REEFS AT RISK

A Map-Based Indicator of Threats to the World's Coral Reefs

Dirk Bryant • Lauretta Burke
John McManus • Mark Spalding

"In some areas human activity has destroyed entire reefs, converting them to algal-covered rubble. Who knows what species, known and unknown alike, have already been wiped out? Who can say which ones will be winking out in the near future, their intricate genetic codes, formed over millennia, suddenly gone. . . ."

—Osha Gray Davidson, *The Enchanted Braid*

More than forty years ago, I slipped into a sunlit ocean, clear as air, not far from Miami, Florida, and glided into a kaleidoscope forest of lavender sea fans, cavernous sponges, and giant stands of elkhorn coral. Thousands of fish moved about like animated fragments of stained glass, and other creatures—red starfish, black urchins, pink cucumbers, translucent anemones, blue shrimp, brown crabs, silver hydroids, and numerous others I could not name—embroidered every inch of aquatic real estate as far as I could see in all directions. I witnessed that afternoon—my first of thousands of dives on coral reefs around the world—a fair cross section of the major divisions of life that have ever existed on this planet. Nearly all of the major phyla of animals and plants, as well as microbes, have at least some representation in the sea, and most include coral reef species. Only about half occur on the land, even in the richest forests, swamps, and grasslands, Diving into a healthy, productive coral reef system as I did on that afternoon long ago, I traveled far into the history of life on earth, a surreal journey into time.

Recently, I returned hoping to relocate that underwater Garden of Eden, but found only barren coral skeletons shrouded with gray-brown sediment. Again, it seemed that I had traveled in time, only now the direction was a swift fast-forward fantasy, a glimpse of the future. In my lifetime, I had witnessed change on a geological scale, wrought by my species. The rapid growth of population in central and south Florida has had hidden costs—the consumption, in decades, of species and natural ecosystems millions of years in the making.

Worldwide, including in some parts of Florida, there are coral reefs and entire reef systems that appear to be as pristine today as they were in ages past, but there is no doubt that there is an alarming global trend of decline. Until half a century ago, the worst threats to coral reefs were storms, volcanic eruptions, periodic ice ages, and occasional comets striking the Earth. However, since the 1950s, and at an accelerating pace, humankind has added significant new pressures ranging from outright mining of coral for building materials, widespread pollution, and destructive fishing practices to loss of vital related mangrove and seagrass ecosystems.

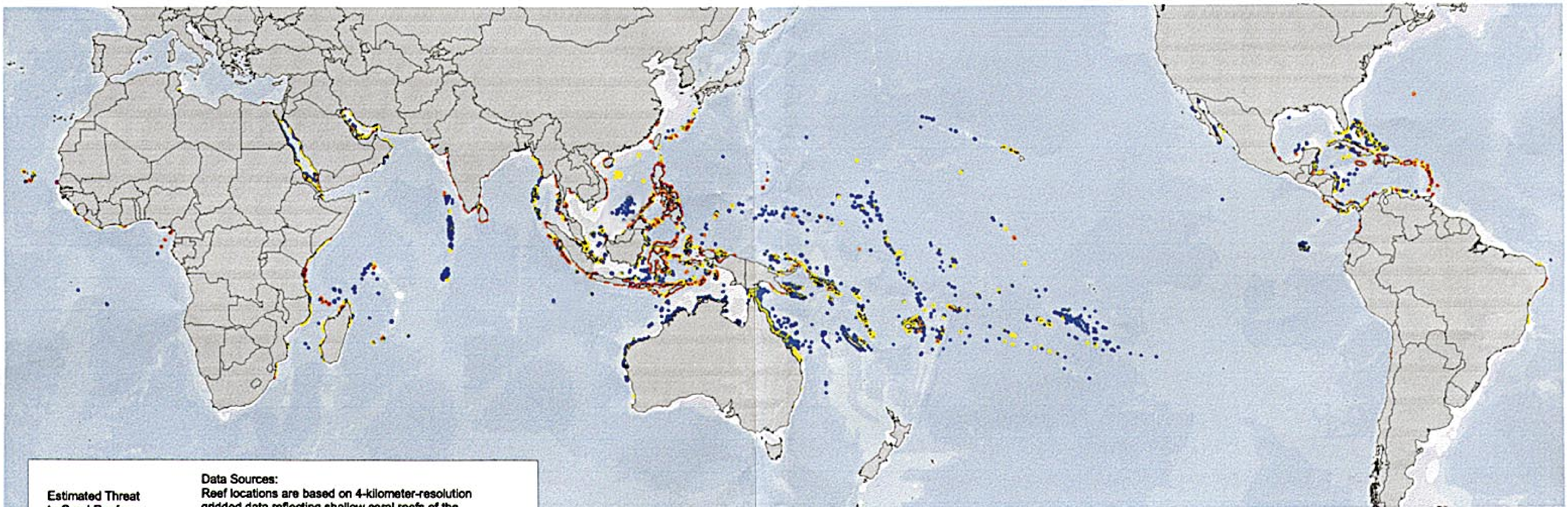
Concern has been growing for decades about the fate of coral reefs, especially in recent years as more and more people have access to these underwater worlds and have come to realize their value for reasons that both embrace and transcend aesthetic, scientific, economic, and environmental considerations. Many more who have not seen these notorious "rainforests of the sea" for themselves have been made aware of their importance and are motivated to want to do something to stay their swift loss. In 1997, which the United Nations declared as the "International Year of the Reef," many questions were raised about just how widespread the problems are and what can be done to help protect what remains of healthy systems—and restore those that are damaged.

