Ratcheting Down the Coral Reefs

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Coral reefs are continuing to deteriorate around the world, despite millions of dollars' worth of government effort per year, the commitment of more than 450 nongovernmental organizations, and a long list of successful accomplishments. Researchers and managers must become more aware of positive feedback, including the self-reinforcing ecological, technological, economic, cultural and conceptual processes that accelerate the degradation of coral reefs. Much of the research on coral reef damage has focused on its proximal causes (e.g., global warming, increased atmospheric carbon dioxide, overfishing, pollution, sedimentation, and disease) rather than its ultimate causes, the increasing human population and associated economic demands. To stop the deterioration of coral reef ecosystems, management must be proactive, terminating the self-reinforcing processes of coral reef degradation rather than perpetually restoring reefs or resource stocks. This can be accomplished only by clarifying the entire economic picture to instill more responsible behavior in the public.

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Nongovernmental organizations (NGOs) and government agencies have committed substantial effort and funds to reversing the decline in coral reefs and coral reef resources, but with little success. As of 25 July 2004, the International Directory of Coral Reef Organizations (*www.coralreef.org*) had listed 691 organizations dedicated to saving coral reefs, including 451 NGOs. In 1998, President Clinton's Executive Order 13089 established the US Coral Reef Task Force, cochaired by the secretary of commerce and the secretary of the interior and composed of the heads of 11 federal agencies, the governors of 7 states and territories, and the presidents of the Federated States of Micronesia, the Republic of Palau, and the Republic of the Marshall Islands. Over a three-year period, Congress appropriated nearly $100 million to the Department of the Interior and the Department of Commerce for the protection of coral reefs (Turgeon et al. 2002). Much has been accomplished in the way of mapping the distribution and extent of reefs, establishing marine protected areas, and producing educational materials and training workshops. These achievements are very important, and it is probable that if they had not been accomplished, the reefs would be in substantially worse condition than they are now. But despite the growing list of accomplishments from organizations committed to protecting coral reefs, the overall deterioration of reef resources is continuing on a scale at least as large as before. There is no evidence that the rate of reef degradation has begun to decrease (Patterson et al. 2002, Szmant 2002, Wilkinson 2002, Buddemeier and Ware 2003, Gardner et al. 2003, Garrison et al. 2003, Lang 2003). With so many resources committed to the battle against coral reef deterioration, why are we still losing?

Ludwig and colleagues (1993) use the term *ratchet* for self-reinforcing or positive feedback mechanisms that do not allow the processes of resource degradation to cease or reverse, even when the original activities that set the trajectory toward deterioration are removed. I will outline five categories of self-reinforcing mechanisms that intensify the degradation of coral reef habitats and resources: ecological, technological, economic, cultural, and conceptual.

Ecological ratchets

Corals are the foundation species of reefs, the organisms that define the habitat and provide its basic three-dimensional structure. Primary ecological ratchets are self-reinforcing processes that inhibit the recruitment and survival of the reef-building corals and favor an alternative stable state dominated by algae. Ecological ratchets can come into play when the abundance of corals is below a threshold at which corals become susceptible to (a) dilution of gametes at spawning, (b) disproportionate survival of predators of corals, (c) algal abundance at levels that can perpetually swamp the abilities of grazers, (d) facilitation of bioerosion, (e) decreased topographic complexity, (f) decreased prevalence of crustose coralline algae, and (g) alteration of habitats and food webs in ways that facilitate the establishment of invasive species that become incumbents. These disparate ecological ratchets can act synergistically.

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Allee effect. Inverse density dependence, or the Allee effect (in which reproductive success decreases with decreasing population densities below a threshold), is especially pertinent for sessile colonies that spawn gametes into the water column. Coma and Lasker (1997) showed that the percentage of successful octocoral fertilizations decreased exponentially downstream of a female octocoral colony and was essentially nil by 4 meters downstream. Another gamete-spawning species, the black-lipped pearl oyster (*Pinctada margaritifera*), has been rare at the Pearl and Hermes Reef in the northwestern Hawaiian Islands for 77 years since more than a hundred metric tons of *P. margaritifera* were harvested in 1927.

