says Stephen R. Carpenter, of the Center for Limnology, University of Wisconsin–Madison. "There's a zillion of them. It's comparatively easy to learn about modular systems." Rangelands, at the scale of individual landholdings, can also be thought of as modular. A great deal is known about those systems as well, because experimentation is possible.

Lessons from lakes

A simplified example of the shift from a clear lake to a turbid one illustrates principles of self-reinforcing feedback that define, stabilize, and maintain two different regimes. In a clear lake, sunlight penetrates to the bottom and fosters growth of submerged plants, the foundation of the clear-vegetated lake community. These plants help hold sediments in place and also provide refuges for small invertebrates that graze on phytoplankton and algae, helping to keep the water clear. If land-use changes in the surrounding landscape begin to contribute excess nutrients, such as phosphorus, plants use it to grow. Vegetation continues to stabilize water clarity and the vegetated community, but only up to a point.

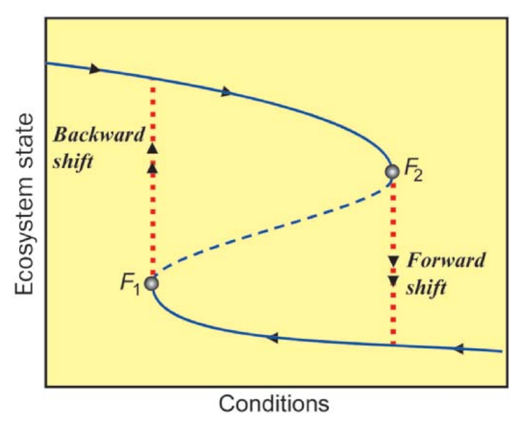
If nutrient loading continues, the lake becomes more and more likely to tip toward turbidity, triggered perhaps by wind, storm runoff, or some other disturbance that the lake was once able to tolerate without apparent ill effect. As nutrient concentrations in the water continue to increase, algae and phytoplankton populations also grow and eventually shade out the submerged plant community, which collapses as a new community arises. Invertebrates associated with the vegetation disappear, as do the birds and fishes that fed on them, but the phytoplankton they grazed upon flourishes. Wind and waves can now stir up unprotected sediments. Often, the fish community becomes dominated by species that forage on the bottom, further agitating the sediment and maintaining the turbid condition. Thus, turbidity stabilizes turbidity.

Restoring such a turbid lake to its previous clear, vegetated state is famously difficult. Simply lowering the nutrient level to what it was when the lake become turbid is insufficient to cause the water to clear. The nutrient level has to be reduced much lower than that, a lag effect known as "hysteresis." One set of self-reinforcing ecological feedback mechanisms stabilizes the clear regime, and another set stabilizes the turbid regime. In between, there's an unstable hump or threshold to cross; the lake cannot settle in some halfway condition. It's almost as though the lake needs convincing to drop one set of processes and system rules, cross the threshold, and take up another set. In the language of complex adaptive systems, these alternate processes create basins of attraction.

For some turbid lakes, after nutrient levels have been lowered, temporarily reducing fish stocks—removing about 80 percent with nets—can supply the needed nudge. Marten Scheffer, of Wageningen University in the Netherlands, calls this one-time treatment "shock therapy." He says that "it's common practice now in this part of the world to use that 'shock therapy' in addition to nutrient reduction to flip lakes." Although it doesn't always work, some lakes remain clear a decade later.

All shallow lakes are not quite so simple, of course. "There's no one single threshold," Scheffer says. For instance, a lake's critical phosphorus level depends on the depth and size of the lake, its climatic zone, and other factors. Lake systems can also exist in more than just these two simplified regimes. Other communities dominated by filamentous cyanobacteria or floating plants may also become self-reinforcing. A few rare lakes flip every five years on their own because of an internal process. "The complete story is much richer if you look in more detail, even if you look just at lakes, which we know well," Scheffer says.

Theoretical modeling coupled with field observation has shown that ecosystems can exhibit a range of responses



This curve depicts how regimes shift. If the system is on the upper branch, but close to the fold point F_2, a slight change in conditions may push it past that point, causing a catastrophic shift to the alternate regime (forward shift). The system exhibits hysteresis when the conditions are reversed; it does not shift back until conditions reach the other fold point, F_1 (backward shift). Reprinted with permission from Macmillan Publishers Ltd: Nature *(doi:10.1038/35098000), © 2001.*

to a change in conditions. Systems that respond proportionally and incrementally with a change in some key variable—linear systems—tend to be predictable and can usually be reversed. In other cases, a system's response to change may be more or less linear, but its rate of change accelerates around a critical threshold condition. These systems, too, can theoretically be coaxed back along their response curve if conditions are adjusted appropriately.