Although coral reefs have become the subject of thousands of research projects in the past few years, remarkably little has been done to attempt a global assessment of *where* and *what* are the most pressing problems. Yet, such information is vital if effective action plans are to be devised. The authors of this report have taken an ingenious approach to gauge the areas most at risk, as well as to highlight those with varying degrees of sanctity, by correlating what is known about the distribution of reefs with the distribution of known human impacts. The result is a monumental overview, one that can be used to help guide conservation efforts on a grand scale—as well as up close, locally.

As human population grows, so will the pressures on the natural systems that sustain us. *Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs* makes it possible to pull back and gain perspective on past problems as an effective way to anticipate—and perhaps prevent—potential disasters in the making. The fate of coral reefs, the ocean, and humankind forty years from now and forevermore will depend on the intelligence, motivation, and caring of people now alive. In that spirit, this report provides hope that we may succeed.

Sylvia A. Earle
Explorer-in-Residence, National Geographic Society
Chairman, Deep Ocean Exploration
and Research Organization

Coral Reefs of the World Classified by Potential Threat from Human Activities



Estimated Threat to Coral Reefs
- low
- medium
- high

Bathymetry
- 0 - 50m
- 50 - 200m
- 200 - 2000m
- 2000 - 4000m
- > 4000m

Map Projection: Mercator

Data Sources:
Reef locations are based on 4-kilometer-resolution gridded data reflecting shallow coral reefs of the World from the World Conservation Monitoring Centre (WCMC).

Reefs are classified according to the Reefs at Risk Indicator, an estimate of potential threat to coral reefs developed at the World Resources Institute (WRI). This estimate is a composite of four separate risk factors:

1) Coastal Development
2) Marine-based Pollution
3) Overexploitation and
4) Inland Pollution and Erosion

1000 0 1000 2000 Kilometers

The Reefs at Risk Analysis produced a map-based indicator of potential threats to coral reefs. In order to capture the potential threats to coral reefs from coastal development, marine pollution, overexploitation of marine resources, and inland pollution, distance-based threat surfaces were developed from 12 representative stressors. These included cities, settlements, airports and military bases, population density, mines, tourist resorts, ports, oil tanks and wells, shipping routes, and areas where blast fishing or fishing using poisons is known to occur. Additionally, a watershed-based model was used to estimate potential erosion within the watershed to produce an estimate of areas potentially threatened by inland pollution and sedimentation. The 13 threat surfaces were integrated with data on coral reefs location, resulting in a global classification of potential threat to coral reefs.

The Reefs at Risk Project is a collaboration of The World Resources Institute, The International Center for Living Aquatic Resources Management, and The World Conservation Monitoring Centre.

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Foreword

Coral reefs, which are among the most biologically diverse ecosystems on the planet, are also some of the most ancient. They first appeared in the Mesozoic era some 225 million years ago and some living coral reefs may be as much as 2.5 million years old. Outstanding examples of our biological and natural heritage, coral reefs are an important asset to local communities—serving as a source of seafood, providing materials for new medicines, generating income from tourism, and buffering coastal cities and settlements from storm damage. Yet, in just a few decades, human activities have devastated many of these biologically rich, ancient ecosystems. In the next two or three decades, more are destined for destruction.

