Mud, Marine Snow and Coral Reefs

The survival of coral reefs requires integrated watershed-based management activities and marine conservation

Eric Wolanski, Robert Richmond, Laurence McCook and Hugh Sweatman

Coral reefs are the most diverse of all marine ecosystems, and they are rivaled in biodiversity by few terrestrial ecosystems. They support people directly and indirectly by building islands and atolls. They protect shorelines from coastal erosion, support fisheries of economic and cultural value, provide diving-related tourism and serve as habitats for organisms that produce natural products of biomedical interest. They are also museums of the planet's natural wealth and places of incredible natural beauty.

Despite their recognized biological, economic and aesthetic value, coral reefs are being destroyed at an alarming rate throughout the world. Some countries have seen 50 percent of their coral reefs destroyed by human activities in the past 15 years. Some human influences are acute—for example, mining reefs for limestone, dumping mine tailings on them, fishing with explosives and cyanide, and land reclamation. Reefs that experience such insults often die; those that deteriorate but survive cannot recover to their original health as long as the disturbances continue. In other countries the disturbances are more chronic than acute. Reefs are assaulted by muddy runoff, nutrients and pesticides from adjacent river catchments, overfishing and global-warming effects. These disturbances affect the key parameters permitting reef resilience: water and substratum quality. As a result, corals fail to reproduce successfully, and the coral larvae arriving from more pristine reefs are unable to settle and thrive on substrata covered by mud, cyanobacteria or fleshy algae. Coral populations thus fail to recover or reestablish themselves.

Can science help save coral reefs? Despite much talk about managing coral reefs, the potential role of science is limited. But it is important: Scientists can demonstrate the key processes controlling the health of coral reefs and how human activities damage them. Then, we can hope, land-use managers and marine-resources managers will be able to modify human behavior to reduce or reverse damage to coral reefs. Toward this end we have developed a large-scale model for illuminating reef degradation and predicting the impact of future human activity.

The Coral Reef Ecosystem

The ecological functioning of a coral reef relies on the symbiotic association between corals and dinoflagellate algae (zooxanthellae). In this system, the dinoflagellates reside as symbionts within the cells of the coral host; the symbionts take in nutrients and produce metabolites from which the corals derive much of their energy. (Corals construct their hard habitat the way mollusks grow their shells, by accreting calcium carbonate.) The main functional components of a coral reef ecosystem include the hard corals, coralline algae, filamentous and fleshy algae, blue-green algae (cyanobacteria), and a host of invertebrates and fishes. Coralline algae are essential to a healthy reef because they cement reef structures and contain chemicals that induce metamorphosis in coral planula larvae. Filamentous and fleshy algae can be very abundant; indeed, the most telltale sign of a degraded coral reef is the replacement of corals by algae *(Figure 2).*

Three genera of corals dominate Pacific reefs: *Acropora, Porites* and *Pocillopora. Acropora* corals are the most spectacular; they are also framework builders, providing habitat for a variety of fishes and other reef organisms. They include the table, elkhorn, staghorn and fast-growing branching species. *Porites* corals include boulder or massive corals. *Pocillopora* corals include both coarsely and finely branching species, widely distributed across the Pacific and into the Red Sea.

Natural disturbances—including hurricanes (tropical cyclones or typhoons), river floods (*Figure 4),* earthquakes and lava flows—have affected coral reefs for millions of years; they are typically acute and have short-lived effects. Reef areas away from human influences often recover within a few years if water and substratum quality remain high. Acute, natural disturbances thus help maintain diversity on coral reefs by knocking back dominant species and allowing less competitive species to reestablish themselves.

Eric Wolanski received his Ph.D. in environmental engineering from the Johns Hopkins University in 1972. He is a leading scientist at the Australian Institute of Marine Science, where he studies tropical coastal oceanography and its biological implications for mangroves and coral reefs. Robert Richmond received his Ph.D. in biology from the State University of New York at Stony Brook in 1983. He is a professor of marine biology at the University of Guam Marine Laboratory. His research interests include sublethal stresses on coral reefs. Laurence McCook received his Ph.D. in biology from Dalhousie University in 1992; he is a research scientist specializing in the ecology of algae and reef degradation at the Australian Institute of Marine Science, working with the Cooperative Research Centre for the Great Barrier Reef World Heritage Area. Hugh Sweatman received his Ph.D. from Macquarie University in 1985; he is a research scientist at the Australian Institute of Marine Science where he leads the long-term reef-monitoring program. Address for Wolanski: AIMS, PMB No. 3, Townsville MC, Qld. 4810, Australia. E-mail: e.wolanksi@aims.gov.au

