CORALS AND CLIMATE CHANGE
Florida's Natural Treasures at Risk

ENVIRONMENTAL DEFENSE FUND

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November 2008

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This report is available online at www.edf.org/floridacorals

Acknowledgments

Diver doing survey. © Paul Humann 2008

Most of the marine-life photographs in this report were graciously provided by Paul Humann, founder and chair of the Reef Environmental Education Foundation (REEF). Founded in 1990, REEF seeks to conserve marine ecosystems by educating, enlisting, and enabling divers and other marine enthusiasts to become active ocean stewards and citizen scientists. REEF's Fish Survey Project trains volunteer scuba divers and snorkelers to collect and report information on marine fish populations; REEF's publicly available database includes the results of more than 120,000 surveys. REEF is headquartered in Key Largo, Florida. Its web site is www.reef.org.

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Cover: All photos courtesy NOAA, except photo of waterfront, which is © Terry Fisher 2008
Title page: Bluestriped Grunts. © Paul Humann 2008

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Staghorn Coral *(Acropora cervicornis)*. NOAA

Executive summary

Coral reefs are not only beautiful but also—at least for now—a huge economic boon to Florida (and the world). Many of the marine species that form the backbone of Florida's recreational and commercial fisheries depend on reefs for shelter, food, or both.

Unfortunately, coral reefs worldwide are under siege, and Florida's magnificent reefs are among the most vulnerable. The reefs just offshore of many of Florida's counties have taken thousands of years to grow and—given their importance to tourism and fisheries—are a key contributor to Florida's prosperity, supporting more than 70,000 jobs for Floridians, attracting millions of tourists, and generating more than $5.5 billion in sales each year.

"If we fail to curb greenhouse gas emissions, coral reefs are likely to dwindle into insignificance; they'll be reduced to rubble."

In recent years, though, Florida's coral reefs have suffered serious damage. One key culprit is unchecked emissions of greenhouse gases such as carbon dioxide (CO_2), largely from burning coal, oil, and natural gas. Rising concentrations of greenhouse gases in the atmosphere hurt coral reefs in many ways, discussed in detail below.

First, rising concentrations of greenhouse gases trap heat and contribute to global warming, which raises ocean temperatures. Warmer waters, in turn, trigger a harmful condition called "coral bleaching," and promote disease. A second impact—and one independent of warming—involves changes in the chemistry of the ocean: higher carbon dioxide concentrations in the atmosphere make the ocean more acidic, which stunts coral growth. Third, warming oceans and melting continental glaciers increase sea levels, potentially "drowning" reefs in depths below which sunlight is too dim to support photosynthesis by the tiny plants that help keep corals healthy, as well as increasing sedimentation. Fourth, global warming and warmer oceans bring bigger storms, which threaten weakened reefs. Finally, climate change makes it harder for corals to survive other environmental perils, including sedimentation, excessive nutrients in ocean water, collisions with boats, and overfishing.

A new report from a group of the world's leading climate scientists warns that to protect coral reefs worldwide—including Florida's reefs—from ruinous decline, it is essential is to take immediate action to reduce greenhouse gas emissions. (It is also important, of course, to address the other serious threats to the health of coral reefs.) As one top coral scientist explained, if we fail to curb greenhouse gas emissions, "coral reefs are likely to dwindle into insignificance; they'll be reduced to rubble."[1]

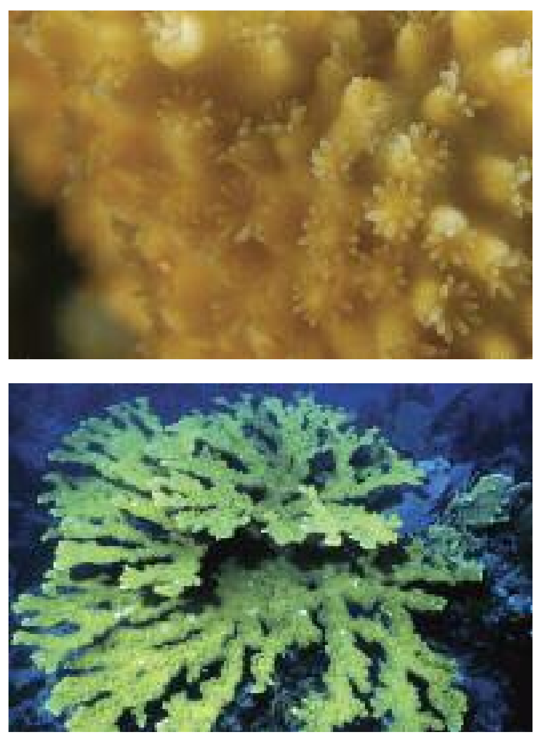
But the story doesn't have to end that way. With prompt action, we can remove the threat that climate change poses to one of the crown jewels of Florida's natural environment—and its economy.

The miracle of corals

A**mong the lower 48 states,** only Florida has significant shallow coral reefs—some 6,000 between Key Biscayne and Dry Tortugas alone.[2] Florida's coral reefs are concentrated in its southernmost counties, with some of the most spectacular reefs in the Florida Keys. Reefs built by elkhorn or staghorn corals currently extend as far north as northern Broward County, and high-relief underwater limestone cliffs (called "escarpments") support staghorn corals as far north as central Palm Beach County and other coral species in Martin, St. Lucie and Indian River counties.[3] (Elkhorn and staghorn corals are species within the genus *Acropora*.)

A coral reef is one of the most complex and diverse ecosystems in the world—but also one of the slowest-growing and most vulnerable. Florida's coral reefs have taken between 5,000 and 7,000 years to reach their present size.[4] After surviving for millennia against their natural enemies, the most important reef-building corals off Florida—staghorn and elkhorn corals—are now at such great risk that they were designated as threatened species in 2006.

Coral reefs are the product of extraordinary natural teamwork between tiny animals and tiny plants. The tiny animals are coral "polyps," which eat passing plankton, extract calcium compounds from seawater, and build stony skeletons to protect themselves. The tiny plants are zooxanthellae ("zoh-zan-THEL-ee"), algae that live in the polyps and use photosynthesis to turn sunlight into food (sugars) for corals—and provide much of the color we see in healthy coral reefs. Although other types of reefs can develop in deep water, coral reefs with symbiotic algae typically develop only in relatively shallow water, where



Top: Closeup of Staghorn Coral polyps. © Wade Cooper 2008. Bottom: Elkhorn Coral *(Acropora palmata)*. NOAA

enough sunlight reaches the tiny plants to enable them to grow.[5] Over time, under the right conditions, coral skeletons can form massive formations, called coral reefs.

As the satellite photograph at left shows, Florida's southern coasts (here, the Keys) are rich in the shallow waters that provide a natural habitat for coral reefs.

On land, tropical rain forests are famous for nurturing an extraordinary diversity of animal and plant life. As Professor Christopher Langdon, a nationally recognized expert at the University of Miami, explains, coral reefs are an "incredibly diverse ecosystem on par with the rainforests of the Amazon."[6]

Because of the many advantages they offer to other species, coral reefs cover a tiny fraction of the ocean floor but support a large portion of all marine life. The intricate nooks and crannies of coral reefs off the Florida coast, in particular, provide a home to hundreds of marine species, including a vast array of fish, lobsters, anemones, eels, crabs, shrimp, sea cucumbers, urchins, sea stars and octopi. For these species, a coral reef provides the perfect environment to feed, hide from predators, and rest.[7] Spiny lobsters, for example, stay hidden (and invisible to predators) inside coral reefs during daylight hours, and then emerge after dark to hunt for food.[8]

Besides nurturing the growth of countless marine species, coral reefs also buffer the shoreline from the full force of massive waves caused by hurricanes and other tropical storms. As waves come to shore, they break and expend some of their energy on the reef, which shelters the adjoining coast. In effect, coral reefs serve as natural breakwaters. But with the more powerful hurricanes that global warming is expected to bring, the ability of coral reefs to continue to perform this valuable function is at risk.

Top: Florida Keys from space. NASA. Middle: Professor Christopher, Langdon Rosenthiel School of Marine and Atmospheric Science, University of Miami. Bottom: Large school of Schoolmaster Snappers hovering around a Brain Coral. © Paul Humann 2008

Stresses on coral reefs

Human activity has imposed a wide range of stresses on coral reefs. Unsustainable methods of harvesting reef fish and shellfish, for example, have put significant strains on coral reefs in Florida and elsewhere. Nutrient loading of seawater—from dumping of sewage into the sea or runoff of nitrogen-rich fertilizer from farms—promotes growth of phytoplankton and seaweed, which compete with corals for space on the reef. Nutrient loading can also encourage the growth of "bioeroders" that grind up coral reef structures.

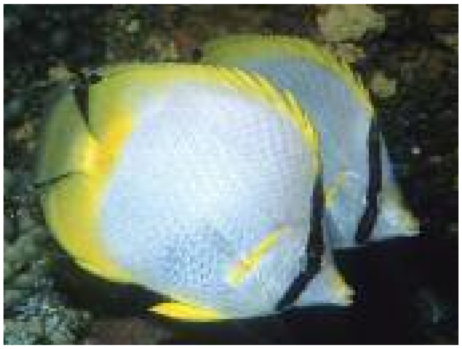
Deposits of sediments onto corals—often the result of development, agriculture, and large-scale dredge-and-fill operations for construction or "shore protection"—can interfere with the functioning of coral polyps and inhibit the establishment of new reefs. Boat collisions, along with vandalism and illegal theft of coral artifacts for sale, also do serious damage to coral reefs. And some types of nearshore construction, such as poorly planned seawalls, docks, and marinas, can result in the accumulation of damaging amounts of sediment on coral reefs.[10]

Although this report concentrates on the impact of climate change on coral reefs, each of these stresses on coral reefs is serious as well—and worthy of serious corrective action.