Until recently, almost nothing was known about the extent and condition of coral reefs. Unlike the change in rainforests, that in coral reefs is difficult to assess from satellites, and information on their status has been scattered, anecdotal, and relatively inaccessible. The state of knowledge began to improve in 1988, when the World Conservation Monitoring Centre (WCMC) completed work on a three-volume collection of preliminary reports on coral reef problems in 108 nations, which was published by the United Nations Environment Programme and the World Conservation Union. In 1993, ReefBase, a global database on coral reefs, was established by the International Center for Living Aquatic Resources Management (ICLARM), and WCMC. This resulted in the first global map depicting the location of shallow reefs around the world, published by WCMC in 1996. Eighty nations now participate in a Global Coral Reef Monitoring Network, to assess the health of reef ecosystems. This network and other efforts will provide a clearer picture of the impact of human activities on coral reefs. However, it will take years to assemble a comprehensive picture of the status of reefs based on field research.

Reefs at Risk: A Map-based Indicator of Threats to the World's Coral Reefs provides the first map-based global analysis of the condition of coral reefs. As such, it marks a significant advance in understanding the condition of coral reefs and should help stimulate further data gathering that will improve subsequent reporting. This study draws on 14 global datasets that are indicators of development pressure, information on 800 ReefBase sites that are known to be degraded, plus scientific expertise—to model areas where existing human pressures indicate that reefs are threatened by sedimentation, pollution, overfishing, and other factors.

The analysis offers a stark warning: the pressure of human activities poses grave danger to reefs in most of the world's oceans, and irreparable damage is occurring rapidly. The exceptions are places still isolated from intense human pressures and those few places that have implemented effective measures to protect reefs. That is the key. Action is needed, and action is possible to protect these treasuries of ocean wealth.

Many of the protective measures needed to ensure the health of these ecosystems are "win-win" options for both reefs and people. For example, creating marine parks and sanctuaries may enrich local communities by attracting tourists and may benefit nearby fisheries by protecting breeding stock of target species. Eliminating perverse and often costly subsidies to fisheries and agriculture, for example, may reduce overfishing, sedimentation, and pollution of reefs, and building sewage treatment facilities within coastal communities may provide both environmental and health benefits.

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Mark Collins
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Meryl J. Williams
Director General
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Jonathan Lash
President
World Resources Institute

KEY FINDINGS

This report presents the first-ever detailed, map-based assessment of potential threats to coral reef ecosystems around the world. "Reefs at Risk" draws on 14 data sets (including maps of land cover, ports, settlements, and shipping lanes), information on 800 sites known to be degraded by people, and scientific expertise to model areas where reef degradation is predicted to occur, given existing human pressures on these areas. Results are an *indicator* of potential threat (risk), not a measure of actual condition. In some places, particularly where good management is practiced, reefs may be at risk but remain relatively healthy. In others, this indicator underestimates the degree to which reefs are threatened and degraded. Our results indicate that:

- Fifty-eight percent of the world's reefs are potentially threatened by human activity—ranging from coastal development and destructive fishing practices to overexploitation of resources, marine pollution, and runoff from inland deforestation and farming.

- Coral reefs of Southeast Asia, the most species-rich on earth, are the most threatened of any region. More than 80 percent are at risk (under medium and high potential threat), and over half are at high risk, primarily from coastal development and fishing-related pressures.

- Overexploitation and coastal development pose the greatest potential threat of the four risk categories considered in this study. Each, individually, affects a third of all reefs.

- The Pacific, which houses more reef area than any other region, is also the least threatened. About 60 percent of reefs here are at low risk.

- Outside of the Pacific, 70 percent of all reefs are at risk.

- At least 11 percent of the world's coral reefs contain high levels of reef fish biodiversity and are under high threat from human activities. These "hot spot" areas include almost all Philippine reefs, and coral communities off the coasts of Indonesia, Tanzania, the Comoros, and the Lesser Antilles in the Caribbean.

- Almost half a billion people—8 percent of the total global population—live within 100 kilometers of a coral reef.

- Globally, more than 400 marine parks, sanctuaries, and reserves (marine protected areas) contain coral reefs. Most of these sites are very small—more than 150 are under one square kilometer in size.