In some systems, the response curve folds back on itself so far that it essentially breaks in two. The two ends of the curve represent two alternate regimes, and for a certain range of conditions, the system can exist in either regime. But these alternate regimes are separated by unstable threshold values that cause the system to fall toward one regime or the other. The hysteretic behavior of the lake makes sense in light of this broken curve. In the lake example, the phosphorus level has to be lowered far enough that the system state can essentially jump from one regime to the other.

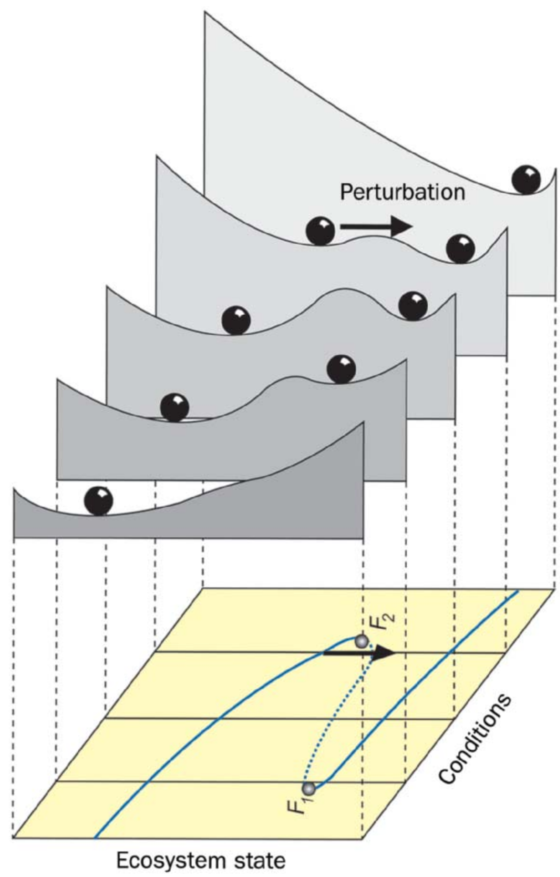
The idea is often illustrated with the metaphor of a stability landscape: a ball in a cup, or a ball in a basin. The ball represents the current state of the ecosystem. The valleys (or basins) are the alternate regimes. The humps or hills in between are thresholds. Picture a ball that dynamically adjusts its position within its basin, while the basins themselves continually fluctuate and change shape as external conditions (such as climate) vary. Some systems may have more than two possible basins.

An important consequence of this paradigm is greater awareness of the sobering prospect of irreversibility. In some systems, the hysteresis is so strong, and the response curve folds back so far, that a regime shift may be permanent. If a system can't be restored, then recognizing and avoiding looming thresholds becomes even more important. "In terms of dryland ecology and grazing land systems, that things are not necessarily reversible with rest has been, and continues to be, the primary conceptual advance," says Brandon T. Bestelmeyer, a range management researcher with the Jornada Experimental Range in New Mexico. Holding a tipping-point perspective leads to a completely different way of going about research and management, he says, from what gets measured to how observations are interpreted.

Resilience mind-set

In the model, the resilience of a regime corresponds to the size of its basin of attraction. In the shallow lake example, the clear-vegetated regime loses resilience (its basin shrinks) as the nutrient load increases. Meanwhile, a new attraction basin, the turbid regime, appears and enlarges. Finally, the ball tips to the alternate regime, which also has its own level of resilience. "Resilience is not always a good thing," says Ann P. Kinzig, of Arizona State University. Indeed, all too often, seemingly perverse resilience characterizes degraded ecosystems.

Even so, resilience provides a potentially hopeful perspective on the two faces of persistent dynamic regimes. Managers who want to preserve a desirable regime would work to increase its resilience and, possibly, try to decrease the resilience of the alternate regime. But if the current regime is not desireable, then the efforts turn to decreasing the resilience of the current state and increasing that of the desired state. Managing for resilience is easier said than done, however, as researchers acknowledge. Biodiversity is



This graphic depicts how external conditions shape multiple-regime ecosystems. The regime shift depicted in the figure on the previous page is shown on the bottom plane. The stability landscapes (vertical planes) depict the regimes possible at five different conditions. Valleys represent basins of attraction, and their size corresponds to resilience. Hills correspond to thresholds, the unstable middle section of the folded curve, while the ball represents the current ecosystem state. When a basin is shallow, even a moderate perturbation can knock the ecosystem into an alternate basin. Reprinted with permission from Macmillan Publishers Ltd: Nature *(doi:10.1038/35098000), © 2001.*