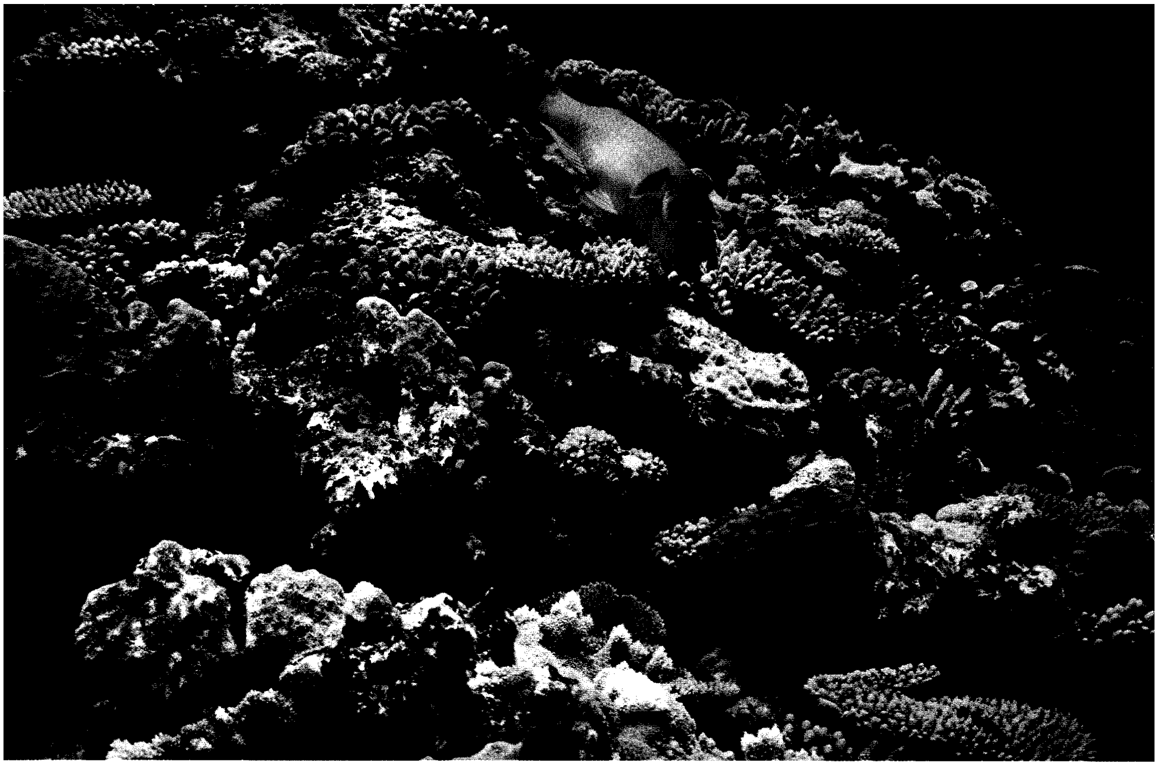

Figure 1. Healthy coral reefs such as this section of Australia's Great Barrier Reef not only are aesthetic treasures but also possess the greatest biodiversity of any aquatic ecosystem. In particular, reefs in which various species of the fast-growing, branching *Acropora* corals dominate provide habitat for a spectacular array of life both large and small. Despite the recognized value of reefs, worldwide they have been degraded dramatically over the past several decades owing to anthropogenic effects, and little has been done to halt their decline. A large part of the problem has been a lack of tools that would allow land- and marine-resource managers to estimate the relative benefits to reef health of various regulatory actions. The authors have developed a model that permits managers to estimate the effects on reefs of regulating various human activities. (Except where noted, photographs by the authors.)

The synergistic and cumulative effects of human disturbances superimposed over natural disturbances make recovery less likely and, in some cases, result in stable states dominated by algae.

Marine Snow

The water around coral reefs sometimes looks clear, but it can contain a variety of suspended matter, starting with inorganic particles such as resuspended calcareous material, fecal material, organic detrital particles, and mucus secreted by plankton, algae and bacteria. Corals themselves secrete mucus to cleanse their colony surfaces and as a metabolic by-product. This mucus prevents corals from becoming clogged with sediment particles and also shields against desiccation if they are exposed to air at low tide. Particles in suspension in water are rapidly aggregated by flocculation as well as by adhesive bridges of exopolymer (mucus). The aggregates resemble snowflakes and hence are called "marine snow" *(Figure 5)*.

Human activities on land often result in increased nutrient concentrations in coastal coral reef waters, which enhances the growth of algae. In turn, increased nutrients also result in an increased prevalence of marine snow. In the nutrient-enriched coastal waters of Guam and the Great Barrier Reef, marine snow flocs can exceed several centimeters in diameter. Wave-exposed waters have smaller flocs than do more sheltered areas.