Motile species also can be susceptible to the positive feedback between decrease in population size and unsuccessful reproduction. A spawning aggregation of groupers in the Denges Channel in Palau was harvested in 1986 and had not begun to return by 1999. Sadovy (1993) summarized the status of the Nassau grouper (*Epinephelus striatus*) in the western Atlantic and found that a number of these populations had not recovered since they were fished down in the 1970s.

There is a common misconception that fish populations will always recover when fishing pressure is released. Recovery has occurred in many cases, but in other cases there has been no recovery after many years. Hutchings and Reynolds (2004) followed 230 overharvested stocks of fishes and found that most of them had not recovered after 15 years. Well-protected marine reserves can reasonably be expected to increase the biomass of fish stocks immediately, and population densities should increase over time, but there is no guarantee that reserves will bring back extirpated species.

The expectation that fish stocks would recover from low population sizes grew out of a theory of community structure and population dynamics based on competition for limiting resources. The logistic equation of population growth and the concept of competition for limiting resources are based on the assumption that when population densities are low, there is always more food and space per capita, and therefore the stock will grow faster and recover rapidly. This may be true for some species in some situations, but it is also possible that species may be reduced to levels below the threshold at which inverse density dependence becomes operative and population size decreases. Coral reef fishes that are especially vulnerable to such reductions include species that are sedentary or territorial; that gather from large areas into spawning aggregations at predictable locations and times; or that are characterized by sequential hermaphroditism, delayed maturation, slow growth rates, large adult size, long life span, sporadically successful recruitment, small population size, or sleeping in exposed sites.

Disproportionate survival of predators of corals. The density of staghorn coral (*Acropora cervicornis*) on the north coast of Jamaica continued to decline for years after Hurricane Allen passed in the early 1980s. This was partly a result of the concentration of predation on the few remaining fragments of coral (Knowlton et al. 1990). Positive feedback on predation intensity, and consequent decreases in coral population, begin once the abundance of living coral declines below a threshold at which the community-wide rate of coral recruitment and growth becomes less than the rate of predation by corallivores (Knowlton et al. 1990).

Algal abundance that swamps the abilities of grazers. Just as predation can outpace the ability of a prey species to recover, a prey species can perpetually outgrow the ability of predators to control it if predators are limited by some factor other than food, such as topographic relief for adequate shelter from their own predators. Williams and colleagues (2001) performed field experiments showing that even in unfished areas with negligible nutrient input, algae can outgrow the ability of herbivores to control them. Abundant algae inhibit coral recruitment, and so there is positive feedback as the few remaining corals die of normal attrition. The algae take over even more space, and the ability of herbivores to control the algae is further reduced.

Facilitation of bioerosion. Bioerosion weakens the coral colony skeleton and generates sediment. When storms bring strong wave action to the areas where corals form large tabletops and other three-dimensional structures, the weakened skeletons can break loose and act as projectiles, breaking off or abrading other colonies and augmenting the potentially damaging effects of wave action. The abrasion of coral colonies by projectiles or coarse sediment facilitates the colonization of their surfaces by algae. Bioeroders can colonize coral skeletons covered by filamentous algae more easily than they can colonize living coral tissue. Therefore, bioeroders act by positive feedback, because when weakened coral skeletons become projectiles, they augment damage to living coral substrata and facilitate the invasion of surviving colonies (Glynn 1997).

Decreased topographic complexity. Removal of living coral surface by crown-of-thorns starfish (*Acanthaster planci*) predation or by bleaching quickly opens areas of reef to infection by bioeroders, causing a rapid decrease in reef topography (Sano et al. 1987). The lowered topographic complexity decreases the amount of shelter available for reef fishes, thereby diminishing their abundance and reducing the grazing potential of herbivore populations. There is a positive feedback as the decreased topographic complexity reduces the ability of herbivores to control algae, and the increased abundance of algae reduces topographic complexity by limiting the ability of corals to recruit and grow.

