ECOLOGY

Are U.S. Coral Reefs on the Slippery Slope to Slime?

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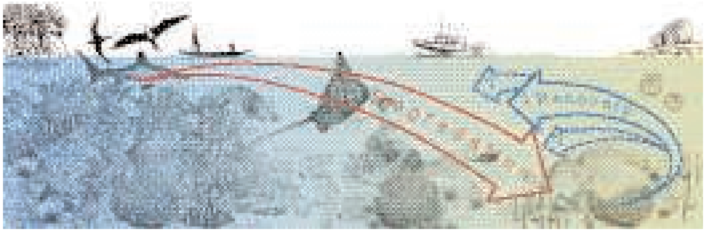
Coral reefs provide ecosystem goods and services worth more than $375 billion to the global economy each year (*1*). Yet, worldwide, reefs are in decline (*1–4*). Examination of the history of degradation reveals three ways to challenge the current state of affairs (*5*, *6*). First, scientists should stop arguing about the relative importance of different causes of coral reef decline: overfishing, pollution, disease, and climate change. Instead, we must simultaneously reduce all threats to have any hope of reversing the decline. Second, the scale of coral reef management—with mechanisms such as protected areas—has been too small and piecemeal. Reefs must be managed as entire ecosystems. Third, a lack of clear conservation goals has limited our ability to define or measure success.


The slippery slope of coral reef decline through time.

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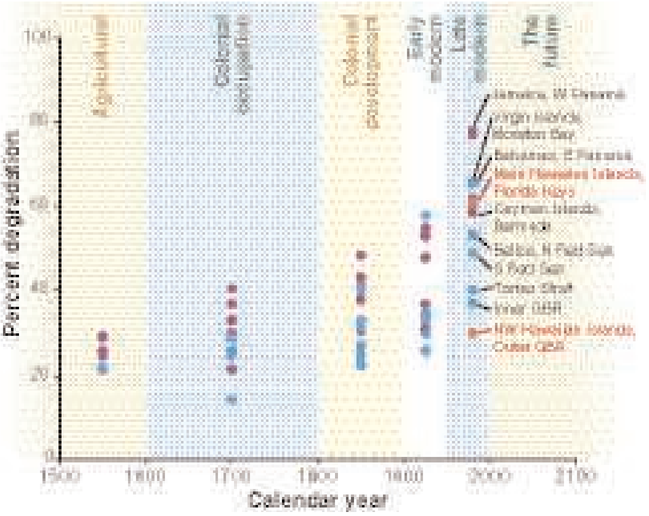
Large animals, like turtles, sharks, and groupers, were once abundant on all coral reefs, and large, long-lived corals created a complex architecture supporting diverse fish and invertebrates (*5*, *6*). Today, the most degraded reefs are little more than rubble, seaweed, and slime. Almost no large animals survive, water quality is poor, and large corals are dead or dying and being replaced by weedy corals, soft corals, and seaweed (*2*, *7*, *8*). Overfishing of megafauna releases population control of smaller fishes and invertebrates, creating booms and busts. This in turn can increase algal overgrowth, or overgrazing, and stress the coral architects, likely making them more vulnerable to other forms of stress. This linked sequence of events is remarkably consistent worldwide (see top figure, this page).

Even on Australia's Great Barrier Reef (GBR), the largest and best-managed reef in the world, decline is ongoing (*9*). Australia's strategy, beginning with the vision to establish the world's largest marine park in 1976, is based on coordinated management at large spatial scales. Recently more than one-third of the GBR was zoned "no take," and new laws and policies to reduce pollution and fishing are in place (*10*). Evaluating benefits of increased no-take zones will require detailed follow-up, but smaller-scale studies elsewhere support increased protection. Two neighboring countries, the Bahamas (*11*) and Cuba (*12*), have also committed to conserve more than 20% of their coral reef ecosystems. By contrast, the Florida Keys and main Hawaiian Islands are far further down the trajectory of decline (see bottom figure, this page), yet much less action has been taken.



Past and present ecosystem conditions of 17 coral reefs, based on historical ecology (*6*). The method consists of determining the status of guilds of organisms for each reef with published data, performing a multivariate, indirect gradient analysis on the guild status database, and estimating the location of each reef along a gradient of degradation from pristine to ecologically extinct reefs. Green, Caribbean sites; blue, Australian and Red Sea sites; red, U.S. reefs from the most recent cultural period.

What is the United States doing to enhance its coral reef assets? In the Florida Keys National Marine Sanctuary, the Governor and the National Oceanic and Atmospheric Administration (NOAA) agreed in 1997 to incorporate zoning with protection from fishing and water quality controls (*13*). But only 6% of the Sanctuary is zoned no take, and these zones are not strategically located. Conversion of 16,000 cesspools to centralized sewage treatment and control of other land-based pollution have only just begun. Florida's reefs are well over halfway toward ecological extinction and much more impaired than reefs of Belize and all but one of the Pacific reefs in the figure below (*6*). Large predatory fishes continue to decrease (*14*), reefs are increasingly dominated by seaweed (*15*, *16*), and alarming diseases have emerged (*17*).