This series of photographs shows a grassland to shrubland regime shift in New Mexico. In resilient grassland, shown on the left, interconnected grass stabilizes soil, and bare patches measure less than 50 centimeters. Resilience declines as grass becomes disconnected, and more bare ground becomes connected (middle); gradual erosion occurs and mesquite shrubs spread. Although vulnerable and nearing the tipping point, system recovery is possible with grazing management. At right, grass has disappeared and erosion has become severe in "streets" between mesquite coppices; recovery is not likely. Photographs: Brandon T. Bestelmeyer.

among the attributes that contribute to resilience, but more is involved than just species numbers, as marine scientists recently demonstrated.

Coral reefs worldwide are ailing from the same constellation of assaults: declining water quality, overfishing, and the effects of climate change. In many places, fleshy seaweeds now blanket the corals, a regime shift that may be irreversible. Over the past 30 years, the Caribbean has lost 80 percent of its hard corals, and the remaining reefs are also in jeopardy. How did it happen? Land-use changes caused an influx of nutrients to the water, fertilizing algae. Grazing fish suppressed the algae, until overfishing reduced their ability to do so. Urchins substituted for a while, but when they were struck by disease, seaweed took over. Blindsided by the shift, scientists pieced the sequence together only afterward.

It is generally thought that the more species that occupy various functional groups, such as grazers, dead coral crushers, and so on, the more response diversity the system musters when disturbance hits and thus the greater its resilience. Compared with Australia's Great Barrier Reef, which is still relatively healthy, the Caribbean is handicapped by less functional diversity. But researchers with the Australian Research Council Centre of Excellence for Coral Reef Studies and James Cook University have found that even rich herbivore biodiversity may not offer the protection one might assume.

To simulate overfishing, Dave Bellwood and colleagues set up large cages along sections of the Great Barrier Reef. Grazers such as parrotfish and surgeon fish usually keep the reefs mowed, and as expected, excluding them allowed seaweed to take over. A few years later, the cages were removed and cameras were set up to record reef recovery. Dozens of species of herbivorous fish pecked at the dense weedy stand, but none made a dent in it. The species that ordinarily prevent regime shift could not reverse it.