Decrease in crustose coralline algae. Ecological ratchets can be synergistic. After a decrease in coral population, predation that focuses on the remaining corals increases their inverse density dependence and further opens the reef surface to algae, facilitating the invasion of bioeroders and foreign species that provide positive feedback for bioerosion. As bioerosion reduces topographic complexity, there are fewer refuges for reef fishes. With fewer herbivorous reef fishes to control them, populations of filamentous and fleshy algae can overgrow the crustose coralline algae (CCA) that provide structural support and inhibit the invasion of bioeroders. The lack of binding by CCA leads to weakening of substratum integrity. The recovery of a coral reef overgrown by algae is contingent on CCA growth, which stabilizes the substratum. Once CCA grows sufficiently to permit juvenile coral survival, the additional accretion and stabilization caused by coral growth creates a positive feedback that encourages further growth (Tucker and Wright 1990).

Alteration of habitats and food webs in favor of invasive species. Another ecological ratchet is the facilitation of invasion by alien species through habitat alteration. Indigenous species are usually adapted to their environmental conditions, but alteration of habitat can shift the competitive or predatory advantage to opportunistic invasive species (Orians 1986, Vitousek et al. 1996). Alteration of habitat is an inevitable result of global warming and human population growth. Once invasion is facilitated by human activities, positive feedback can occur when the growing population of foreign invaders alters the local habitat or food supply. With positive feedback, the invaders may become incumbent and nearly impossible to remove.

Technological ratchets

Technological advances such as scuba, night lights, dynamite, high-powered boats, GPS (global positioning system), monofilament line, and sonar have permanently altered the playing field for coral reef fishes, eliminating their places to hide. Traditional fisheries had technological limitations, and therefore a substantial breeding stock could often persist. When the population density of a fish species became low, it attained a relative refuge in scarcity as fishers switched to alternative prey. These adjustments tended to stabilize the system. In modern times, technological advances, in combination with the human population increase, have reduced the carrying capacity of the local fish populations. In Florida, for example, 50,000 sport divers put on diving gear each year to catch spiny lobsters (*Panulirus argus*) during a two-day sport season (Eggleston et al. 2003). Before the season begins, divers search for aggregations and mark locations with GPS so that they can anchor at key sites before dawn on the first day of the season. During the two-day season, 76 to 95 percent of the stock is taken. Eggleston and colleagues (2003) showed that there was no decrease in fishing pressure as the lobster became scarce. By removing all natural refuges, technology made the relationship between fishing pressure and resource abundance a density-independent functional response, destabilizing lobster populations and facilitating local extinction.

Technology has also facilitated the efficient and inexpensive manufacture of traps and monofilament gill nets. The efficient production of these devices makes them essentially disposable; they are often abandoned because they are relatively inexpensive to replace. The synthetic materials are enduring, however, and so abandoned nets and traps can "ghost fish" for decades. The National Oceanic and Atmospheric Administration has removed more than 434 metric tons of nets from coral reefs in the northwestern Hawaiian Islands, but they are being replaced as more abandoned nets drift in. In a six-month period, enforcement personnel for the State of Hawaii gathered nearly 5 miles (8 kilometers) of net from coral reefs on Oahu in the main Hawaiian Islands.

Refrigeration is also a technological ratchet. Before refrigeration, people would catch only what they needed for the immediate future. Once refrigeration and long-distance transportation became available, the world became a potential market, and there was no longer an asymptote on need.

With natural refuges rendered ineffectual by technological advances such as scuba, underwater lights, GPS, and high-powered boats, marine reserves are a necessary substitute that permits the protection of some reproductive stock. Quotas and temporary fishery closures do not effectively protect the larger individuals, which produce a disproportionate percentage of a fish population's reproductive potential.

Economic ratchets

Ecologists and economists traditionally have opposite perspectives on how "time is money." Considering the sale of a tree or a chicken, for example, an ecologist might consider that if it is sold later, the tree will be larger and bring a higher price, or the chicken will have laid more eggs, producing more chickens to sell. Thus, time allows the growth and reproduction of a resource. But an economist might consider that if it is sold later, the same resource depreciates in value. If the tree is sold now, the money will grow by compound interest. If the rate of the tree's growth is less than the rate of interest on the profits, then its owner should sell it now to avoid losing its value. Descendants of the person who sells sea turtles (or other slow-growing resources) will have more money in the long run if these resources are liquidated, because their growth and reproduction will be less than the compound interest on investments from their sale. The discipline of ecological economics, which considers the long-term value of environmental sustainability, has been developed for academicians (Costanza 1991), but it has not become mainstream.