The importance of coral reefs to the Florida economy

The economic value of coral reef-related recreation

Florida's coral reefs attract millions of people to Florida's shores. The Florida Keys alone attract more than four million domestic and foreign visitors who drive, fly, or cruise each year to the most accessible coral reefs in the Caribbean Basin.[11] To put that number in perspective, about 16 million total visitors per year came to Southeast Florida (Monroe, Miami-Dade, Broward, Palm Beach and Martin counties) from out of state or abroad.[12]



Spotfin Butterflyfish. © Paul Humann 2008

The enormous value of coral reefs to Florida's economy was quantified in two authoritative studies focused on these five counties. Those studies were performed by the respected engineering firm Hazen & Sawyer, in conjunction with the National Oceanic and Atmospheric Administration (NOAA) and the Florida Fish and Wildlife Conservation Commission.[13] The Hazen & Sawyer researchers sought to determine the recreational value of coral reefs—whether for fishing, snorkeling, scuba diving, or viewing through a glass-bottomed boat.

The research team gathered data from hundreds of county residents, including owners of both private boats and commercial vessels, such as charter boats. They also interviewed hundreds of visitors about their reef-related tourism.

Applying their survey results to the five counties as a whole, the Hazen & Sawyer researchers estimated the total number of residents (and visitors) who participated in recreational activities connected to reefs, how much they spent pursuing these activities, and, ultimately, how much this money contributed to the regional economy.

In addition to its natural coral reefs, Florida has a variety of artificial reefs, ranging from

Top: Coral viewing from glass-bottomed boat. Key Caribbean Residences

Middle: Queen Angelfish. © Paul Humann 2008

Bottom: Butter Hamlet, Florida Keys National Marine Sanctuary. Source: NOAA

sunken ships and railroad ties to specially-designed plastic and fiberglass structures. These structures provide a physical base—or "substrate"—that coral polyps can colonize. If successful, an artificial reef becomes covered with living corals and the countless marine species that they support.

The Hazen & Sawyer studies showed that in Miami-Dade, Broward, Monroe, Martin, and Palm Beach counties alone, recreation relating to coral reefs is responsible for more than 70,000 jobs and over $5.5 billion in annual sales (in 2008 dollars). In fact, the number of reef-related jobs across these five counties (70,582) is more than twice Monroe County's total job base of approximately 30,600 jobs. Employment relating to coral reefs generates more than $2.5 billion in annual income (in 2008 dollars).

The Hazen & Sawyer research team asked both visiting and resident reefs users how much they would be willing to pay—above and beyond their existing travel expenses—to help preserve natural and artificial reefs. (This is an established technique for quantifying the "user value" of a resource.) While those interviewed placed greater value on natural reefs, overall users were willing to pay an additional $10.51 per day (in 2008 dollars) to fund efforts to preserve natural coral reefs and construct new artificial reefs. Since each year sees nearly 25 million person-days of reef use in Florida, that translates to more than $327 million of user value annually for Florida's coral reefs.

Just as it is possible to "capitalize" a future stream of income (that is, to capture in a single dollar figure the value of future payments), one can capitalize the future user benefits from enjoyment of coral reefs. Based

Coral-rich areas of southernmost Florida counties.

on the data collected by Hazen & Sawyer, the capitalized value of coral reefs in these five Florida counties was over $10.9 billion in 2008 dollars. And this figure reflects only the extra value placed on coral reefs by users beyond the expenses (for boats, hotels, scuba equipment and the like) they incurred to engage in reef-related recreation. Nor does it include the benefits to others of living in a place that offers this tremendous natural resource—akin to the benefits that Americans enjoy from knowing that the Grand Canyon or Old Faithful exist, even if they are unsure whether they will actually visit them.

In 2003, researchers at Florida International University looked at the extent to which differences in coral quality and fish abundance would make tourism more attractive in the Florida Keys National Marine Sanctuary. The study found that these environmental changes would have a dramatic impact on the appeal of the Sanctuary to visitors. For example, the study estimated that substantial improvements in fish abundance, water quality and coral quality would increase consumer surplus (the benefit people enjoy beyond what they pay in dollars) by 287% per person over a five-year period, by 69% per person-trip, and by 69% per day. It seems fair to infer that the converse is true—that the attractiveness of visiting the Keys will decline if the quality of marine life in the Keys continues to erode.

Still another study looked at the motivations of people who travel to the Florida Keys to engage in snorkeling. The authors found that snorkelers usually have a focused set of objectives—for example, adding to their "life list" of reef fish—and are unlikely to visit Monroe County for other reasons if healthy coral reefs are no longer available.[14]

Coral-rich areas of southwestern Florida counties.

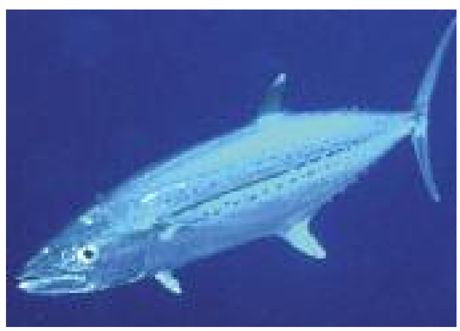
The Hazen & Sawyer reports, along with the other studies described above, show that recreational uses of natural coral reefs are important to residents of—and visitors to—Miami-Dade, Broward, Monroe and Palm Beach Counties, with reefs having capitalized value of well over $1 billion in each of these counties. The natural reefs off Martin County and counties further to the north, though not quite as valuable, nevertheless generate substantial value through recreational use.

The commercial and recreational value of reef fish and shellfish

Many of Florida's most economically important species of fish—including snapper, grouper, and jacks—depend heavily on healthy coral reefs. So do some of Florida's most important shellfish, including stone crabs and spiny lobsters. Both recreational anglers and commercial fishing operations prize a variety of reef creatures.

Florida hunters and anglers recognize that climate change threatens their continued enjoyment of these sports. In a recent survey of about 300 anglers and hunters in Florida, the vast majority—73%—believe global warming is a serious threat to wildlife. And 74% of those surveyed say that global warming is an urgent problem requiring immediate attention.[15]

Recreational fishing



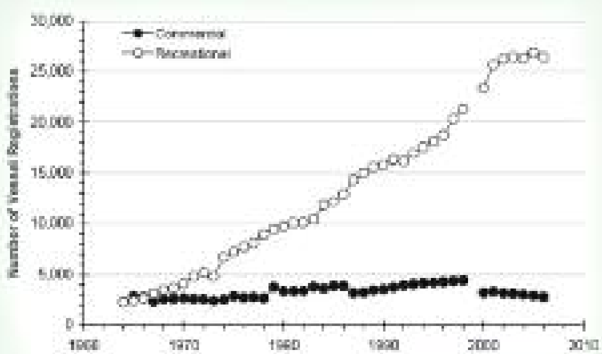
Left to right: Mahogany Snapper; Cero; Hogfish. All © Paul Humann 2008

REEF FISH

Recreational fishing in South Florida is enormously popular, as demonstrated by the nearly 1.2 million saltwater fishing licenses issued by the Florida Fish and Wildlife Commission during 2006–07. For recreational anglers in South Florida, yellowtail snapper, black grouper, and mutton snapper are the most sought-after reef species, followed by gray snapper, greater amberjack, grunts, hogfishes, and other jacks.

U.S. Census Bureau research confirms the remarkable popularity of recreational fishing in Florida. Florida calls itself the Fishing Capital of the World, and in the U.S., at least, the state can back that up: according to the Census Bureau, Florida is the top recreational fishing destination in the United States. All told, some 885,000 people came to Florida from outside the state to fish in 2006, more than the combined total of visitors to the next two largest fishing magnets (North Carolina and Wisconsin). And including both Floridians and visitors, 60% more people went fishing in Florida in 2006 than in California, even though California has a long coastline and twice as many residents as Florida.[16] Fishermen in Florida spent $4.4 billion in

Left: Key West Hotel.
Right: Fishing at Canaveral National Sea Shore, Florida.
Ed Reschke / Peter Arnold Inc.



Growth in Florida recreational and commercial fishing licenses (1964–2007).

2006, and recreational fishing helped to support more than 75,068 jobs in Florida. And state and local taxes from fishing-related sales generated $441 million in 2006.[17] (Of course, these statewide figures include fishing both for reef fish and freshwater fish and other ocean fish.)

In 2006, fishermen enjoyed more than 46 million days of recreational fishing in Florida. Florida also ranked first in number of fishing participants age 16 and older, with a whopping 2.77 million participants. These millions of recreational anglers are, of course, more likely than commercial fishermen to travel and spend money in restaurants and hotels on their fishing trips.

SPINY LOBSTERS

Spiny lobster fishing (and diving) attracts huge crowds to Florida during the special "two-day sport season" in late July each year, and even larger numbers (cumulatively) during the regular season. Nearly 47,000 people fished during the special two-day season, and some 57,000 people fished at some time during the first month of the regular season. Recreational lobster fishermen catch nearly two million pounds of lobster each year, or about 22% of total lobster landings.[18]

Spiny Lobster.
NOAA

Spiny lobsters benefit all eight Florida counties with coral reefs, with Miami-Dade, Broward and Monroe Counties leading the way. The impact on Monroe County is particularly striking: in one recent year, tourists and residents together spent approximately $24 million pursuing spiny lobster in Monroe County alone, for a total of 230,000 person-days of lobster fishing. These expenditures supported nearly 500 jobs in Monroe County. All told, recreational lobster fishing contributed $26.4 million in total economic activity and $8.4 million in income (salaries, wages and business profits) to Monroe County that year. And visitors to the county—who need lodging and food when they visit—were responsible for 96% of this total.[19]

Table 3: Florida Commercial Landings of Reef-Associated Fish and Shellfish in 1998 for the State of Florida and Five Southeast Florida Counties