Marine snow is almost neutrally buoyant and can remain in suspension for hours in turbulent reef waters. Near-shore waters, however, may contain additional suspended fine clay particles, rich in nutrients and detritus derived from land runoff. This mud in suspension readily attaches to the sticky marine snow, forming muddy marine snow. The clay particles act as ballast that makes the flocs settle onto coral reefs. Muddy marine snow flocs settle fast, typically at a speed of about 5 centimeters per minute—about 1,000 times faster than individual mud particles settle. The settled muddy marine snow has detrimental or even lethal effects on small coral reef organisms.

Corals and reef organisms such as barnacles are able to clean themselves of small settling flocs as long as the silt content remains low—less than 0.5 milligrams per square centimeter. At high siltation levels (4 to 5 milligrams per square centimeter) or when flocs are large (particles 200 to 2,000 micrometers in diameter), the coral polyps initially exude thick layers of mucus and die after less than one hour of exposure—a short time compared with the rate of natural marine snow deposition on coral reefs. Katharina Fabricius, at the Australian Institute of Marine Science, found, from laboratory experiments, that settling muddy marine snow flocs are far more hazardous to young than to older corals; the mortality rate is 10 times greater for young coral recruits (newly established animals) than for adult corals. Coral recruits typically die after 43 hours of exposure to muddy marine snow, a threshold that is routinely exceeded in nutrient-enriched coastal waters of the Great Barrier Reef but not in areas farther offshore. The presence of muddy marine snow on coral is often short-lived, resulting from a river flood or from resuspension by wind-generated waves in a storm. The settled muddy marine snow, having done its dirty work, is consumed by plankton and reef organisms, or flushed out by waves and currents. It usually leaves no "smoking gun," just a degraded reef.

Pollutants, including pesticides, heavy metals and hydrocarbons, also degrade coastal reefs. They can interfere with the chemically sensitive processes of reproduction and recruitment in corals and other reef organisms, such as synchronization of spawning, egg-sperm interactions, fertilization, embryological development, larval settlement, larval metamorphosis and acquisition of symbiotic zooxanthellae by young corals following recruitment.

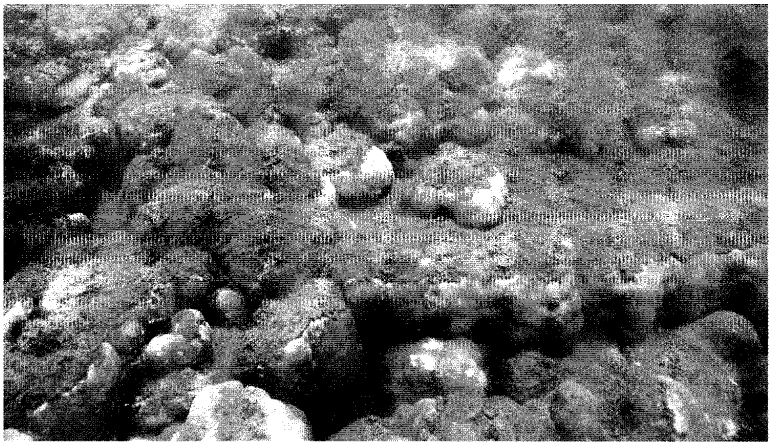

Figure 2. Most coral-reef decline, including this example at Palau, is tied in subtle but predictable ways to sediment-laden runoff from human activities within adjacent watersheds. Such runoff may not initiate the decline of a reef; more often, in fact, it prevents a reef from recovering from an acute shock such as a tropical cyclone. The effects are multiple. First, coral larvae, which may have drifted from a distant healthy reef, are unable to colonize because the reef has become covered in a muddy algal mat. Second, those larvae that do establish a foothold may be smothered by newly deposited mud. Third, and at least as significant, the prevalence of herbivorous fish, which feed on the fleshy algae that damage coral larvae, is inversely proportional to water turbidity. In much the same way that regular mowing maintains a fast-growing suburban lawn, herbivorous fish control filamentous algae and enable coral growth. A reef with adult corals but no recruitment of juveniles is in reality dead, but just doesn't know it yet.