- At least 40 countries lack any marine protected areas for conserving their coral reef systems.

INTRODUCTION

Although they occupy less than one quarter of 1 percent of the marine environment, coral reefs are home to more than a quarter of all known marine fish species.[1] These habitats have been called the rainforests of the marine world: highly productive, rich in species, and—because they predominate in many regions noted for extreme poverty and high population growth rates—particularly vulnerable to future degradation.

Seventy percent of the planet is covered by oceans, yet humans have barely begun to catalog the biota found within marine environments. Over recent decades, scientists, policy-makers, and the public have become increasingly aware of the magnitude of destruction of terrestrial habitats, especially the biologically rich tropical rainforests, and the need to stem the onslaught of human pressures on remaining natural places. Knowledge has proved key to raising awareness: by at least roughly gauging—through such figures as deforestation rates and estimates of species loss—the extent and magnitude of human impact on terrestrial biodiversity, scientists have demonstrated what is at stake should poorly planned development continue unchecked.

Midway through the 1998 "Year of the Ocean" and following the 1997 "Year of the Reef"—two campaigns aimed at raising global awareness of the importance of our marine heritage—we still lack comprehensive estimates regarding the status of, and the magnitude of threats to, these aquatic ecosystems. In terms of addressing knowledge gaps, coral reefs are a priority because of their extraordinarily high biological richness and the multitude of products and ecosystem services they provide to human beings.

This report presents a detailed, map-based analysis of threats to (and pressures on) the world's coral reefs. Until now the only information on the status of coral reefs worldwide was an estimate, first published in 1993, which indicated that 10 percent of the world's reefs were dead, and that 30 percent were likely to die within 10 to 20 years.[2] These figures, which have since been widely quoted, were based on guesswork by a number of scientists and on anecdotal evidence. *Reefs at Risk*—the first systematic and data-driven global assessment of these habitats—confirms that coral reefs are seriously threatened in most parts of the world. The maps in this report provide a detailed picture of where reefs are in jeopardy, identify reefs at risk that are of high biodiversity value, and show where reefs lack protection through parks, sanctuaries, and reserves.

Our results serve as an *indicator* of the threats to these ecosystems, not as an actual measure of degradation. Scientists do not know the actual condition of the vast majority of the world's reefs. In the Pacific, for example, 90 percent of the coral reefs have never been assessed.[3] In the absence of complete information on reef condition, we have drawn together available global maps and other data sets that measure human activity and, using a geographic information system and more than 800 mapped ReefBase sites* known to be degraded by humans, have modeled areas where one might *predict* degradation to occur, given existing anthropogenic pressures on the land- and seascape. *Reefs at Risk* draws on 14 distinct data sets and the input of coral reef experts and scientists from around the world.

*ReefBase—a database produced by the International Center for Living Aquatic Resources Management—is the most comprehensive source of global information available on coral reefs.

JAN C. POST, WORLD BANK

REEFS AND PEOPLE:
What Is at Stake?

Coral reefs are among the most valuable ecosystems on earth because of their immense biological wealth and the economic and environmental services they provide to millions of people. According to one estimate, reef habitats provide humans with living resources (such as fish) and services (such as tourism returns and coastal protection) worth about $375 billion each year.[4]

Coral reefs are important for the following reasons:

Biodiversity: Coral reefs are among the most biologically rich ecosystems on earth. About 4,000 species of fish and 800 species of reef-building corals have been described to date.[5] However, experts have barely begun to catalog the total number of species found within these habitats. One prominent scientist, Marjorie Reaka-Kudla, estimates there may be between one and nine million species associated with coral reefs.* Using this figure and rough estimates of human-caused reef degradation, Dr. Reaka-Kudla projected that over a million of these species may face extinction within the coming four decades.[6]

Coral Reef Ecosystems

Coral reefs resemble tropical rainforests in two ways: both thrive under nutrient-poor conditions (where nutrients are largely tied up in living matter), yet support rich communities through incredibly efficient recycling processes. Additionally, both exhibit very high levels of species diversity. Coral reefs and other marine ecosystems, however, contain more varied life forms than do land habitats. All but one of the world's 33 phyla (major kinds of organisms) are found in marine environments—15 exclusively so.[7]

Coral reefs are noted for some of the highest levels of total (gross) productivity on earth. Coral polyps—the thin living layer covering reef structures—provide much of the energy that fuels these communities. These tiny animals contain algae, which convert sunlight to fuel, deriving nutrients from polyp wastes in the process. Reef-building corals and certain calcareous algae (which may constitute more than half of a reef's stony substance) lay down a foundation of calcium carbonate. Over generations this accumulation results in often massive structures, providing homes and hiding places for countless other creatures. Coral reefs, then, are the net result of thousands of years of growth. As such, many are among the planet's oldest living communities.