	Total for State			Monroe		Martin		Miami-Dade		Palm Beach		Broward	
Landings and Value	pounds	value	avg $/lb	pounds	value	pounds	value	pounds	value	pounds	value	pounds	value
Amberjacks	1,398,884	$1,509,977	$1.07	451,140	$486,967	17,341	$18,718	15,903	$17,166	40,593	$43,816	808	$873
All groupers	9,300,162	$20,710,809	$2.22	449,337	$1,000,642	25,891	$57,658	17,358	$38,655	59,375	$132,224	15,240	$33,938
Grunts	564,937	$$446,768	$0.80	83,737	$66,221	1,705	$1,349	12,076	$9,550	23,227	$18,369	11,768	$9,307
Hogfish	47,209	$99,363	$2.11	22,802	$47,992	72	$152	1,601	$3,370	2,690	$5,662	2,010	$4,231
All snappers	3,625,126	$7,517,969	$2.07	1,819,762	$3,773,914	21,812	$45,235	120,942	$250,816	60,825	$126,142	36,640	$75,986
Spiny lobster	5,831,407	$23,584,066	$4.04	5,268,000	$21,305,469	7,044	$28,488	377,816	$1,528,008	66,251	$267,940	43,121	$174,395
Stone crab	3,522,033	$24,726,242	$7.02	1,390,034	$9,758,658	2,906	$20,402	32,870	$230,763	459	$3,223	1,507	$10,580
Total Receipts by Harvesters	24,289,758	$78,595,193	$3.23	9,484,812	$36,439,864	76,771	$172,000	578,566	$2,078,326	253,420	$597,376	111,094	$309,309

Commercial fishing

Black Grouper. Florida Museum of Natural History

Florida's commercial fisheries likewise make a major contribution to its economy each year. Major commercial fishing harvests range from spiny lobsters to jacks, snapper, grouper, and a wide variety of other species. Spiny lobsters are considered the most valuable catch by operators of commercial fishing boats, while amberjacks dominated sales among reef fish. Yellowtail snapper catches supported more fishing operations in the Keys year round than any other species. Black grouper and mutton snapper were next in order of importance for commercial fishermen.[20]

Table 3 shows the overall economic benefits of commercial landings of reef-associated fish and shellfish, based on data from the Florida Fish and Wildlife Research Institute and economic formulas developed at the University of Florida. For simplicity, Table 3 combines all species of grouper as well as all species of snapper, while individually representing amberjacks, grunts, hogfish, spiny lobster, and stone crab (weight for claws only). The results include the economic benefits created by seafood processing and distribution.

As Table 3 reflects, catches of reef-associated seafood species in the five southern Florida counties of Monroe, Martin, Miami-Dade, Palm Beach, and Broward accounted for $158 million in total landings. In other words, these five counties account for fully half of Florida's annual catches of these species, with most occurring in Monroe County. And these figures capture only part of the economic benefits of these commercial catches; for example, the data do not include retail or restaurant sales.

Five Counties Combined	
pounds	value
525,785	$567,540
567,201	$1,263,117
132,513	$104,795
29,175	$61,406
2,059,981	$4,272,093
5,762,232	$23,304,300
1,427,776	$10,023,624
10,504,663	$39,596,875

Healthy coral reef in the Florida Keys. NOAA

Yellowtail snapper. © Paul Humann 2008

Coral reefs as a source for new medicines

Like tropical forests, coral reefs are a source of incalculable biological diversity, and thus a rich resource for important pharmaceuticals, pesticides and enzymes.[21] Since 1983, approximately 100 new compounds have been discovered in the U.S. alone, and 170 U.S. patents issued, on products extracted from marine species. By one account, marine systems are 300 times more likely than terrestrial systems to harbor useful compounds.[22]

Coral reefs—including both shallow- and deep-water reefs—are a particularly promising source for medicines. The reason: many reef plants and animals "are firmly attached to the reef and cannot escape environmental perturbations, predators or other stressors." To survive in this difficult environment, many of these species "engage in a form of chemical warfare," creating bioactive compounds to fight predators and stave off disease.[23] The unique compounds these plants and animals create to stay alive may help us do the same.

The most famous medicine to emerge from coral reef research is the antiretroviral drug AZT, which is used to treat HIV. AZT had its origins in a chemical first discovered in a Caribbean sponge.[24] Research on coral reefs has also contributed to development of bone grafting materials, as well as treatments for heart disease, skin cancer, and leukemia.[25]

Florida is banking on biotechnology to help diversify its economy. The state recently recruited the Scripps Research Institute and its biotech laboratories to St. Lucie County on the Treasure Coast. The State has also incorporated Harbor Branch Oceanographic Institute, which focuses on research into medicinal uses of marine resources, into Florida Atlantic University.

Left: Sea fan. NOAA.

Right: Soft coral, Florida Keys National Wildlife Refuge. NOAA

Controlled harvesting of soft corals and "live rock"

A healthy coral reef may include not only hard corals such as elkhorns and staghorns but also soft corals, such as sea fans.

Under a plan administered by the South Atlantic Fishery Management Council, sea fans and other soft corals may be harvested—in strictly limited amounts—from certain coral reefs off South Florida, for sale in the aquarium trade. In addition, an aquaculture industry has developed in South Florida to grow "live rock" —coral reef organisms attached to "seeded" mudstone (called "marl") or limestone fragments—without disturbing naturally growing coral reefs.[26] Florida is one of the world centers for traffic in live rock. In addition to providing economic benefits to Floridians, culturing of live rock can reduce pressure on wild-harvested corals and natural live rock from coral reef ecosystems.

The threat to corals from global warming: new scientific evidence

Over the past few years, new research—much of it by Florida scientists—has greatly strengthened our understanding of the impact of global warming on coral reefs. And while there are a few bright spots, most of the news is bad.

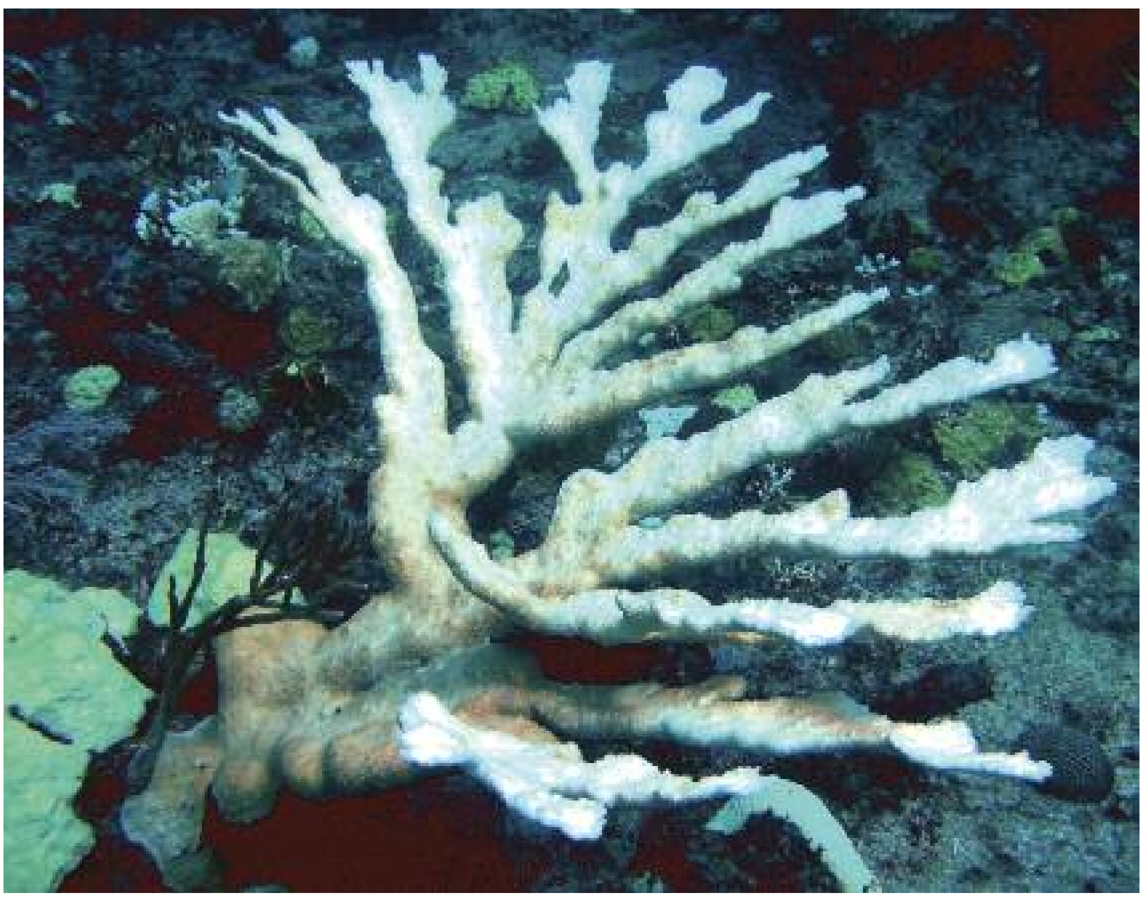
One of the most important contributions to this body of research was published in *Science* magazine (one of the top peer-reviewed journals in the world) in December 2007 by a group of many of the world's leading coral scientists, working together as the Coral Reef Targeted Research Program. Drawing on the entire body of international coral research, the article synthesizes what is known about the impact of global warming on coral reefs.

As the authors explain, coral reefs play an essential role in providing habitat for a vast array of marine species on which humans depend. But emissions of greenhouse gases are making oceans both warmer and more acidic—each harmful to coral reefs in its own way.

As lead author Ove Hoegh-Guldberg of Australia's University of Queensland explains, coral reefs occupy a unique niche in the world's environment, where water temperatures are "just right." When water temperatures rise above the natural comfort zone for corals, they undergo "bleaching"—a loss of color caused by the loss of zooxanthellae, which have a mutual back-scratching arrangement with coral polyps. Professor Hoegh-Guldberg explains that "raising as little as 1°C [2°F] the temperature that ocean surface waters reach in summer subjects coral reefs to stresses which lead quickly to mass bleaching. Raise the temperature a little more, and the corals that build reefs die in great numbers. No coral, no coral reef ecosystem."