Coral reef species targeted for commercial exploitation are mostly long lived, slow growing, site attached, and characterized by sporadically successful recruitment. These life history traits make liquidation rather than sustainable culture the favored economic procedure, because the rate of interest on the profit is greater than the rate of growth of the resource.

Depreciation is not the only factor that encourages liquidation. Overhead costs, poverty, present value, potential change in the market, and added value of rare and wild-caught resources can all favor liquidation. The large ships that have been customized for transporting live reef fish for the live-fish restaurant trade are expensive to operate and must return fully loaded to recover their costs. From a different perspective, people in poverty have families to feed and cannot wait to allow fish stocks to recover to sustainable levels. If the value of a stock is high at present, it may go down in the future, and so it is best to liquidate. Finally, the restaurant trade in live reef fish favors rare and wild-caught fishes. Fish that are common or raised in aquaculture are considered not to taste as good. This is a positive feedback ratchet because the value of the resource and the increased intensity of fishing pressure reinforce one another as the resource becomes more scarce and vulnerable.

A common view is that catch is limited by fishing equipment, not by fish stocks. Thus when a population is overfished, fishers invest in more sophisticated gear to catch the less accessible fish. This is also a positive feedback ratchet, because increasing investment in capital creates a greater obligation to catch fish to pay the debt (Ludwig et al. 1993). When fisheries harvest more than the carrying capacity of an aquatic ecosystem, the carrying capacity is lowered in a powerful positive feedback that further decreases fish stocks.

Cultural ratchets

In the traditional cultures of Pacific islands such as Hawaii, Yap, and Palau, the coastal coral reefs were not open to harvest by everyone. Local villages or districts had jurisdiction over their area of the coast. More vulnerable resources were restricted to a few consumers. In Hawaii, only the ali'i, or ruling chiefs, could eat the moi (*Polydactylus sexfilis*). (Female moi are generally larger than the males, so moi are particularly vulnerable to overharvest, because taking a substantial portion of larger individuals severely reduces the reproductive capacity of the species.) At least half the Hawaiian population was not allowed to eat ulua (*Caranx ignobilis*), kumu (goatfish [Mullidae]), or sea turtles (*Chelonia mydas;* Abbott 1984). On the other hand, some fishes that were not especially vulnerable to overfishing, such as the more common surgeonfishes (manini, kole, palani) and parrotfishes (uhu), could be consumed by anyone.

Some communities of indigenous fishers never developed a conservation ethic, because their local resources were vastly greater than their subsistence needs and harvesting abilities. When technological advances and global markets arrived, the local fishers were compelled to overharvest their resources before they were able to develop a conservation ethic.

The local management of resources is becoming more difficult with the globalization of the economy. It is possible for villages in American Samoa and Yap to manage local coastal marine resources, but how can indigenous people manage coastal resources in Waikiki or Hong Kong? There is general concern about global warming of the climate and of surface seawater, but the effects of global mixing of cultures on responsible management of resources by indigenous people is arguably as serious as global climate change. Economic centers such as Hong Kong have an economic pull over the entire tropical Pacific in the live-fish restaurant trade, and this influence has had a substantial effect on the populations of reef fish in the Pacific.

Conceptual ratchets

The primary conceptual ratchet is the "sliding baseline": a reduction in expectations and goals for each subsequent generation, with positive feedback in reduced expectations as the generations continue. Scientists are just as much affected by the sliding baseline as are fishers and the general public. They perceive as normal the status of coral reefs and coral reef fisheries as they first observed it when they entered their profession.

What can we do to sustain coral reefs?

No-take reserves, in which fish harvesting is prohibited, have increased the biomass and population density of fishery resources in numerous cases (Roberts and Hawkins 2000, Palumbi 2001). Likewise, the protection of certain areas with physical properties favorable to corals (e.g., frequent and constant water motion) may ameliorate the effects of increased seawater temperature and help protect brood stocks of corals (West and Salm 2003). But as human populations and economic pressures grow, the external influences of sedimentation, eutrophication, and chemical pollution often increase, even in no-take reserves. The positive effects of reduced fishing pressure can be overridden (Hutchings and Reynolds 2004, Jones et al. 2004). Even if many more marine reserves are created, the influence of detrimental processes may increase worldwide because of the increasing global population and economic demand. In the face of large-scale environmental factors such as increased atmospheric carbon dioxide, ultraviolet radiation, continental dust, disease, sediment, and pollution, relying on marine reserves to protect brood stocks of corals and fisheries is responding to the proximal causes rather than the ultimate causes of coral reef decline. Even if they cannot act directly to reduce human population growth and economic demands, scientists and policymakers must still not succumb to the ostrich factor (Hardin 1999) and be content with restoring reefs and repairing damage from proximal causes.