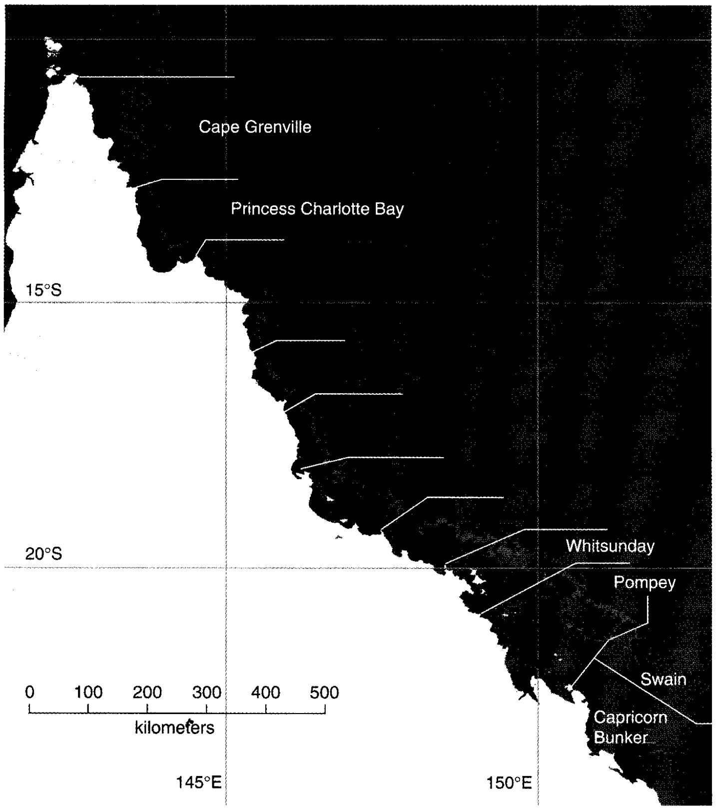

Figure 3. Model area included 261 reefs in several zones (*black type*) of Australia's Great Barrier Reef. Coral cover on 48 of these reefs has been monitored annually for more than a decade and shows great variability in time and space. This variability is characterized by a major decrease in coral cover following acute disturbances, such as a tropical cyclone or a river flood, and slow recovery thereafter. For instance, tropical cyclone Ivor in 1990 affected the coral cover on all the outer shelf reefs in the Cooktown/Lizard Island sector; 10 years later, the coral had recovered to cover more than 50 percent of the reef surface. Inshore reefs in the Cairns sector recovered slowly after losing coral cover through the combined effects of bleaching, an infestion of coral-eating crown-of-thorns starfish and tropical cyclone Rona in 1999. Among midshelf reefs near Townsville, Rib Reef is dominated by fast-growing tabulate *Acropora* corals. The reef cover was severely reduced by starfish infestation in the 1980s. Recovery was reversed by tropical cyclone Justin in 1997 and by another outbreak of starfish. Coral cover declined sharply on two midshelf reefs in the Whitsunday sector in 1997 as a result of tropical cyclone Justin.

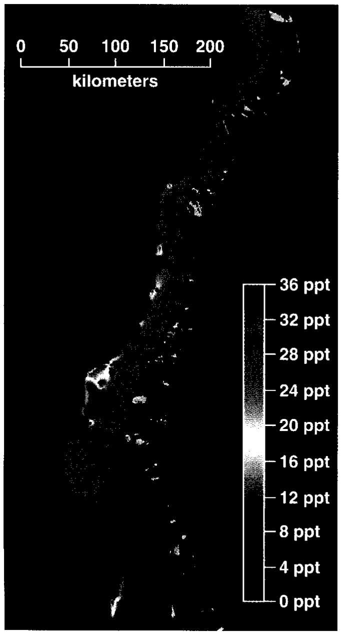

Figure 4. Muddy plume of the Burdekin River during a river flood, in the Great Barrier Reef near Townsville, can be seen in this oblique aerial photograph. The plume at this location spans 5 kilometers in width and is made readily visible by its high turbidity. Both the entrained mud and reduced salinity can cause acute damage to coral reefs. The map *(above)* shows the salinity distribution in a 400-kilometer-long section of the Great Barrier Reef for the 1991 river flood, predicted by Brian King using a three-dimensional hydrodynamic model. (By contrast, during times of normal river outflow, no reductions in salinity would be evident.) The model uses historical data on daily river discharges, as well as wind speed and direction data, to calculate the movement of river flood plumes from 1969 onwards.

The Toll

If, through increased muddiness or pollution, a single link in the coral reproductive chain is broken, the system cascades toward eventual demise. One hundred percent successful fertilization followed by 0 percent recruitment has the same outcome as 100 percent fertilization failure. Therefore many reefs near human population centers simply do not recover from disturbances. Less attractive *Porites* and *Pocillopora* corals replace the habitat-building *Acropora* corals, and, quite often, the benthos becomes covered by fleshy algae, sponges and worms. This in turn causes a shift in resident fish populations. Environmental degradation can also result from overexploitation of populations of herbivorous fishes, such as parrotfish and surgeonfish, which feed on fleshy algae. In overfished systems, fleshy algae can overgrow corals and prevent coral larvae from recruiting.

Human activity will continue to increase. As a result, coral reefs will increasingly degrade—as long as human activities on land and in coral reef waters continue to be managed independently. In both developing and developed countries, including Australia, the U.S., Japan and the French overseas territories, different government agencies deal with land-based issues and with marine and reef issues. In Australia, about four agencies deal with land-based issues and two with reefs (not counting fishing). It is as if land and sea were not interconnected ecosystems. This disconnect between watershed-based activities and marine conservation has resulted in serious environmental degradation throughout the world.