Just as alarming, rapid increases in carbon dioxide cause "acidification," which adds a new threat to coral polyps: the inability to build their own skeletons from calcium in ocean waters. According to Professor Drew Harvell of Cornell University, "[a]cidification actually threatens all marine animals and plants with [calcium-based] skeletons, including corals, snails, clams and crabs. Our study shows that levels of CO_2 could become unsustainable for coral reefs in as little as five decades."

The 2007 *Science* article lays out three potential scenarios for the future of coral reefs. Absent immediate efforts to cut emissions, the future is troubling: "If current CO_2 emission trends continue the most conservative estimates predict CO_2 concentrations exceeding 500 ppm



Bleached Elkhorn Coral. NOAA Center for Coastal Monitoring and Assessment

Bleached Porites Coral with Christmas Tree Worm. © Wade Cooper

and global temperature increases of 2°C [3.6°F] or more by the end of the century," Professor Hoegh-Guldberg says. If this happens, the beautiful coral reefs that remain will become wastelands. As the authors explain, there is still time to avoid this tragic outcome, but only if we begin reducing greenhouse gas emissions in the very near future.[27]

Warmer ocean waters = coral bleaching

Widespread coral bleaching was little known before the 1980s. But because of warmer seawater, bleaching is today a threat to corals around the world, including Florida's own coral reefs. There is already a scientific consensus on this point: as the Intergovernmental Panel on Climate Change explained in 2007, "[m]any studies incontrovertibly link coral bleaching to warmer sea surface temperature." (The Intergovernmental Panel is comprised of more than 2,000 scientists; their consensus findings are approved by all participating governments, including the U.S. government.)

A July 2008 report by the National Oceanic and Atmospheric Administration (NOAA) reached the same conclusion: "warming ocean temperatures associated with global climate change are a major factor in coral bleaching."[28] As NOAA pointed out, exposure for only a few weeks to temperatures just a few degrees above normal can cause coral bleaching.

Bleaching has its roots in the relationship between the living part of a reef—coral polyps—and the tiny zooxanthellae plants with which they share living quarters. Zooxanthellae live in coral tissues in extremely high densities. Thanks to their ability to perform photosynthesis, the plants provide up to 90% of a coral's nutritional requirements in the form of sugars, while simultaneously assimilating coral waste products such as nitrogen and CO_2.[29] The symbiosis between the two has a geological history of more than 200 million years.[30]

But even slight increases in ocean temperatures can end this mutually beneficial relationship. As the 2007 *Science* article explains, "when [ocean] temperatures exceed summer maxima by 1° to 2°C [2–3.6° F] for 3 to 4 weeks," the symbiotic relationship between coral polyps and zooxanthellae ends: the zooxanthellae leave the corals, and the corals thereafter assume the ghostly white pallor of coral bleaching. While corals can recover if conditions quickly improve, "[b]leaching and mortality become progressively worse as thermal anomalies intensify and lengthen." Indeed, in 1997-98, because of unusually warm waters, "mass bleaching spread from the Eastern Pacific to most coral reefs worldwide, accompanied by increasing coral mortality during the following 12 months." Bleaching hurts corals in many ways, including loss of food, disruption of normal metabolic processes such as waste removal, and reduced energy. These conditions, in turn, make corals more susceptible to a variety of diseases.

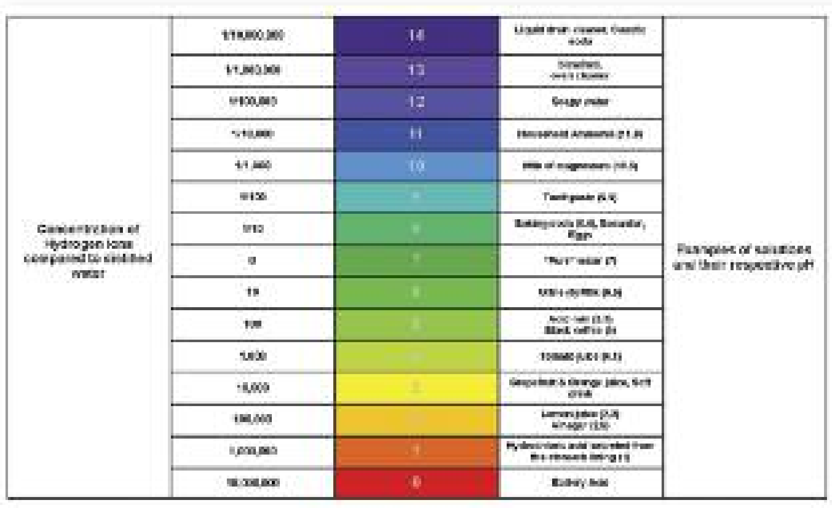
While the patterns of coral bleaching episodes are complex, there is general agreement that thermal stress leading to bleaching and mass mortality increased during the past 25 years.[31] In particular, during the years 1987, 1995, 1998 and 2005, widespread coral bleaching was seen throughout the greater Caribbean region, including the Florida Keys, as a result of higher sea-surface temperatures.[32] The bleaching of Florida corals in 2005 would have been much worse but for the cooler waters caused by major hurricanes, including Hurricane Katrina.

More recently, researchers used Princeton University climate models to evaluate the role of human-caused climate change in the 2005 Caribbean bleaching event—and the probability of similar events occurring in the future.[33] The models suggest that human-caused warming likely increased thermal stress events on corals in the region by an order of magnitude, and that mass coral bleaching events similar to that of 2005 may become a regular event in 20–30 years.[34]

In short, warmer ocean waters are a double whammy: they not only lead directly to bleaching, but also simultaneously intensify other stresses—most notably pathogens.

The regional director of the Southeast Region of NOAA's Office of National Marine Sanctuaries, Billy Causey, summarizes the situation as follows: "Corals are faced with four major threats, the greatest of which on a global scale are the impacts due to climate change. The other threats are land-based pollution, habitat destruction and overfishing."[35]

More acidic oceans thwart coral growth



The pH Scale

Besides pushing up ocean temperatures by more than 1° degree F during the 20th century, higher concentrations of carbon dioxide in the atmosphere have a second harmful effect on coral reefs: some of the additional airborne carbon dioxide dissolves in ocean waters, making them more acidic, which in turn makes it harder for coral polyps to build the shells that ultimately help create permanent reefs.[36]

During the past century, the acidity of the world's oceans increased by a dramatic 30%, with most of the increase occurring in the last few decades. It's basic chemistry: as the concentration of CO_2 in the atmosphere increases, more of it is available to diffuse into the ocean. Indeed, the harmful effects of greenhouse gases on the *atmosphere* have been mitigated by the ocean's ability to serve as a gigantic sink for atmospheric carbon dioxide. As the 2007 *Science* article explains, "[a]pproximately 25% . . . of the CO_2 emitted from all anthropogenic sources currently enters the ocean, where it reacts with water to produce carbonic acid." The amounts involved are vast: the ocean absorbs human-made CO_2 at a rate of 22 million tons a day.

But while the ocean's capacity to absorb CO_2 helps reduce the amount of CO_2 in the atmosphere (thus reducing the resulting warming), that capacity comes at a cost: during the 20th century, the oceans' absorption of CO_2 resulted in an increase of ocean acidity by .1 pH unit.[37] That sounds minor, but the pH scale is logarithmic—that is, each point represents a 10-fold increase (like the Richter scale for earthquakes or the decibel scale for loudness). Accordingly, the increase of .1 pH unit over the past century represents a more than 25% increase in acidity.[38] The result, through a well-understood series of chemical reactions, is a reduction of the availability in sea water of shell-building material—carbonate—to marine animals, including corals.

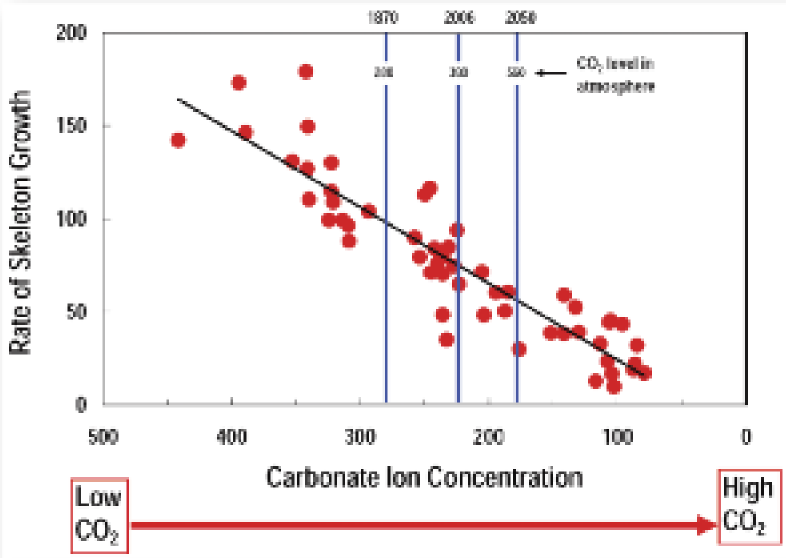


Figure 1. Effect of ocean acidity on coral growth

This is a new, and extraordinarily important, discovery. As Professor Christopher Langdon of the University of Miami has pointed out, "it is only in the last 10 years that scientists have possessed conclusive proof that ocean chemistry is undergoing a historic and potentially disastrous change."[39]

Professor Langdon's own research has played a crucial role in illustrating this point. In a special lab built to mimic real-world coral conditions, Professor Langdon exposed corals to seawater conditions carefully planned to track those that may occur in the coming decades. The coral's skeletal growth was cut in half as the water became more acidic, and the beneficial relationship between coral and their zooxanthellae "guests" broke down. Remarkably, these adverse effects occurred even without the higher water temperatures that unchecked global warming will bring.[40]

Even more recently, a research team at the University of Miami has found that not only coral growth but coral reproduction is harmed by elevated CO_2 and reduced pH. The researchers found that by the middle to end of this century, the rate at which coral larvae survive after settlement on the reef could be only half what it is today. By the end of the century, corals may not be able to replace colonies lost due to bleaching, disease, or other disturbances.[41]

The latest research only strengthens the scientific consensus about the impact of more-acidic ocean waters on coral growth. According to the December 2007 *Science* article, geological records show that, over the past 420,000 years, corals have been dominant in offshore environments only in a relatively narrow range of water temperatures and levels of ocean acidity. (See Fig. 2.) Today, the world's oceans are already well outside the range in which corals have historically been successful—and are rapidly heading even further away from that range.