Pacific Islanders such as the Yapese, who live on a small archipelago between Guam and Palau, have been aware of the need to take human behavior into account when the scale of the ultimate problem is beyond direct control. I am not claiming that the wisdom of the Pacific Islanders in resource management is superior to science or to continental cultures, but it is worth giving some attention to their traditional approaches, because they live close to their resources and because their thoughts are not constrained by the same paradigms that we have inherited.

Margie Falanruw runs the Yap Science Institute. For a number of years, Falanruw produced an almanac calendar with traditional information and advice on ecology and resource management for the citizens of Yap. The calendar included a note that "when a Yapese woman harvests a corm of giant swamp taro, she plants three or four young plants in its place, and tends the taro patch in which they grow, in order to sustain the production of the taro patch that has passed into her care.... When men go fishing, they take without transplanting. We have less control over the sea." The microscopic larvae of fish and corals go out to sea, and their abundance and their arrival are beyond human control, even if scientists understand their biology and the current patterns affecting their survival and behavior. The Yapese understand that people can manage resources directly in the terrestrial environment, but to enhance resources in the marine environment, they must manage people.

In the marine environment, managers do not replace the fish, but instead set up kapu (taboo) areas or no-take marine reserves and let the fish replace themselves. A central element of fisheries management is human behavior. Gardner and colleagues (2003) determined that human activities are the main problems of coral reefs. They concluded that if human behavior were managed successfully, corals and fishes could handle the natural stresses in their environment.

Some Pacific Islanders have shown considerable acumen in dealing with global problems through local action. The seawater warming of 1997–1998 severely affected coral reefs at sites around the world (Wilkinson 2002). Most of the adult colonies of *Acropora* and many of the corals of other genera in Palau died of seawater warming, and living coral cover was replaced by algae. The citizens of Palau might well have thought that there was nothing they could do to control the problem of global warming. But Tommy Remengesau Jr., then vice president and now president of the Republic of Palau, published advice in the local newspaper about how citizens might facilitate reef recovery. He advised that residents avoid taking herbivorous reef fishes for food, because these herbivores, which control destructive algae, are essential for the survival of coral recruits. He also asked people not to step on the few living nearshore coral colonies that remained, because in doing so they would damage the brood stock needed for recovery of coral populations. Like marine reserves, these small-scale actions will not stop global warming, but they might at least facilitate replenishment of coral populations, and they could focus and secure a perception of community and responsibility among the stakeholders. The renovation of traditional community awareness of responsibility may be the most effective path to take in addressing the problem of coral reef degradation.

Restoring the concept of responsibility and awareness is a goal of most of the 451 NGOs currently working toward halting the degradation of coral reefs. One approach that has brought about changes in resource management with the support of the local citizenry is the use of economic reasoning. Long-term analyses of resource management can often show sustainable alternative uses to be more profitable than liquidation. An exemplary case is from Bermuda. Marine-based tourism and recreation grossed more than $9 million in 1988, over four times the gross income from commercial pot fishing. Evidence showed that fishing catches were declining substantially and that coral reef communities were deteriorating because of the overharvesting of herbivorous fishes and the subsequent takeover by algae (Butler et al. 1993). Hotel managers, charter-boat fishers, dive-boat and tour-boat owners, and other businesspeople agreed that the incomes of many people were threatened by the activities of a few fishers. They went to the Chamber of Commerce, which, in turn, made a request to the government of Bermuda. The government decided that the overall economics of the community would be best served if the fisheries were bought out, and so the commercial fishers were paid up to $75,000 per person, in addition to compensation for their gear (Butler et al. 1993).