In general, coral reefs are found in shallow waters, between the Tropic of Capricorn and the Tropic of Cancer. Their total extent is unknown, although it probably exceeds 600,000 square kilometers.[8] The World Conservation Monitoring Centre recently mapped the global distribution of shallow reefs (the base maps for this study). Using these data, Mark Spalding and A. M. Grenfell estimated the total global area of near-surface reefs (these being the most diverse, productive and economically important reefs) to be some 255,000 square kilometers.[9] Coral reefs represent less than 0.2 percent of the total area of oceans (and cover an area equivalent to 4 percent of the world's cropland area).

Levels of species diversity vary within these ecosystems, depending on location. The most species-rich reefs are found in a swath extending through Southeast Asia to the Great Barrier Reef, off northeastern Australia. More than 700 species of corals alone are found in this region. Within the Great Barrier Reef, 1,500 species of fish and 4,000 species of mollusks have been counted. Reefs outside this region are important for the distinct populations and species they contain. For example, although fewer types of corals are found in the Red Sea, this basin contains more endemics (species found nowhere else) than other portions of the Eastern Indian Ocean.[10,11]

Reef-associated plants and animals provide people with:

Seafood: Much of the world's poor, most of whom are located within the coastal zones of developing regions, depend directly on reef species for their protein needs. Globally, one-fifth of all animal protein consumed by humans comes from marine environments—an annual catch valued at $50 billion to $100 billion.[12] In developing countries, coral reefs contribute about one-quarter of the total fish catch, providing food, according to one estimate, for one billion people in Asia alone.[13, 14] If properly managed, reefs can yield, on average, 15 tons of fish and other seafood per square kilometer per year. However, in many areas of the world, fishers are depleting this resource through overexploitation and destructive fishing practices. According to a World Bank estimate, Indonesia forfeits more than $10 million a year in lost productivity, coastal protection, and other benefits through large-scale poison fishing alone. Through careful management, these reefs could support a $320 million industry, employing 10,000 Indonesian fishers.[15]

New medicines: In recent years, human bacterial infections have become increasingly resistant to existing antibiotics. Scientists are turning to the oceans in the search for new cures for these and other diseases. Coral reef species offer particular promise because of the array of chemicals produced by many of these organisms for self-protection. This potential has only barely been explored. Corals are already being used for bone grafts, and chemicals found within several species appear useful for treating viruses. Chemicals within reef-associated species may offer new treatments for leukemia, skin cancer, and other tumors.[16] According to one estimate, one-half of all new cancer drug research now focuses on marine organisms.[17, 18]

Other products: Reef ecosystems yield a host of other economic goods, ranging from corals and shells made

* Reaka-Kudla's figures may be high. Scientists who helped prepare the Global Biodiversity Assessment (United Nations Environment Programme, 1992) estimated that there are perhaps 14 million species altogether, counting those within land and aquatic environments. Others suggest even greater diversity is possible, when microbial life is fully considered.

into jewelry and tourism curios to live fish and corals used in aquariums, to sand and limestone used by the construction industry. However, such extractive activities are usually damaging to these habitats.

Coral reefs offer a wide range of environmental services, some of which are difficult to quantify, but are of enormous importance to nearby inhabitants. These services include:

Recreational value: The tourism industry is one of the fastest growing sectors of the global economy. Coral reefs are a major draw for snorkelers, scuba divers, recreational fishers, and those seeking vacations in the sun (some of the finest beaches are maintained through the natural erosion of nearby reefs). More than 100 countries stand to benefit from the recreational value provided by their reefs. Florida's reefs pump $1.6 billion into the economy each year from tourism alone.[19] Caribbean countries, which attract millions of visitors annually to their beaches and reefs, derive, on average, half of their gross national product from the tourism industry, valued at $8.9 billion in 1990.[20]


JAN C. POST, WORLD BANK

Complex chemistry—the clownfish is immune to and protected by the stinging tentacles of the sea anemones.