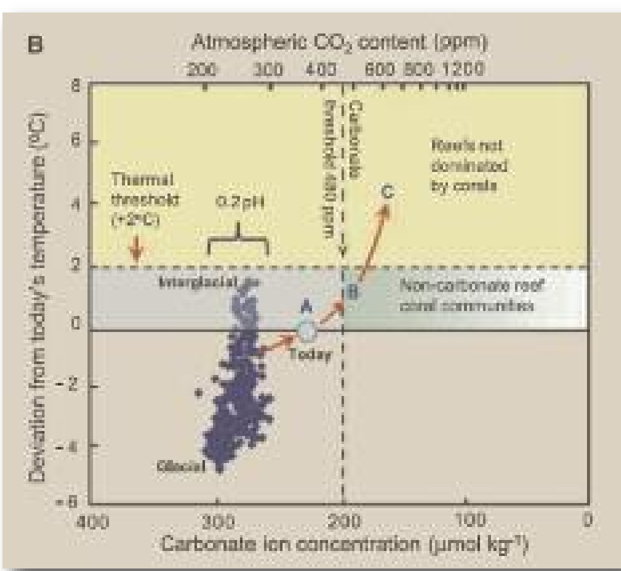


Figure 2. Ocean conditions are rapidly deteriorating from those in which corals thrive.

As the authors of the 2007 *Science* article explain, "[s]ea temperatures are warmer (+0.7°C) [1.3°F] , and pH (–0.1 pH units) and carbonate-ion concentrations (~210 mmol kg–1) lower than at any other time during the past 420,000 years." Moreover, the changes are happening with breakneck speed compared to past changes: "rates of change in global temperature and [CO_2 concentration] over the past century are 2 to 3 orders of magnitude higher than most of the changes seen in [the past] 740,000 years." In the future, rates of change are expected to be still higher, as reflected in both the low- and high-emissions growth scenarios postulated by the Intergovernmental Panel on Climate Change (though the high-emissions scenario projects an even steeper rate of change).

Elkhorn Coral with reef fish. © Marilyn Brandt 2008

Rising sea levels may "drown"—or bury—corals and deprive them of sunlight

Besides making ocean water warmer and more acidic, global warming also causes rising sea levels. Although it may seem surprising, since corals are already underwater, higher seas could threaten coral polyps: if sea level rises too quickly, corals can "drown" by being too far from the sunlight that allows zooxanthellae to perform photosynthesis. As NOAA points out in a July 2008 report, the high rates at which sea level has been rising in south Florida "could directly impact corals by shifting them to a deeper, lower light position in the water column."[42]

Beginning about 1930, tide gauges recorded acceleration in the rate of sea-level rise in South Florida. Since then, sea level has taken another giant step up, about 23 centimeters (9 inches). Thus far, this rise is at a rate of about 30 cm (one foot) per century, about ten times faster than the average rate over the past 1,000 years. As recent research has shown, sea-level rises occur "not as a gradually changing linear trend, but as a series of pauses and then rapid steps."[43]

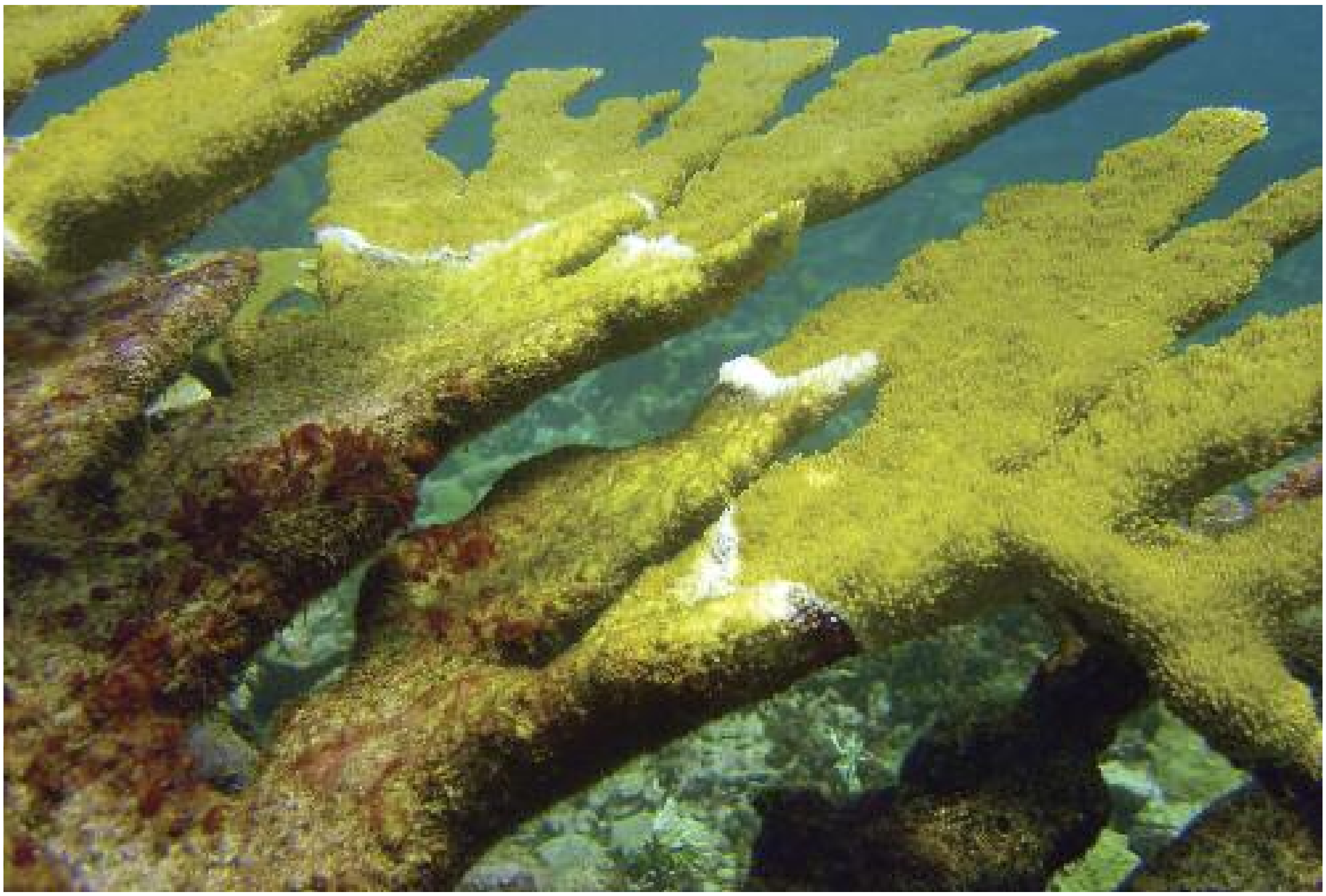
Besides depriving coral reefs of vital sunlight, rising sea levels hurt corals in at least two other ways. First, rising sea levels stir up mud and other sediments trapped by seagrasses, mangroves, and dune vegetation in coastal areas (such as bays, estuaries, and barrier islands). Tides and other forces then deposit some of those sediments onto coral reefs, potentially smothering them. Second, short-sighted efforts to combat sea-level rise—such as dredge-and-fill operations—can make matters still worse for coral reefs.[44]

Global warming increases vulnerability to other threats

Global warming is not the only threat to healthy coral reefs. But as coral scientists are discovering, climate change appears to make coral reefs more susceptible to a wide range of other harms.

Among the greatest threats are a variety of coral diseases. The first coral disease was not widely recognized until the 1970s.[45] There are now 29 described diseases known to afflict corals,[46] including white band disease, white pox, white plague and black band disease.[47]

While episodes of coral bleaching are more dramatic, some of the most devastating losses to reefs within the Florida Keys and greater Caribbean region have been due to white band and



White Band Disease on Elkhorn Corals. © Marilyn Brandt 2008

other diseases.[48] Since the early 1980s, losses of more than 97% of the most important type of coral in the Caribbean—elkhorn and staghorn corals—have been reported throughout the Keys.[49] The primary causes of these coral deaths were the "white" diseases—white band disease, white plague, and white pox. The most recent report of the Coral Reef Evaluation and Monitoring Project (CREMP) in the Florida Keys reported white diseases at 54 of 105 monitoring stations located throughout the Keys. Black band disease was noted at four stations, and other diseases were found at 74 stations.[50]

Coral diseases are part of a worldwide crisis in the health of coral reefs over the past 30 years. For example, the mass-mortality deposits of coral skeletons generated during a recent widespread outbreak of white band disease in Belize were unprecedented over the past 3,000 years, as indicated by the fossil record.[51] Scientists cannot conduct a controlled experiment in the world's oceans to demonstrate conclusively the impact of global warming on increased virulence

Schoolmaster snapper at artificial reef (sunken ship). © Paul Humann 2008

of coral diseases. But as a recent report explained, "multiple, concurrent chronic stresses may interact to weaken the resistance of corals and other reef organisms to agents that they might otherwise withstand." Global warming may thus be an important factor in "the apparent downward spiral of coral reef ecosystems that seems to involve many causes and agents."[52]

Just as humans harbor a wide variety of microorganisms in our digestive systems, corals live in close association with a wide variety of bacteria and other microorganisms. Like healthy intestines that are lined with beneficial bacteria, the majority of coral microbes are helpful, or at worst harmless. But under certain conditions, some of these bacteria can cause lethal diseases. Warmer oceans can stimulate rapid growth of these pathogens, even as they weaken the coral colonies' ability to ward off infection.[53]

Several coral pathogens are known to reside on healthy coral tissues and merely need to be triggered to initiate disease.[54] White pox, which is highly contagious and exclusively attacks elkhorn corals, is caused by a common, heat-resistant bacteria, Serratia marcescens.[55] And research indicates the coral diseases prefer warmer waters: optimal water temperatures for those infectious agents for which data are available are at least 1°C [1.8° F] higher than the optimal temperatures for their coral hosts.[56] By warming ocean waters, climate change may thus lengthen the period each year in which diseases are most potent.[57]

In 2006, researchers at the Center for Coral Reef Research in Sarasota uncovered what may be a crucial link between warmer ocean temperatures and the spread of coral diseases.[58] Through painstaking research, a team led by Dr. Kimberly Ritchie (pictured on the next page) discovered that elkhorn corals—one of the two pre-eminent reef-building coral species off Florida's coasts—"employ a biochemical mechanism for disease resistance that may act as a primary defense against pathogens." In effect, under normal conditions, these corals relied on "good" bacteria to generate antibiotics that protected the corals from disease-producing microbes. But during times of warmer ocean water, the corals "did not show significant antibiotic activity against the same suite of sources and tester strains, suggesting that the protective mechanism employed by [elkhorn corals] is lost when temperatures increase." This may explain how warmer ocean waters lead to coral disease: by thwarting corals' natural defenses against harmful bacteria.