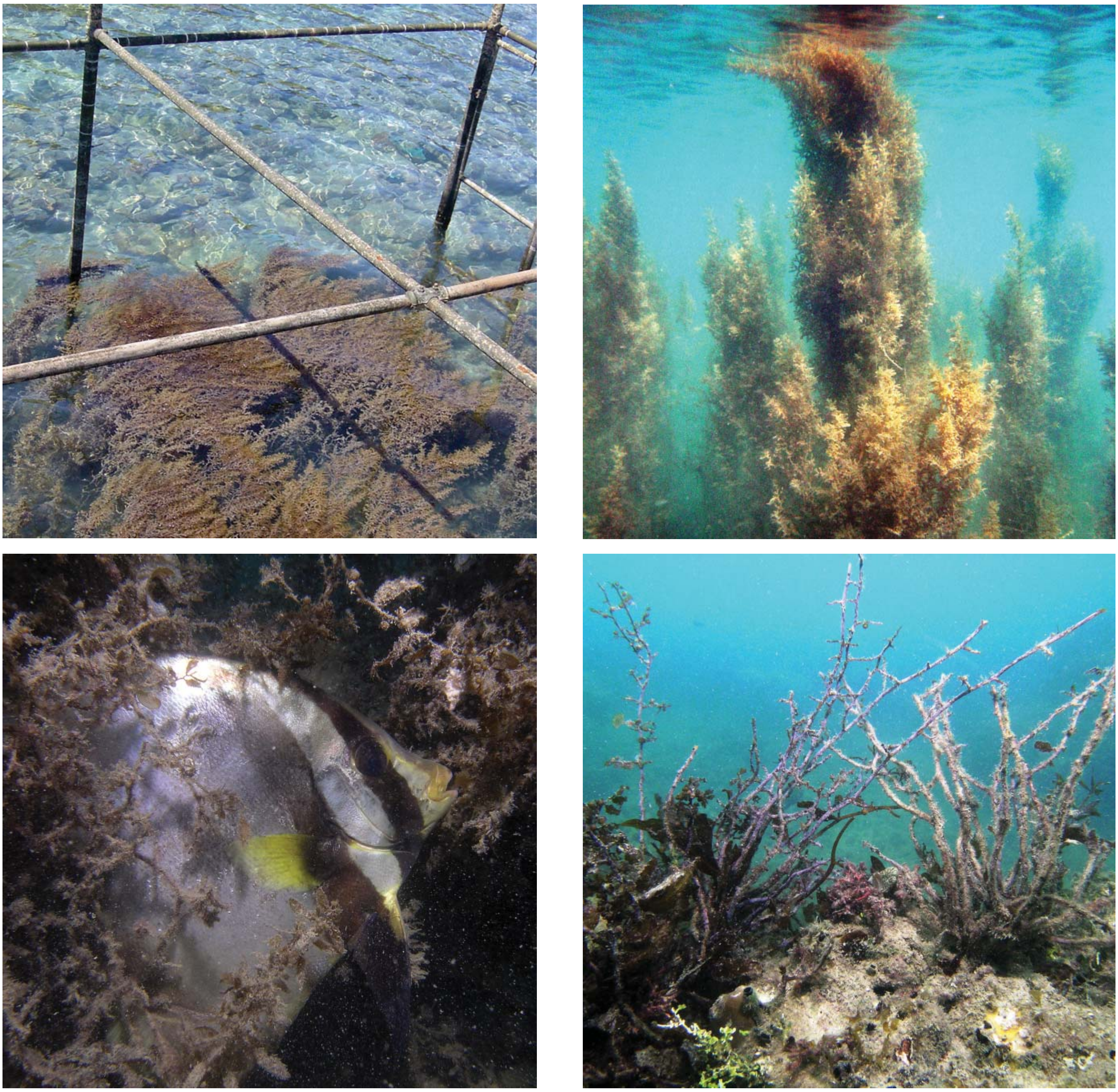
Unexpected aid did arrive, however. Within five days of showing up, batfish halved the size of the weedy stand, and they removed it altogether in eight weeks. Surprisingly, batfish are relatively rare and were thought to feed only on plankton and invertebrates. Batfish represent a "sleeping functional group," Bellwood says, meaning they are capable of performing a vital role in the reef but do so only under exceptional conditions. Other major weed eaters are already nearly gone (dugongs) or seriously endangered (green turtles). Yet batfish, attractive to spearfishers, have no specific legal protection, and their young depend on mangroves, also in decline in many areas. The resilience of the inshore Great Barrier Reef, then, may be linked to the fate of mangroves. Identifying the functional groups that underpin the resilience and regeneration of complex ecosystems and protecting them remain a challenge.

Prediction, prevention, and reversal

Unfortunately, the best way to find tipping points so far has been to cross them—a dangerous proposition—so researchers hope to find early warning signals of impending regime shifts, particularly desertification. Arid ecosystems constitute 40 percent of Earth's land, and the Millennium Ecosystem Assessment predicts that the increasing pressures of human activities and climate change will lead to desertification affecting more than one-fourth of the world's population.

With the help of computer modeling, researchers are learning to read vegetation patterns in some arid ecosystems. Given ecosystems' complexity and magnitude in space and time, mathematical models are indispensable tools for generating and testing hypotheses, developing ecological theory and advancing knowledge. Despite ecosystem complexity, a handful of variables usually controls most systems. The trick is finding the variables that characterize the dominant processes in a particular place.

Because water is the limiting resource in an African system under study, plants have to make a spatial compromise in a process called local facilitation. Rain that falls near a plant is more likely to infiltrate the soil (assisted by penetration of roots) than to run off, and less likely to evaporate (because of shading). Plants, therefore, benefit from being near a neighbor, and they also benefit from harvesting



Cages over a section of the Great Barrier Reef exclude fish to mimic overfishing (top left). Unchecked by grazers, seaweed overtook the coral (top right). When the cages were removed, grazers returned, but they couldn't restore the reef. Surprisingly, batfish (bottom left) cleaned off the seaweed within weeks (bottom right), even though they are relatively rare and were not thought to be herbivores. Photographs courtesy of ARC Centre of Excellence for Coral Reef Studies.

their own water from unoccupied soil; but if the plants are too far apart, they suffer. Vegetation can survive once it is present, but bare soil is too hostile to colonize alone.

Changes in vegetation patterns follow a sequence as stress (such as less rainfall or more grazing) grows. First, gaps appear within the homogeneous cover. As stress increases, the gaps widen, producing labyrinth and stripe patterns, which then fall apart into spots. Models show the patches becoming smaller and smaller until they disappear when rainfall decreases beyond a threshold, leaving bare soil.