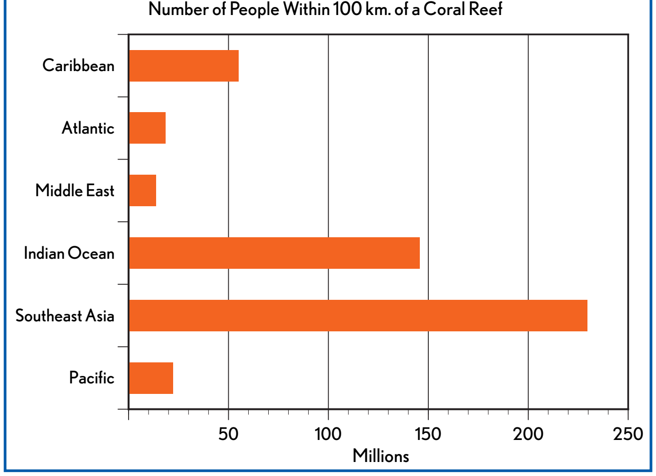

SOURCE: COREL PHOTO CD

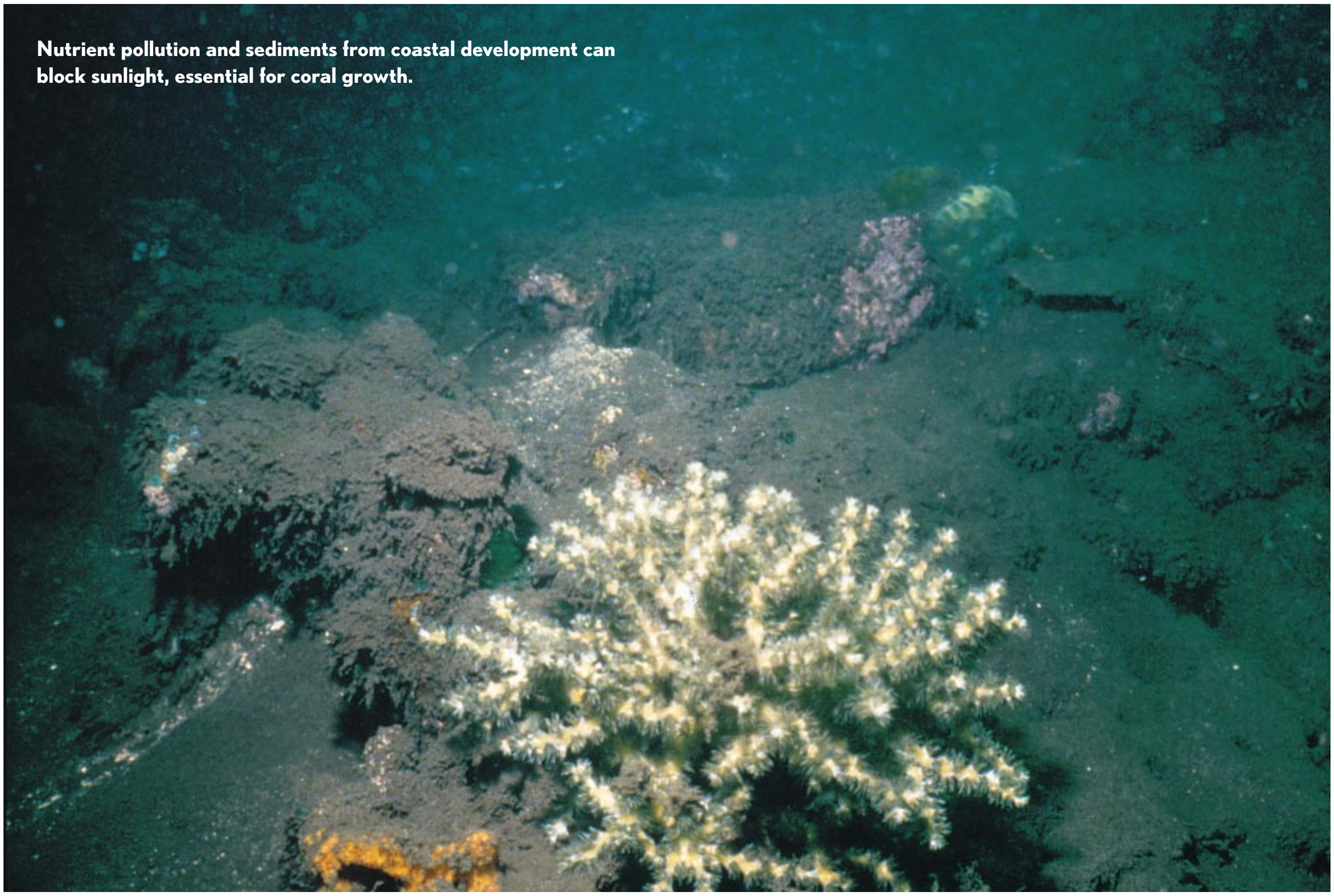
Diving and snorkeling allow up-close viewing of some of the wonders of the undersea world.