Can evolutionary adaptation save the corals?

When any species faces a changing environment, there is a chance that adaptation—including both evolutionary changes and migration to a different environment—will enable the species to survive in altered circumstances. Over geological time periods, corals have certainly adapted: corals in the Arabian Gulf, for example, tolerate conditions that would be fatal if imposed rapidly on the same species in more temperate environments.[59] Thus, "the pressing question is not 'can corals adapt?' but 'how fast and to what extent can they adapt?'"[60] In other words, can corals adapt when climate change is happening not slowly (over millennia) but rapidly (over decades), and is imposing many stresses on corals simultaneously—and on top of other environmental stressors such as nutrient runoff, physical damage from boats, and vandalism?

Dr. Kimberly Ritchie, Manager, Marine Microbiology Program, Mote Marine Laboratory, Sarasota, Fla. Janos Balla/ Mote Marine Laboratory

Some recent studies offer hope that corals can in fact adapt to warmer ocean waters—provided that we act quickly to reduce greenhouse gas emissions. A 2004 report by Dr. Andrew Baker, now of the University of Miami, for example, studied coral reefs in Kenya, Saudi Arabia, and Panama that had recently faced heat stress. The results suggest that when faced with higher water temperatures, coral polyps may team up with specific types of zooxanthellae that tolerate higher water temperatures. The Baker team found that "corals containing unusual algal symbionts that are thermally tolerant and commonly associated with high-temperature environments are much more abundant on reefs that have been severely affected by recent climate change." Based on that finding, the Baker team "predict[s] that these adaptive shifts will increase the resistance of these recovering reefs to future bleaching."

Other scientists, including the authors of the 2007 *Science* article, are less confident that corals can adapt to global warming: They argue that "evidence that corals and their [zooxanthellae partners] can adapt rapidly to coral bleaching is equivocal or nonexistent."

The scientific debate will continue. If the more optimistic researchers are correct, does this mean that global warming is no threat to corals? Not at all: it means that with prompt steps to reduce greenhouse gas emissions, we can help buy time for corals to adapt to the threats posed by global warming and other human-created stresses.

The impact of declining coral health on reef fish

Studies of Caribbean reefs strongly suggest that reef fishes—damselfishes, grunts, snappers, groupers, and others—are more abundant and have greater species diversity in areas with healthy corals. These fish, which are important to both recreational and commercial fisheries in Florida and throughout the Caribbean basin, apparently prefer complex, high-topography coral reefs. These coral reef habitats are all classified as "essential fish habitat" by the National Marine Fisheries Service; in the South Atlantic region, living coral reefs get the highest status, "habitat areas of particular concern." Although overfishing of large predatory fishes (and ecosystem-engineer species like large lobsters) can have a major impact on overall reef health, even in marine reserves where fishing is prohibited, declining coral health is correlated with reductions in fish community condition. For example, in a study in Papua New Guinea, researchers

Reef fish, Florida Keys. © Paul Humann 2008

found that in a marine reserve, declines in overall coral cover from 66% in 1996 to 7% in 2002 was correlated with parallel losses in fish diversity and abundance.[61] Juveniles of many reef fishes strongly prefer live coral colonies, even if somewhat degraded, to dead, algae-covered colonies. One exception is the three-spot damselfish, which actively "farms" algae on reefs, and can proliferate to the detriment of reef health when predatory fishes are removed from reef ecosystems.

The Seychelles: a reminder of the need for prompt action

Location of the Seychelles. NationsOnline.org

In 2006, six coral scientists published a groundbreaking study of the long-term impacts of severe stresses to coral reefs.[62] The authors' conclusion is stark: "climate change-driven loss of live coral . . . in the Seychelles [island chain off of Africa] results in local extinctions, substantial reductions in species richness . . . and a loss of species within key functional groups of reef fish."

The harm to reef fish in the Seychelles has happened quickly. As recently as 1994, Seychelles reefs "were characterized by high cover of live branching and massive coral, soft coral, and high structural complexity." In 1998, however, the Seychelles, like most corals throughout the world, were slammed by a massive bleaching caused by a periodic El Niño weather pattern, which led to warmer ocean waters. Seven years later, in 2005, the once-thriving reefs remained devastated: they have "low complexity, rubble, standing dead branching coral, and algal fields."

Reflecting the central role of coral reefs as homes for other marine species, the poor health

Damaged reefs in the Seychelles. University of Newcastle Upon Tyne

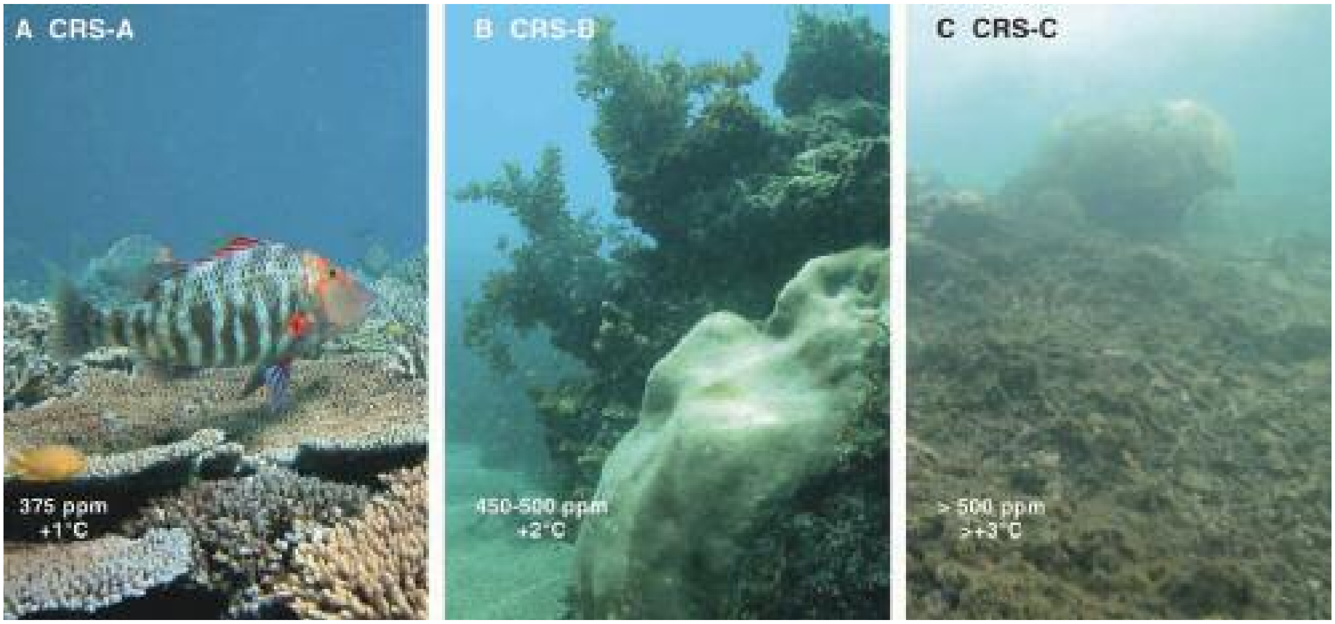
of the Seychelles' coral reefs "had a profound effect on reef-associated fish." The researchers "identify the possible local extinction of four fish species," and "a reduction to critically low levels for six [other] species . . . all of which rely on live coral for key life processes, such as [reproduction], shelter, or diet." If the future holds more ocean warming events such as the 1998 El Niño—as climate scientists warn is likely—the prospects for recovery of the Seychelles' reefs are poor. (An El Niño is a periodic weather pattern that is associated with floods, droughts, and other disturbances in a range of locations around the world.) Although El Niños are historically periodic, they are becoming more frequent—and scientists are concerned that we may soon have nearly permanent El Niño conditions.

The authors hypothesize that because the Seychelles corals are relatively isolated, their ability to recover from extreme stresses, such as a major bleaching event, is more limited than those in areas with a larger expanse of coral reefs that could help re-seed stricken areas. While Florida's corals are better placed than those of the Seychelles to recover from bleaching events, the sorry condition of the Seychelles' corals is a vivid reminder of the importance of taking immediate steps to slash greenhouse gas emissions.

The big picture: greenhouse gas emissions and the future of coral reefs

In the 2007 *Science* article, a group of leading coral scientists describe three future scenarios for coral reefs, depending on the extent to which humans control greenhouse gas emissions in the future. In Scenario A, carbon dioxide concentration in the atmosphere remains about where it is now—around 380 parts per million (ppm). In Scenario B, atmospheric CO_2 concentration reaches 450 to 500 ppm for an extended period. In Scenario C, airborne CO_2 exceeds 500 ppm for a substantial period. As the authors explain, even the worst of these scenarios is towards the lower end of the possible outcomes modeled by the Intergovernmental Panel on Climate Change. (The primary difference between these scenarios is how fast the world reduces emissions of global warming gases.)