Annual revenues from reef tourism are $1.6 billion (*1*), but the economic future of the Keys is gloomy owing to accelerating ecological degradation. Why? Without a clear goal for recovery, development and ratification of the management plan became a goal in itself.

Reefs of the northwest Hawaiian Islands have been partially protected by isolation from the main Hawaiian Islands (which show

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A ROADMAP FOR REVERSING THE TRAJECTORY OF DECLINE OF U.S. CORAL REEFS

Threat (time frame)	Critical first step	Results	Benefits
Overfishing (years)	Immediate increase of cumulative no-take areas of all U.S. reefs to >30%; reduce fishing efforts in adjacent areas	Increase in short-lived species, such as lobsters, conch, parrotfish, and sea urchins	Economic viability to lost or weakened fisheries; reduction in algal competition with corals
Overfishing (decades)	Establishment of large fish, shark, turtle, and manatee breeding programs; mandatory turtle exclusion devices (TEDs) and bycatch reduction devices (BRDs)	Increase in megafauna populations	Return of key functional components and trophic structure
Pollution (years-decades)	Stringent controls over land-based pollution	Increase in water quality	Reduction in algal competition with corals; reduced coral disease
Coastal development (years-decades)	Moratorium on coastal development in proximity to coral reefs	Increase in coral reef habitat	Increase of coral reef populations (i.e., reduced mortality)
Global change (decades)	International engagement in emission caps	Reduction in global sea surface temperatures and CO_2	Lower incidence of coral bleaching; increase calcification potential

degradation similar to that of the Florida Keys) and are in relatively good condition (see figure at the bottom of page 1725). Corals are healthy (*2*, *18*), and the average biomass of commercially important large predators such as sharks, jacks, and groupers is 65 times as great (*19*) as that at Oahu, Hawaii, Maui, and Kauai. Even in the northwestern islands, however, there are signs of decline. Monk seals and green turtles are endangered (*20*, *21*); large amounts of marine debris are accumulating, which injure or kill corals, seabirds, mammals, turtles, and fishes (*2*, *18*, *22*); and levels of contaminants, including lead and PCBs are high (*18*).

Until recently, small-scale impacts from overfishing and pollution could be managed locally, but thermal stress and coral bleaching are already changing community structure of reefs. Impacts of climate change may depend critically on the extent to which a reef is already degraded (*8*, *23*). Polluted and overfished reefs like in Jamaica and Florida have failed to recover from bouts of bleaching, and their corals have been replaced by seaweed (*2*). We believe that restoring food webs and controlling eutrophication provides a first line of defense against climate change (*8*, *23*); however, slowing or reversing global warming trends is essential for the long-term health of all tropical coral reefs.

For too long, single actions such as making a plan, reducing fishing or pollution, or conserving a part of the system were viewed as goals. But only combined actions addressing all these threats will achieve the ultimate goal of reversing the trajectory of decline (see the table above).

We need to act now to curtail processes adversely affecting reefs. Stopping overfishing will require integrated systems of no-take areas and quotas to restore key functional groups. Terrestrial runoff of nutrients, sediments, and toxins must be greatly reduced by wiser land use and coastal development. Reduction of emissions of greenhouse gases are needed to reduce coral bleaching and disease. Progress on all fronts can be measured by comparison with the past ecosystem state through the methods of historical ecology to determine whether or not we are succeeding in ameliorating or reversing decline. Sequential return of key groups, such as parrot fish and sea urchins that graze down seaweed; mature stands of corals that create forest-like complexity; and sharks, turtles, large jacks, and groupers that maintain a more stable food web (*4*, *5*, *6*, *24*) constitutes success.

This consistent way of measuring recovery (see the figure at the bottom of page 1725) and the possibility of short-term gains set a benchmark for managing other marine ecosystems. Like any other successful business, managing coral reefs requires investment in infrastructure. Hence, we also need more strategic interventions to restore species that provide key ecological functions. For example, green turtles and sea cows not only once helped maintain healthy seagrass ecosystems, but also were an important source of high-quality protein for coastal communities (*25*).

Our vision of how to reverse the decline of U.S. reefs rests on addressing all threats simultaneously (see the table above). By active investment, major changes can be achieved through practical solutions with short- and long-term benefits. Short-lived species, like lobster, conch, and aquarium fish will recover and generate income in just a few years, and benefits will continue to compound over time. Longer-lived species will recover, water quality will improve, and the ecosystem will be more resilient to unforeseen future threats. Ultimately, we will have increased tourism, and the possibility of renewed sustainable extraction of abundant megafauna. One day, reefs of the United States could be the pride of the nation.