Coastal protection: Coral reefs buffer adjacent shorelines from wave action and the impact of storms. The benefits from this protection are widespread, and range from maintenance of highly productive mangrove fisheries and wetlands to supporting local economies built around ports and harbors, where, as is often the case in the tropics, these are sheltered by nearby reefs.

Globally, we estimate almost half a *billion* people live within 100 kilometers of a coral reef, benefiting from the production and protection these ecosystems provide *(see Figure 1)*. A recent study found that the costs of destroying just *one* kilometer of reef range from about $137,000 to almost $1.2 million over a 25-year period, when fishery, tourism, and protection values alone are considered.[21]

FIGURE 1. Almost Half a Billion People Live Near Reefs





Nutrient pollution and sediments from coastal development can block sunlight, essential for coral growth.

JIM MARAGOS, EAST-WEST CENTER

THREATS TO REEFS

Coral reefs around the world are threatened by an onslaught of human activities. These include:

Effects of coastal development: The growth of coastal cities and towns generates a range of threats to nearby coral reefs. Where space is limited, airports and other construction projects are built upon reef communities. Dredging of harbors and shipping channels and the dumping of spoils result in the outright destruction of these habitats. In many areas, coral ecosystems are mined for construction materials—sand and limestone, which is made into cement—for new buildings.

The indirect effects of development are the most damaging. Reef-building corals—specifically the algae (zooxanthellae) within their coral polyps, which generate energy through photosynthesis—require sunlit waters to survive. Algal blooms resulting from excess nutrients that come from sewage releases and other sources block sunlight, reducing coral growth. Shoreline construction and modification disturbs sediments, which smother corals. Nutrient-rich runoff promotes the growth of bottom-dwelling algal competitors and interferes with coral reproduction. Other threats include hot-water discharges from power plants, and mine runoff and industrial toxic waste effluents, which poison reef communities.[22, 23, 24]

Even tourism, where it is unregulated, can pose a threat. Swimmers and divers in the Gulf of Aqaba (bounded by Saudi Arabia, Jordan, Israel, and Egypt), for example, have destroyed corals through trampling, while boat anchors create further damage to some areas.[25] In many other places, hotels and resorts discharge sewage directly into the ocean, polluting reef waters and promoting algal growth. Demand for food fish and tourism curios results in overfishing of key reef species.

Overexploitation and destructive fishing practices: Although measured together in the Reefs at Risk indicator, overexploitation and destructive fishing can be separated into two types of threats.

Overexploitation affects the vast majority of the world's reefs. *(See box "Overfishing of Target Species.")* At a minimum, overfishing results in shifts in fish size, abundance, and species composition within reef communities. Evidence suggests that removal of key herbivore and predator species may ultimately affect large-scale ecosystem changes. For example, removal of triggerfish has been linked with explosions in burrowing urchin populations, their prey, who subsequently accelerate reef erosion through feeding activities.

In the Caribbean, decades of overfishing has led, in many places, to very low levels of grazing fish species. Because of this, herbivorous sea urchins (a nonburrowing species) have played an increasingly important role in keeping down algal growth. In the early 1980s, huge numbers of these urchins succumbed to disease. Without grazing fish or urchin populations, and spurred on in many areas by organic pollution, algae quickly dominated the reefs, inhibiting coral settlement and sometimes overgrowing living corals. In areas such as Jamaica, hurricanes further compounded the damage, reducing coral to rubble. Formerly thriving reefs were replaced by low-diversity and low-productivity algal systems. Some scientists claim this is a harbinger of events to come, as reefs around the world continue to be overfished. Others argue that these major ecosystem effects may be reversible in the short term, if degradation has not gone too far.[26, 27, 28, 29]


JULIE HARLAN, WRI

The live fish trade is leaving many reefs devoid of showcase species.