The most important message of the 2007 *Science* article is that if we simply proceed with business as usual—ever-increasing emissions of greenhouse gases—the impact on coral reefs will be disastrous. In Scenario B, with atmospheric CO_2 between 450 and 500 ppm, "reef erosion will exceed calcification." As a result, "[t]he density and diversity of corals on reefs are likely to decline, leading to vastly reduced habitat complexity and loss of biodiversity, including losses of coral-associated fish and invertebrates." In the view of this research team, the truly disastrous potential outcome—Scenario C—would be likely to "reduce coral reef ecosystems to crumbling frameworks with few [calcium-shell-building] corals." With much warmer—and more acidic—ocean waters, "reefs will become rapidly eroding rubble banks such as those seen in some inshore regions of the Great Barrier Reef, where dense populations of corals have van-



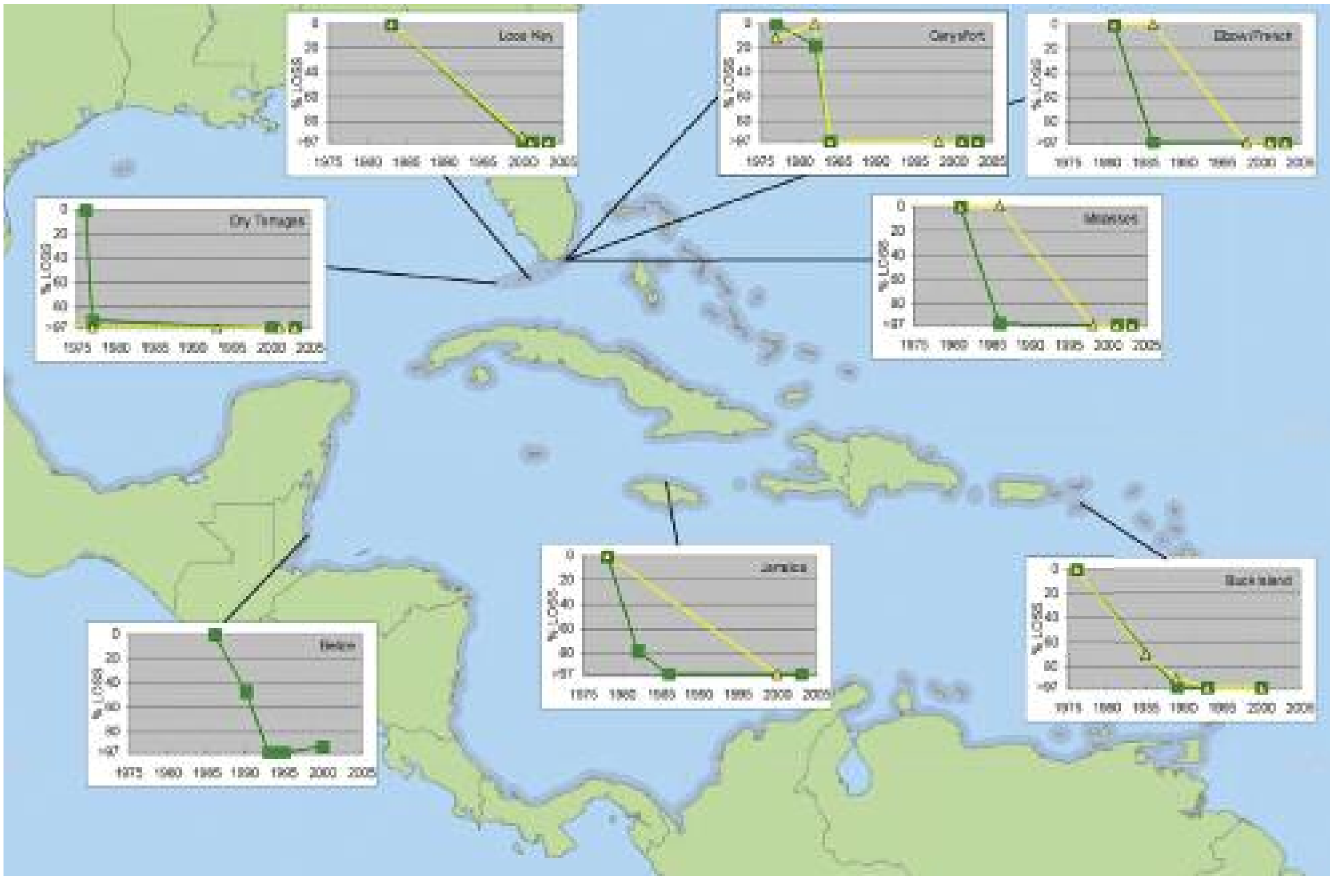
ished over the past 50 to 100 years." As discussed earlier, rapid changes in sea level may also lead to "drowned" reefs in which coral growth fails to keep up with rising sea levels, leaving corals too far from sunlight to survive.

The authors of the 2007 *Science* report provided photographs (above) to illustrate the likely state of the world's corals in the three scenarios just described:

The world's corals—including Florida's economically vital reefs—are at risk of descending into Scenario C if the world fails to slow its current pace of greenhouse gas emissions. According to Professor Hoegh-Guldberg, "[i]f current CO_2 emission trends continue, then even the most conservative estimates predict CO_2 concentrations exceeding 500 ppm and global temperature increases of 2°C [3.6° F] or more by the end of the century." Under those conditions, he predicts, what will remain of coral reefs—in South Florida and elsewhere—will be no more than a "crumbling framework" of what was once a spectacularly beautiful ecosystem that nurtured innumerable marine species.

Other scientists are more optimistic, noting that some corals—especially certain species of Acropora corals—have "an underappreciated ability to adapt rapidly to changing environments."[63] These scientists point out that these species of coral mature early and grow rapidly, giving them the ability to respond more quickly than corals that take decades to develop.[64] In addition, as discussed earlier, different varieties of zooxathellae have different tolerances for warmer water, potentially serving as better partners for coral polyps in the future.

In any event, coral scientists are unanimous that greenhouse gas emissions are adding greatly to the stresses already bearing down on coral reefs. And scientists on all sides of the adaptation debate agree that we must act swiftly to reduce those emissions to give corals the best chance to retain their current vibrancy and beauty.



The special threat to Florida's coral reefs

The worldwide hazards to coral reefs are particularly acute for Florida. Caribbean reefs have repeatedly been shown to take longer to recover from stresses (such as bleaching) than do reefs in the Pacific and Indian Oceans.[65] In addition, corals in Florida (and the Caribbean as a whole) are much less genetically diverse than in other parts of the world, such as the Pacific: "the Indo-Pacific has approximately 750 species of reef-building corals . . . compared to about 50 coral species . . . in the Caribbean."[66]

In part because of its lack of species diversity, the corals that build Florida's coral reefs—elkhorns and staghorns—have been particularly hard-hit by human-caused environmental "insults" to date, and remain highly vulnerable to the still higher ocean temperatures and acidification that the next few decades will bring if present trends continue. According to NOAA, for example, staghorn coral declined by 73% in the Florida Keys over the past 12 years.[67] The cumulative effects of the environmental harassment endured by staghorn and elkhorn coral reefs in Florida and other portions of the Caribbean are captured in the map above, which was prepared by coral reef researchers.

As the map shows, elkhorn and staghorn corals have declined by 97% at five different (measured) locations off the Florida coast. The drastic decline in the coverage of elkhorn and staghorn corals has long been recognized by scientists, tourists, divers, and anglers.[68] While Florida's reefs were hard-hit by disease in the 1980s, recent reports show still-further declines in Florida reefs. Between 1996 and 2004, for example, hard coral cover, including elkhorn and

staghorn corals, declined from 11.9% to 6.6% across the Florida Keys National Marine Sanctuary (FKNMS).[69] Compared to other species of coral, elkhorn and staghorn coral grow relatively quickly. But in the world of corals, "fast" growth can take decades or centuries, depending on the type of damage inflicted the coral.[70]

Although the corals that build Florida's reefs grow faster than some, the state's reefs face a special challenge because of Florida's vulnerability to hurricanes, which can inflict severe physical damage on reefs. Not surprisingly, corals have evolved an ability to tolerate, and even benefit from, a certain degree of hurricane damage. Coral debris from hurricane damage can accumulate in low areas and build up the overall reef. As one scholar explained, broken-off coral fragments "accumulate between coral colonies and are . . . cemented together to form a massive wave-resistant limestone reef."[71] But reefs that are too frequently or violently damaged by hurricanes have difficulty recovering, particularly if they have been weakened by bleaching, dis-

Atlantic Spadefish. © Paul Humann 2008

ease or pollution. The result is a low, zero, or negative expansion of the overall reef, especially depending on the rate of bioerosion initiated by boring organisms, such as urchins.

Florida's recent history shows that extremely severe storms are becoming commonplace: a list of the 11 worst hurricanes to hit Florida in the past century includes four since 1992 (Andrew, Frances, Jeanne, and Wilma), and three since 2003. And because of warmer ocean waters, Florida's exposure to hurricane is likely to increase, not decrease. According to the June 2008 report of the U.S. Climate Change Science Program, called Weather and Climate Extremes in a Changing Climate, for example, "[i]t is likely that hurricane/typhoon wind speeds and core rainfall rates will increase in response to human-caused warming. Analyses of model simulations suggest that for each 1°C [1.8°F} increase in tropical sea surface temperatures, hurricane surface wind speeds will increase by 1 to 8% and core rainfall rates by 6 to 18%."[72]

Hurricanes and tropical storms also pose special environmental risks to Florida because of its canal systems. Wetter, more powerful storms will lead to massive canal discharge events, such as the hundreds of billions of gallons of Lake Okeechobee water that discharged through the St. Lucie River and across Martin County reefs as a result of Hurricanes Fran, Jeanne, and other major storms.