Science can help save coral reefs by providing land- and marine-resource managers with accurate and adequate data on key threats and the synergisms involved, specific indicators of reef resilience, as well as science-based models to predict the impact of various de-

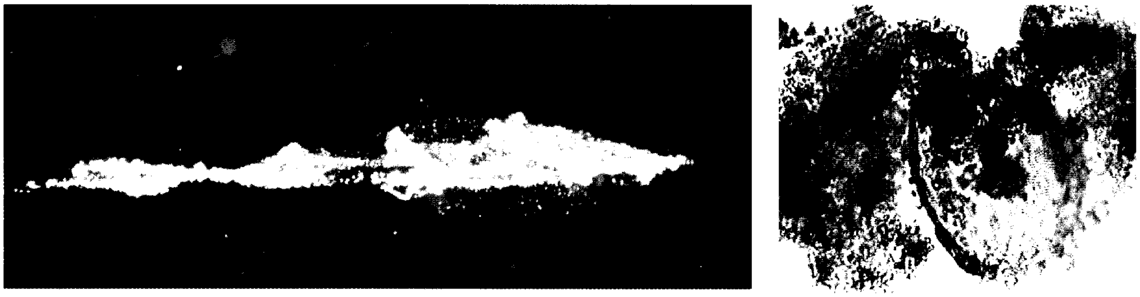

Figure 5. Marine snow flocs such as the one at left—photographed by Katharina Fabricius in reefal waters of Palau, Micronesia—may reach 30 centimeters in length but are typically smaller—0.5 to 5 millimeters in size. Flocs are formed by colonies of phytoplankton, fecal pellets, mucus secreted by bacteria and plankton, macroscopic aggregates of *Thalassiosira nana*, large diatoms, dinoflagellates and tintinnid ciliates, as well as a variety of other plankton and their remains. Additional mucus is produced by diatoms and microbes that colonize the nutrient-rich clay particles derived from erosion in river catchments. Mud readily aggregates on marine snow because it is sticky, forming muddy marine snow flocs, shown spanning 0.8 millimeters in the photograph at right. The mud acts as ballast, forcing the marine snow to settle on the corals, which they smother, particularly the juvenile recruits.

cisions about land use and reef fisheries on reef health. We have developed such a mathematical model for the Great Barrier Reef, for which extensive physical and biological data are available.

Modeling Reef Health

Australia's Great Barrier Reef stretches along 2,600 kilometers of the east coast of Australia from 25°S to 10°S. The domain of our model comprises 261 reefs in a 400-kilometer-long swath that extends from Lizard Island in the north to the Whitsunday Islands in the south. We wished to model the region believed to be most susceptible to anthropogenic impacts from land runoff *(Figure 4)*. Data to develop the model came from the Long-term Monitoring Program at the Australian Institute of Marine Science, which has surveyed 48 reefs annually since 1992 for assemblages of reef fishes and communities of benthic organisms in the upper northeast reef slope. Reefs for the program were chosen from three shelf positions (inshore, midshelf and outer shelf) at six latitudes, four of which fall within the model domain. Coastal reefs are the most affected by runoff but are not monitored because of poor visibility and the presence of crocodiles. The data on algal and coral cover *(Figures 6 and 9)* present evidence of large changes in the reefs over time in each region; the changes vary among regions. The data show a strong linear relationship between the abundance of herbivorous fish and water visibility *(Figure 7)*—as might be expected, since the fish keep algae populations down—and this observation is central to the formulation of a reef-health model.

The model uses algal cover as a proxy measure of reef health. The ecological components of the model include hard corals in two age groups, juvenile and adult, together with algae and herbivorous fish. Corals and fleshy algae compete for space, and herbivorous fish consume algae. Reef distur-