This is another example of hysteresis: a modest increase in rainfall does not restore vegetation, nor does it reverse the pattern sequence, because again the internal positive feedback mechanism—local facilitation—fails. Increasing the rainfall well beyond the level preceding the catastrophic shift eventually brings back labyrinth patterns, but not spots. "From looking at the pattern alone, you know the history," says Max Rietkerk, of

Overuse threatens drylands around the world, transforming shrublands (top left) into small shrub patches (middle left) and degraded savannas (bottom left). Rainfall pulses may help reestablish trees in degraded landscapes, depending on the herbivores present (top and bottom right). Fast-growing tree seedlings can escape native lizards in north Peru, but growing conditions are less favorable in central Chile, and more voracious introduced herbivores (not pictured) limit tree recruitment. Herbivore exclusion combined with a rainy pulse might restore such areas. Photographs: Milena Holmgren (left three, top right), Alessandro Catenazzi (bottom right).

Utrecht University in the Netherlands. A spotted pattern heralds a trend of diminishing rainfall. He cautions that not all drylands operate this way. Models must be customized to each specific system and verified against real-world observations.

Rietkerk hopes to couple satellite or aerial photography with this understanding of vegetation patterning to create regional resilience maps that would allow researchers to predict when vulnerable regions are dangerously close to a threshold. Ideally, policymakers would respond by, for instance, encouraging people to remove cattle from stressed areas, so that a disastrous shift could be prevented.

Alternate dynamic regime theory has also suggested taking advantage of the rainy pulses of climatic oscillations to restore degraded arid ecosystems. During El Niño episodes, rainfall increases dramatically in South America and the central Pacific islands, and droughts parch large parts of Australia, the Philippines, and Indonesia. The alternate phase, La Niña, is roughly the reverse. The oscillation is irregular, about every three to six years, and climate change may increase the frequency.

Milena Holmgren, of Wageningen University, studies dry, hot South American woodlands, where seedlings struggle to survive—they die unless they're under a canopy of adult plants. Excluding the

Visit these Web sites for more information:

Resilience Alliance: *www.resalliance.org*

Ecology and Society (formerly Conservation Ecology): *www.ecologyandsociety.org*

World Resources Institute: A report of the "Reefs at Risk in the Caribbean," *http://pubs.wri.org/pubs_pdf.cfm?PubID=3944* herbivores that normally eat the plants doesn't boost the plants' chances of survival, because it's still too hot and dry for the seedlings. An El Niño year can deliver up to 10 times more rain in some regions, yet the extra water may not help if the herbivores remain. But by excluding herbivores during a rainy pulse, the system could flip back to a woodland state.

Tree ring studies in northern Peru indicate that extreme rainy pulses have facilitated the establishment of tress and shrubs in the past, providing some proof of principle. Seedlings in Peru grow fast enough to escape being decimated by the native lizards that prey upon them. In central Chile, however, seedlings grow more slowly and cannot escape introduced European rabbits and hares. Temporarily excluding the grazers may help in Chile, allowing a woodland regime to become established. As in the shallow lake example, a one-time reduction of certain animals, combined with an altered resource level, changes the basins of attraction so the ball can tip back into another trough.

Social–ecological systems

With the ever-increasing human pressure on ecosystems, scientists say, a tipping-point perspective is essential. They warn against using the old resource-management paradigm—the one that assumes ecosystems are linear, predictable, and controllable—to monitor ecosystem services.

Attempting to dial up some optimal mix of ecosystem services may well backfire, because different ecosystem services are strongly linked together ecologically, and changing one thing changes others, often in unpredictable ways. Furthermore, different landscapes produce different bundles of ecosystem services. "You can't just go halfway between them," says Garry Peterson, of McGill University in Montreal. "The reinforcing processes are either going to push you one way or the other."

Social dynamics such as economic incentives or regulatory constraints are often what keep an ecosystem on one side or the other of a threshold. Many researchers routinely refer to social–ecological systems, giving the two domains equal weight. "You can't divorce the two of them and think about them independently," says Lance H. Gunderson, of Emory University in Georgia, who studies the policy and management tangle in Florida's Everglades.

In a human-dominated world that is undergoing multiple global changes and is increasingly likely to toss up surprises, building greater social capacity to cope with uncertainty becomes part of the challenge. Social resilience and ecological resilience intertwine.

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