Because of the combined impact of warmer waters, hurricanes and other threats, in March 2005, the National Marine Fisheries Service (an agency within the National Oceanic and Atmospheric Administration) determined that elkhorn and staghorn corals are likely to become endangered within the foreseeable future throughout their entire ranges. The Fisheries Service made that determination after a panel of scientists concluded that elkhorn and staghorn corals are threatened by a variety of perils, led by "disease, temperature-induced bleaching and physical damage from hurricanes."[73]

All of these dangers are linked to global warming. In 2008, the Fisheries Service proposed to designate four areas as protected habitats for elkhorn and staghorn corals under the Endangered Species Act of 1973, including approximately 3,300 square miles of marine habitat in Florida.

The website Reefbase.org provides interactive maps showing locations of confirmed bleaching events or disease at locations monitored by scientists. As the maps shown here reflect, Florida's reefs have been hit hard by both bleaching and diseases.

Multiple species of fish at reef. © Paul Humann 2008

Conclusion

Florida's coral reefs are a priceless natural resource and support a multibillion dollar economy in the state. Human activity, including greenhouse gases and the harms that follow in their wake, have already done grave damage to Florida's reefs, and will inflict still more grievous harm unless we take immediate action.

"Today's reefs are as much as 5,000 years old, and they will start to fall apart within a decade or so if we don't radically change how we do business," says Professor Christopher Langdon of the University of Miami. Global warming brings with it warmer water temperatures, more acidic oceans, and stronger hurricanes—all powerful enemies of healthy corals. These stresses on corals add to—and make it harder for corals to recover from—many other human-caused impacts, including nutrient loading, overfishing, sedimentation, and physical damage from boats. To help preserve this unique national resource and to protect the lucrative economy that depends on it, Florida's policymakers should support strong and immediate action to block global warming by reducing emissions of CO_2 and other greenhouse gases.

Notes

[1] Coral Reef Targeted Research Program, 2007.

[2] Langdon 2006. In addition to its shallow coral reefs, Florida also boasts deep-water (also called cold-water) reefs further offshore, including the spectacular deepwater Lophelia reefs, which extend from North Carolina to Florida. According to the Intergovernmental Panel on Climate Change, the oceans' increasing acidity—resulting from absorption of carbon dioxide—may threaten deep-water as well as shallow-water corals. (IPCC 2007, Working Group 2 Report, Chapter 19). This report, however, focuses on shallow-water corals.

[3] www.eflorida.com/uploadedImages/Floridas_Regions/Floridas_Counties/Floridas_Individual_ Counties/county_map_name_florida.jpg.

[4] Fla. Dep't of Environmental Protection

[5] Scientists have recently explored, for the first time, a vast coral reef called Pulley Ridge on the southwest Florida Shelf roughly 150 miles west of Cape Sable, Florida. The reef, which is about 200 feet below water, may be the deepest coral reef in the United States employing photosynthesis, thanks to zooxanthellae adapted to exploit the minimal light that reaches that deeply into the ocean. U.S. Geological Service, Coastal and Marine Geology Program, Pulley Ridge, available at http://coastal .er.usgs.gov/pulley-ridge/.

[6] Langdon, 2006.

[7] National Aquarium in Baltimore.

[8] Florida Fish & Wildlife Commission, 2008.

[9] UNESCO.

[10] Although the role of humans is unclear, in the early 1980s a disease epidemic killed off nearly all of the long–spined black sea urchins in the Caribbean and south Atlantic. With their seaweed-eating ways, urchins are sometimes described as "the sheep of the reef." The absence of sea urchins may have contributed to the overgrowth of sun-blocking seaweed, another threat to coral reefs. Dr. Steven Miller, *Why Do Reefs Look the Way They Do in Florida?*, available at www.uncw.edu/aquarius/education/ reef_information.html.

[11] Florida Keys National Marine Sanctuary website.

[12] VisitFlorida.org web site and emails with VisitFlorida staff.

[13] Hazen & Sawyer published their original study in 2001, and published a revision in 2003 that corrected a modeling error. In 2004, Hazen & Sawyer published an additional report, addressing Martin County. The 2001 report used 2000 dollar values, while the 2004 Martin County report used 2003 dollar values. All values in Tables 1 and 2 have been converted to 2006 dollar values using U.S. Bureau of Labor Statistics inflation data (http://data.bls.gov/cgi-bin/cpicalc.pl).

[14] Park et al., 2002.

[15] McNitt, 2006.

[16] U.S. Department of the Interior, 2008, at 97, 103.

[17] State of Florida.

[18] Florida Fish & Wildlife Institute, 2000.

[19] NOAA, 2001.

[20] Waters et al, 2001.

[21] Bruckner, A.W., 2002.

[22] Ibid.

[23] Ibid.

[24] Vogel, 2000.

[25] Epathko.

[26] South Atlantic Fishery Management Council web site, www.safmc.net/Library/Coral/tabid/409/Default.aspx.

[27] *Science Daily*, 2007.

[28] NOAA, 2008 at 135.

[29] Muscatine and Porter 1977.

[30] Wood 1999.

[31] Brown 1997.

[32] U.S. Acropora Biological Review Team 2005.

[33] Donner et al., 2007.

[34] Ibid.

[35] Personal email from Dr. Billy Causey.

[36] Lowering of pH levels is commonly referred to as "acidification," although ocean waters remain in the alkaline range even after a shift to lower pH. The same process could be referred to as "dealkalinization."

[37] Hoegh-Guldberg et al. 2007.

[38] Burns, 2008.

[39] Langdon, 2006.

[40] Rosenthiel School of Marine and Atmospheric Science, 2005.

[41] Albright 2008.

[42] NOAA 2008, Southeast Florida chapter, at 135.

[43] Dominguez and Wanless 1991.

[44] Wanless and Maier. Dredge-and-fill projects advertised as "beach renourishment" along the South Florida coast, as well as shoreline armoring, are in part a response to rising seas and to hurricanes. Nearly all of these projects use poor-quality sand, which often washes quickly from the beach or pulverizes in the surf zone. Drifting offshore, this fine sediment can settle on—and smother—reefs and other near-shore ecosystems.

[45] Antonius 1973.

[46] Weil 2004.

[47] Coral reefs, both in Florida and elsewhere, also face increasing threats from the presence of excessive nutrients in ocean waters, whether from acid rain or from nitrogen runoff from agricultural or residential lands. Corals typically thrive in nutrient-poor waters; the addition of nutrients encourages the growth of other species (such as seaweed and phytoplankton) that compete with coral polyps. In the extreme case, nutrient loading in ocean waters leads to Harmful Algae Blooms (HABs), including "red tides." While the link between global warming and red tides is not yet clear in the scientific literature, the harm done to corals by red tides clearly makes it more difficult to recover from the damage caused by warmer, fresher, and more acidic ocean waters.

In addition, although beyond the scope of this report, the illegal trade in coral "souvenirs" adds yet another important stress to coral ecosystems.

[48] Richardson et al. 1998a, 1998b; Kuta and Richardson 1996; Patterson et al. 2002.

[49] U.S. Acropora Biological Review Team 2005.

[50] Beaver et al. 2005.

[51] Aronson et al. 2001.

[52] Buddemeier, 2004.

[53] Rohwer et al.

[54] Rosenberg and Falkovitz 2004, Klaus et al., 2007.

[55] Patterson et al, 2001; Porter et al.

[56] Harvell et al., 2002.

[57] Patterson et al, 2001.

[58] Ritchie et al., 2006.

[59] Buddemeier, 2004 at 28.

[60] Ibid.

[61] Jones et al, 2004, *Population Biology*.

[62] Graham, N.A.J., et al 2006.

[63] Baird 2008.

[64] Ibid.

[65] Sammarco, 1985; Kojis and Quinn, 1994; Done, 1999.

[66] Buddemeier 2004. at 21.

[67] NOAA, 2008.

[68] Chiappone and Sullivan 1997; Dustan and Halas 1987; Gischler in press; Jaap et al. 1988; Jaap and Sargent 1993; Porter and Meier 1992; Shinn et al. 2003; Wheaton et al. 2001.

[69] Beaver et al. 2005.

[70] Craig 2007.

[71] Hoffmeister .

[72] U.S. Climate Change Science Program, 2008.

[73] U.S. Atlantic Acropora Status Review, 2005.

APPENDIX

Table 1: Economic Returns of Resident and Non-Resident Recreation Relating to Natural Reefs[a]

	Palm Beach	Broward	Miami-Dade	Monroe	Martin[2]	TOTALS
Sales (in millions)	$445	$1,393	$1,103	$469	$7	$3,417
Income (in millions)	$179	$688	$527	$135	$3	$1,531
Employment (full & part-time jobs)[3]	4,500	18,700	12,600	7,600	84	43,484

a. For both Tables 1 and 2, data for sales and income for all counties other than Martin are from Hazen & Sawyer (2003), originally reported in 2000 dollars but converted to 2008 dollars here. The results are estimates, and are intended to provide an approximate idea of reef contribution to the local economies.

b. Data for Martin County are from Hazen and Sawyer (2004), originally reported in 2003 dollars but converted to 2008 dollars here.

Table 2: Annual Use Value and Capitalized Value Associated with Natural Reef Use in Southern Florida

	Palm Beach	Broward	Miami-Dade	Monroe	Martin	All Counties Combined
Person-days of reef use (in millions)	2.83	5.47	6.22	3.88	0.27	18.67
Use value per person-day	$17.23	$19.05	$9.48	$18.63	$17.47	$15.58
Annual use value (in millions)	$52.93	$104.12	$58.91	$72.24	$4.70	$292.91
Capitalized value (in billions)	$1.764	$3.471	$1.964	$2.408	$0.157	$9.764

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Figure and map sources

Page 5: Map: U.S. Geological Survey

Page 9: Maps: July 2008 NOAA Report

Page 11: Growth in Florida fishing licenses. Source: July 2008 NOAA Corals Report

Page 17: pH scale. Source: Richmond River (Australia) County Council

Page 18: Figure 1. Source: National Center for Atmospheric Research
Figure 2. Source: Hoegh-Guldberg et al, 2007

Page 26: U.S. Acropora Biological Review Team

Page 29: Maps: REEFBase database