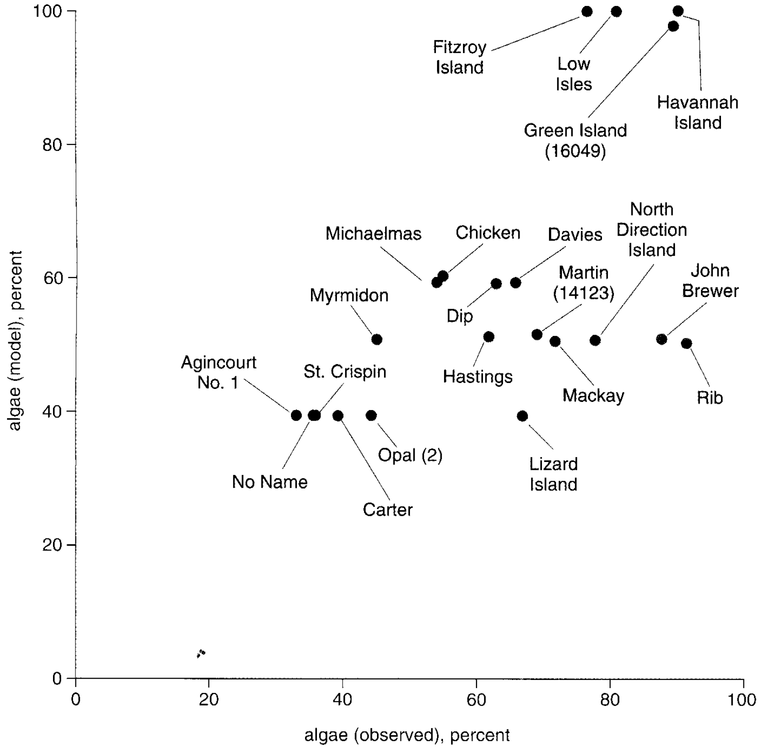

Figure 6. Algal cover, which displaces corals, serves in the model as a parameter for the health of the Great Barrier Reef. Its distribution has been monitored yearly since 1992 for the 48 reefs. This scatter plot of observed and predicted algal cover suggests that the model has promise. The outlier points *(red)* are reefs infested with the coral-eating crown-of-thorns starfish, *Acanthaster planci*. Such infestations are not incorporated into the model because the ecology of the starfish is insufficiently understood—in particular the ability of the starfish to migrate within a reef and between reefs. Masahra Ogura at Tokai University, Japan, has measured crown-of-thorns starfish migrating at speeds of up to 546 meters per day.

bances are of two types: acute and chronic. Acute, natural disturbances include river plumes, tropical cyclones and warm-water events resulting in bleaching. These events kill coral, thereby providing free space that is rapidly colonized by filamentous and then fleshy algae. Chronic disturbances come in the form of increased nutrient concentration and the influence of increased turbidity—at least 90 percent of the nutrients from land runoff arrive attached to mud particles. Corals can slowly recover from tissue remnants or through recruitment of larvae from healthier reefs. The recovery rate depends on nutrient concentration and the number of herbivorous fish available to consume algae.

It is not necessary to calculate herbivorous fish dynamics because people do not target herbivorous fish in the Great Barrier Reef; their abundance is predicted by water visibility. It is thus sufficient for the model to set the prevailing visibility conditions from field observations. The mean visibility has apparently halved since 1927—that is, turbidity has doubled—in the Low Isles area near Port Douglas.

Corals spawn each year at night in the early summer, on a date set by the moon phase. In the model, the spawn material is carried by water currents for about 10 days, a conservative estimated time of survival for coral larvae capable of recruitment, by which time most of the coral larvae have left their natal reef. The currents are affected by tides, forcing by the Coral Sea and wind, resulting in connectivity among reefs *(Figure 8)*. Recruitment rates were calculated for every spawning year since 1969, when reliable wind data became available. Outside of spawning periods, coral populations on individual reefs are isolated from each other.

Natural disturbances were determined from historical records of river floods and of the trajectory and intensity of tropical cyclones, for which data also are available since 1969. The coral die-off from tropical cyclones was calculated from the trajectory and intensity of the storms, using an empirical function derived from surveys of coral cover immediately before and after the passage of a storm. From models of river plumes, we extracted two key parameters: the minimum salinity and the duration of the river plume at each reef. These parameters in turn were used to calculate the die-off of coral.

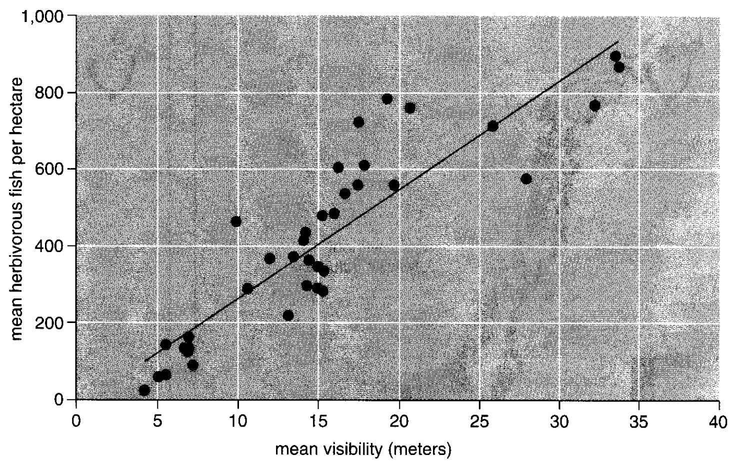

Figure 7. In Australia's Great Barrier Reef, a relation exists between visibility and the abundance of herbivorous fish. These data were averaged for 10 years of surveys at 48 reefs scattered along a 400-kilometer stretch of the coast. In the model, visibility is used as a proxy for herbivorous fish prevalence.