As the human population and economic demands increase, as technologies advance, and as governments and societies spread across a more extensive realm, people's conceptual frameworks change. In the past, islanders were very much aware of their limited resources and of the consequences of overharvesting. If they overharvested their resources, they did not have the option of going to the grocery store or importing supplies from somewhere else. Traditionally, the reef resources of islands in the tropical Pacific, such as Yap, Palau, and Hawaii, were tightly regulated. In Yap, for example, when the owners of a particular stretch of reef decided that their fish were becoming too small or too scarce, they set out sticks with flags made of coconut fronds to indicate that a particular stretch was taboo or off limits. This section of reef could stay off limits for as long as two years, or until the owners decided the stocks had recovered (Brower 1983). In small, self-supporting isolated societies, responsibility was imperative because people were dependent on local resources.

The "Freedom to Fish Act" pending before Congress proposes that citizens should be free to take fish until there is proof that overfishing is the major cause of a decline. However, it is practically impossible to prove that overfishing is the cause of a decline: Any interest group that wants to delay a regulation that would moderate fishing activities can easily find alternative explanations for the decline in fish stock, argue that more data are needed, or focus on the uniqueness of the situation when the data were collected (Dayton 1998). Various colleagues, frustrated with this quagmire, have suggested to me that we should let the fishers carry out their objectives and suffer the consequences. The fishers would then accept the hard facts of the situation and allow recovery of the stocks. This would be risky, however, because the fish stocks may be low enough that inverse density dependence would prevent their recovery after depletion (Hutchings and Reynolds 2004).

Why have responsibility and accountability declined? In modern times, with the vast protection of the larger society and government, much of the public does not perceive an immediate dependence on responsible resource management, because modern society has a vast web of buffers that protect its citizens from the effects of local resource depletion. Without having to confront these serious consequences, human society can become detached from the results of its actions.

On a local scale, for example, high-powered boats or airplanes can take recreational fishers to farther sites when the sites nearby have been depleted. If they fail to catch any fish on a given day, people can go to the store and buy fish from a foreign country, an option not available to the traditional Pacific Islander. Commercial fishers who harvest their stock to the point that revenues no longer cover their costs can apply for government subsidies for more technological equipment (Ludwig et al. 1993, Iudicello et al. 1999). Even if fishery resources are totally depleted, island and coastal communities will not starve. When resources are overfished to the point that inverse density dependence comes into play, fishers can count on welfare. In modern, interconnected metropolitan societies, overfishing of local resources is not a life-threatening matter.

The restoration of individual responsibility despite the globalization of the economy and the buffering effects of modern society is a large-scale objective. Is there any hope for accomplishing it? A reconnaissance of traditional local control of resources in a number of sites in the tropical Pacific may indicate a path toward restoring responsibility. In the 1970s, Bob Johannes wrote about the demise of community-based resource management that was taking place in the islands of the tropical Pacific because of new technologies, the loss of local authority, the globalization of economic pressures, and the change of cultures to export-based cash economies. In order to build the local economy and join the world market, the management and control of resources from coral reefs was moved from local villages and expanded to a central market with open access to the resources. When outsiders had the legal right to harvest fish anywhere in the surrounding fishing grounds, any incentive for responsible management by the local residents was undercut. But over the past few years, community-based resource management has been restored in a number of sites across the tropical Pacific (Johannes 2002). The return to local management was motivated by a growing awareness of resource scarcity, by observation of the enhanced resource production by neighbors who were able to control access and activities in their traditional fishing grounds, and by renewed pride in traditional culture (Johannes 2002). Vanuatu recognizes the customary marine tenure of villages in its constitution, and Samoa recognizes village regulations concerning its nearshore fishing grounds as legal bylaws. When the local community is given authority to make management decisions, the motivation for responsible management is restored.

To take the Pacific Islanders' approach for reversing the deterioration in coral reef resources as the human population and economic demand increase may seem unrealistic for the global scale of the problem. But in view of the fact that the efforts of 691 agencies and the tens of millions of dollars per year of government support have not been successful, we should at least consider expanding three aspects of the islanders' approach: (1) develop interventions that are proactive rather than reactive—that is, focus on prevention, not just restoration; (2) deal with the ultimate causes (human population growth and associated economic demands), as well as the proximate causes of coral reef decline (seawater warming, sedimentation, overfishing, and others); and (3) promote responsible human behavior.

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