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Materials and Methods

To determine the state of U.S. coral reefs along a global gradient of reef degradation, we used the methodology proposed by Pandolfi *et al*. (*S1*). The method consists of (i) determining the status of guilds of organisms for each reef using published data, (ii) performing a (multivariate) indirect gradient analysis on the guild status database, and (iii) estimating the location of each reef along a gradient of degradation from pristine to ecologically extinct reefs.

Guilds of organisms were defined on the basis of mode of nutrition (herbivore, carnivore), life habit (mobile free-living, sessile architectural), and size (for free-living species, large > 1 m, small < 1 m). The four free-living guilds with common examples are large herbivores (sea cows, green turtle, bump-head parrotfish), small herbivores (most parrotfish, sea urchins), large carnivores (sharks, crocodiles, monk seals, loggerhead and hawksbill turtles, barracuda, large groupers), and small carnivores (most fish and invertebrates). The three sessile, architectural guilds are reef corals, seagrasses, and suspension feeders (sponges, oysters).

Ecological status was scored on the basis of the most frequent status of species within each guild. The ecosystem state was scored for all 7 guilds for all regions. Each data entry was converted to an ordered multistate ranging from 1 (pristine) to 6 (globally extinct) (Table S1). The analysis conducted in (*S1*) included data on seven cultural periods, from prehuman to present, for 14 reef regions. In the present analysis, we used the entire database with all cultural periods used in (*S1*) plus data on only the present state of Florida Keys, main Hawaii islands, and northwest Hawaiian archipelago. The final data matrix had 714 cells (Table S2). Each of the scored cells had one or more literature references (Table S3).

We used standard principal components analysis (PCA). For this analysis, we added a single depleted reef with all 7 guilds classified as ecologically extinct (*S1*). To focus on patterns among regions rather than among guilds, eigenvectors were normalized to 1 and the analysis was calculated on the variance-covariance matrix. Thus, we preserved the Euclidean distances among the region-times in the reduced space and the 7 guilds could then be used to help explain the patterns in the regions. A scree plot of eigenvalues versus PC showed that only PC1 was significant ($\lambda_1 = 6.35$, $\lambda_2 = 0.36$, $\lambda_3 = 0.26$). PC1 explained 90% of the variance. To determine the degradation state of reefs we plotted the percent degradation as a function of the scores of each reef on the PC1 axis normalized so that the pristine state was equal to 0% degradation and the ecologically extinct state was 100% degradation.

Table S1. Ecological states and criteria used to assess the reef regions analyzed.

Ecological state	Criteria for classification
Pristine	Marine resource lacks any evidence of human use or damage. Example: Any prehuman population
Abundant/common	Human use with no evidence of reduction of marine resource. Example: No reduction in relative abundance or size of species
Depleted/uncommon	Human use and evidence of reduced abundance (number, size, biomass, etc.). Examples: Shift to smaller sized fish; decrease in abundance, size, or proportional representation of species
Rare	Evidence of severe human impact. Examples: Truncated geographic ranges; greatly reduced population size; harvesting of pre-reproductive individuals
Ecologically extinct	Rarely observed and further reduction would have no further environmental effect. Examples: Observation of individual sighting considered worthy of publication; local extinctions
Globally extinct	No longer in existence. Example: Caribbean monk seal

Table S2. Data matrix for the Florida Keys and Hawaiian islands. The larger data matrix used in this analysis is in the online supplemental material of (*S1*).

Site	Large carnivores	Small carnivores	Large herbivores	Small herbivores	Corals	Seagrass	Suspension feeders
Florida Keys	5	3	5	3	3	2	2
NW Hawaii	2	2	3	2	2	no data	2
Main Hawaii	5	3	4	3	3	no data	2

Legend: Ecological State
1 pristine
2 abundant/common
3 depleted/uncommon
4 rare
5 ecologically extinct
6 globally extinct
no data: no data exist to evaluate ecosystem state

Table S3. References for data matrix.

Site	Large carnivores	Small carnivores	Large herbivores	Small herbivores	Corals	Seagrass	Suspension feeders
Florida Keys	S2–S9	S6–S8	S3, S6, S7, S10, S11	S6, S7, S12	S13	S14, S15	S16, S17
NW Hawaii	S18–S22	S18, S21, S22	S18–S21	S18, S21, S22	S18, S23	no data	S18
Main Hawaiian Islands	S18, S21, S22 S24, S25	S18, S21, S22, S24–S28	S18–S21,	S18, S21, S22, S24–S28	S18, S27, S29, S30	no data	S18

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