The model predicts reef health as parameterized by algal cover in a 400-kilometer-long stretch of the Great Barrier Reef *(Figure 9)*. Without human influences, coastal runoff degrades the reef in a zone whose width and degree of impact vary with latitude, with maximum damage in the Cairns region. Impacts within the zone vary considerably owing to the passage of tropical cyclones; as a result, reefs outside the coastal zone are occasionally covered with algae. The model further predicts that, with human activities on land, the zone of damage has already grown much larger than the natural state and will increase in size and intensity in the future, unless human influences are curtailed. At least as important, the model enables one to quantify the effects of various scenarios for control of land-use activities—anywhere from "do nothing" to "strict control." It offers decision makers and the public a science-based tool to decide what activities should be allowed, and how they should be controlled, on land and at sea, in order to produce a desired state of health for coral reefs. The model could presumably also be used to test the impact on reef health of various levels of fishing for herbivorous fish; this does not apply to Australia's Great Barrier Reef at present, but the question is relevant to most reefs elsewhere in the world, including Micronesia and the

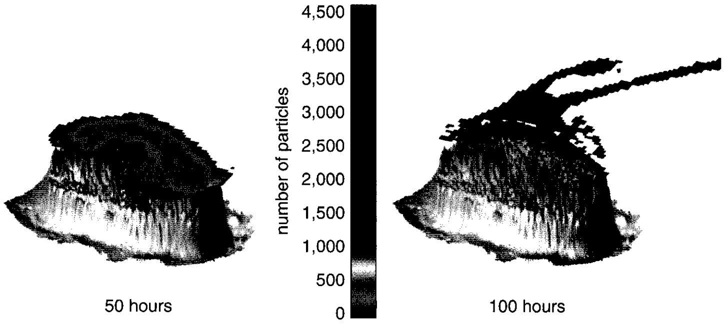

Figure 8. As visualized from the oceanographic model for Bowden Reef in the Great Barrier Reef, mass spawning of corals creates a plume *(left)* of coral larvae over the reef. This plume slowly mixes and is diluted by ambient oceanic waters while at the same time being carried away by the oceanic currents *(right)*. Larvae from one reef can settle on other reefs. This process enables degraded reefs to recruit coral larvae from healthier reefs. The distribution of source and sink reefs varies yearly with the wind after annual coral spawning.

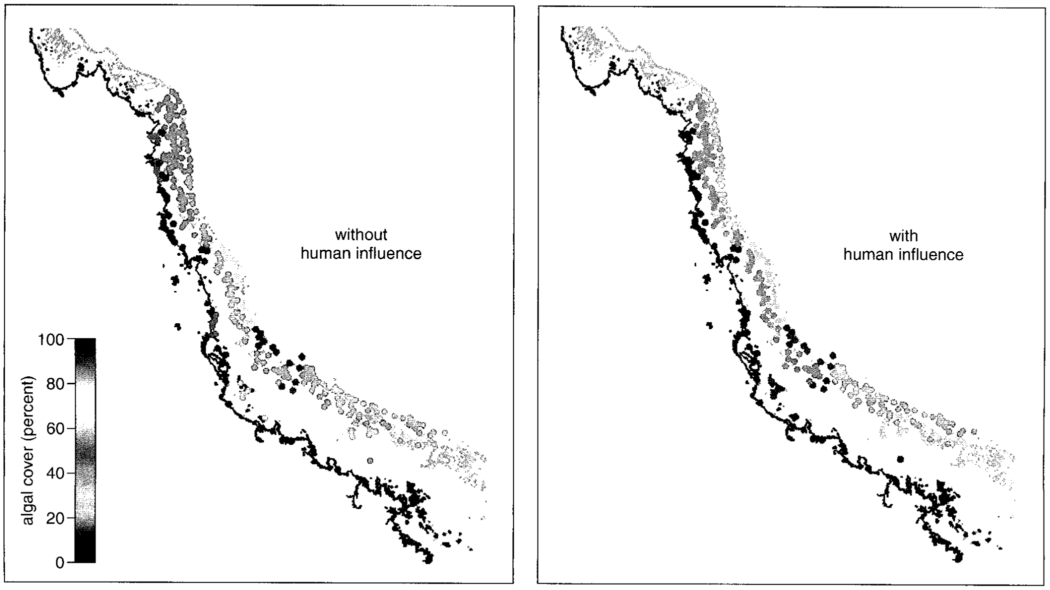

Figure 9. Model of coral health in this 400-kilometer-long stretch of the Great Barrier Reef was run with and without human influences. The parameter for reef degradation is algal cover. These results suggest that a wide swath is degraded by human activities on land, particularly in near-shore and mid-shelf reefs. The immediate cause of coral death at some sites may be natural, acute disturbances such as hurricanes and river floods. Anthropogenic effects, via land runoff, on water quality appear responsible for the failure of reefs to recover after disturbance. This results in a long-term decline in reef health.

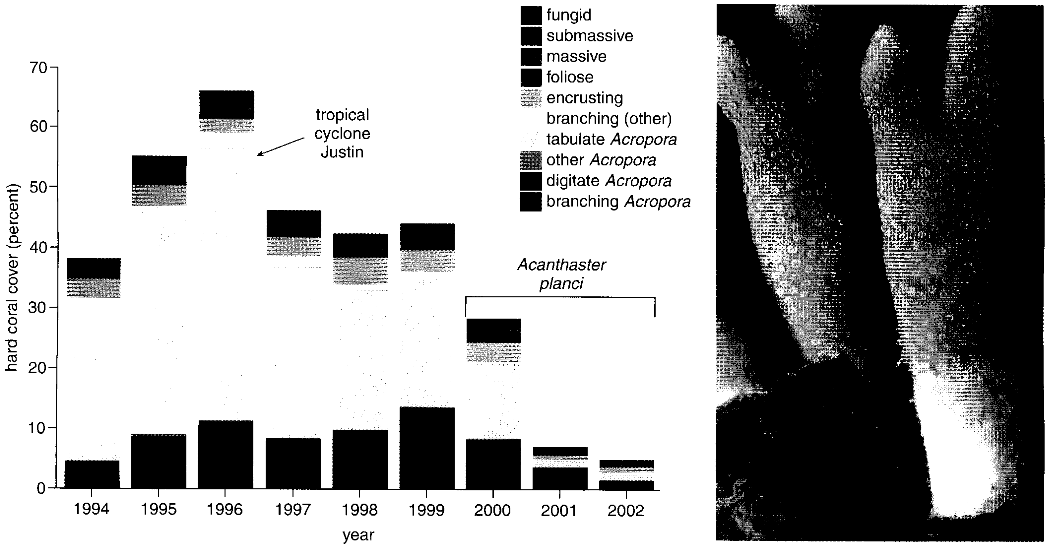

Figure 10. Annual surveys of hard corals at Rib Reef on the Great Barrier Reef show the effects of disturbances such as tropical storms and outbreaks of the coral-eating, crown-of-thorns starfish, *Acanthaster planci*. Such disturbances have different effects on corals with different growth forms. The horizontal plates of fast-growing table *Acropora* spp. rapidly overgrow other corals but are easily broken during tropical cyclones and are a preferred food for crown-of-thorns starfish. Massive corals grow slowly, their round shape helps limit storm damage, and their perforate skeleton allows coral tissue to be sequestered during episodes of stress from reduced salinity, sedimentation and eutrophication associated with agricultural runoff and sewer outfalls. After such disturbances, the dead corals are colonized by filamentous or fleshy algae. Algae also replace corals by direct overgrowth. In the photograph *(right)*, the brown seaweed *Lobophora variegata* is growing up around the branches of *Porites cylindrica*, smothering the coral tissue (shown by the dead, white skeleton where the researchers removed the algae covering the coral tissue).

U.S. Mariana Islands, where these fish are relentlessly pursued.

Limitations to Action

Like all ecosystem models, our model has limitations. These include unknown or poorly understood ecosystem processes, the lack of sufficient data on predisturbance water quality or habitat status, the lack of data from undisturbed sites and inadequacies in the measurement of water-quality parameters. Additional ecological processes could be added to the model, but this does not make it more useful because these new processes require additional parameters for which data are unavailable. Prediction of the response of a reef to human influences is thus inherently uncertain.

Unfortunately, uncertainty in ecosystem models cannot readily be quantified; too often, this is used as an excuse for inactivity, citing that "more research is needed before a sound decision can be made." Rather, the major impediment at this point appears to be political will. Scientists could do much more to exert influence—for example, by translating existing scientific data into the social and economic costs of inaction and making this information available to stakeholders and the broader community. Otherwise, "proof" of impacts will have to wait for serious degradation—and in comparison to current data, rather than to the undocumented predisturbance state. Clearly this outcome must be avoided. The objective should be prevention, not demonstration, of extensive degradation. Effective monitoring programs must go beyond documentation of coral reef demise and be used as tools to guide responses that prevent outright mortality.

Examples from Guam and Hawaii show that once a reef has been killed, it cannot be restored, even by importing outside corals, unless the underlying cause—for example, soil erosion in the adjoining catchment—is first addressed. The most logical approach to coral reef restoration is to alleviate those conditions that caused the decline and allow natural recovery to occur. More specifically, restore the water and substratum quality that allows corals and other reef organisms to successfully reproduce and recruit. This means controlling poor land-use practices that spill mud, nutrients and pesticides into coral reef waters; managing fisheries through quotas and fishing-gear restrictions; reducing tourism impacts; and establishing marine protected areas. Science has a crucial role to play in demonstrating the connections between land and reef ecosystems and the profound effects those connections can have.

Acknowledgments

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Links to Internet resources for "Mud, Marine Snow and Coral Reefs" are available on the *American Scientist* Web site:

http://www.americanscientist.org/articles/03articles/wolanski.html

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