LAURETTA BURKE, WRI

Pollution and erosion from land-clearing activities far inland contribute to reef sedimentation.

Destructive fishing: Blast fishing; fishing with cyanide and other poisonous chemicals; muro-ami netting (pounding reefs with weighted bags to scare fish out of crevices); and in deeper waters, trawling directly damage corals. Because these methods are generally nonselective, large numbers of other species, along with undersized target species, may be swept up in nets or killed by poisons or explosives in the process. *(See box "Cyanide Fishing.")* As not all fishing methods are destructive, this is less of a widespread threat than overexploitation.

Impact from inland pollution and erosion: Sediment, pesticides, and pollution from human activities inland can damage coral reefs when transported by rivers into coastal waters. These result in the smothering of corals, reduced light levels (affecting growth), and overnutrification of reef communities. Pollution is a particular threat to coral reefs near the mouths of small and medium-sized watersheds, as the high volume of freshwater flow and sediments carried by major rivers naturally inhibits coral growth. Land clearing can expand the extent of this no-growth zone. Watersheds cleared of their forests and other vegetation cover are vulnerable to erosion and flooding. During high water periods, silt and pollutants within these basins are carried far beyond the normal "plume," or the area where coral reef growth would normally be limited by river discharges, had they been intact.[30, 31]

Marine-based pollution: In comparison to the other stresses, oil spills and the deliberate discharge of oily ballast water by passing

VAUGHAN R. PRATT, INTERNATIONAL MARINELIFE ALLIANCE

Destructive fishing practices, such as the use of cyanide, and overfishing pose the greatest threats to the integrity of coral reefs.

Overfishing of Target Species

Many reef species, including giant clams, sea cucumbers, sharks, lobsters, large groupers, snappers, and wrasses, are now fetching high prices both on domestic markets and internationally. In order to capture these "target species," commercial fisheries operations are moving further and further afield, and now regularly visit even the most remote reefs in the world. In many areas such harvesting is clearly unsustainable.

Fishers sweep reefs of their valuable species and then move on, eliminating entire populations within the areas they leave behind. Two examples from the Philippines illustrate this threat. During the 1960s and 1970s, several giant clam species became locally extinct due to overharvest for food and for their large shells, which are popular as decorations, sinks, and bird baths. As recently as 1987, the sea urchin *Tripneustes gratilla* was found in dense populations across a 24-square-kilometer sea grass bed on a reef flat in Bolinao. Exploitation rates increased suddenly with the appearance of a trader from China and by 1995 the sea urchin was believed to have become locally extinct.[32]

There are increasing reports of buyers for specialty markets appearing in reef areas and overfishing species to local extinction. Sea urchin and sea cucumber have reportedly disappeared from certain reefs in the Galapagos and the western Caribbean. Concerns about the overexploitation of sea horses for Chinese medicine and the aquarium trade have prompted the initiation of successful projects in the Philippines to educate villagers to properly manage the wild stocks and to grow sea horses for controlled export.

A very obvious change to many of the world's reefs is the lack of large, predatory fish. A long-standing symbol of coral reefs, the large grouper is becoming a rarity. Much of the problem is related to the ease with which these often very sociable fish can be shot with spear guns. Rampant blast fishing has also contributed to their demise. The capture of sharks for sharkfin soup and other products has made sharks rare on many reefs, especially in the Southeast Asian region. Of particular importance is the loss of large reef fish in connection with the live fish trade supplying Chinese restaurants. This trade has led to widespread reductions of populations of groupers, humphead wrasses, and others.[33]

Experts contributing to the *Reefs at Risk* study concluded, during a 1997 mapping workshop held in Manila, that target species fishing now occurs on most of the world's reefs. This fact was confirmed during the recent Reef Check volunteer survey covering hundreds of reefs around the world, which showed that even some of the most isolated reefs on the planet are affected. Because this activity is so widespread and difficult to document, the threat of target species overfishing is underrepresented in the Reefs at Risk indicator. Although, to date, few marine species are known to have become completely extinct, the important message is that because of the pervasive nature of this threat, very few reefs can truly be considered pristine.

Coral Reef Bleaching

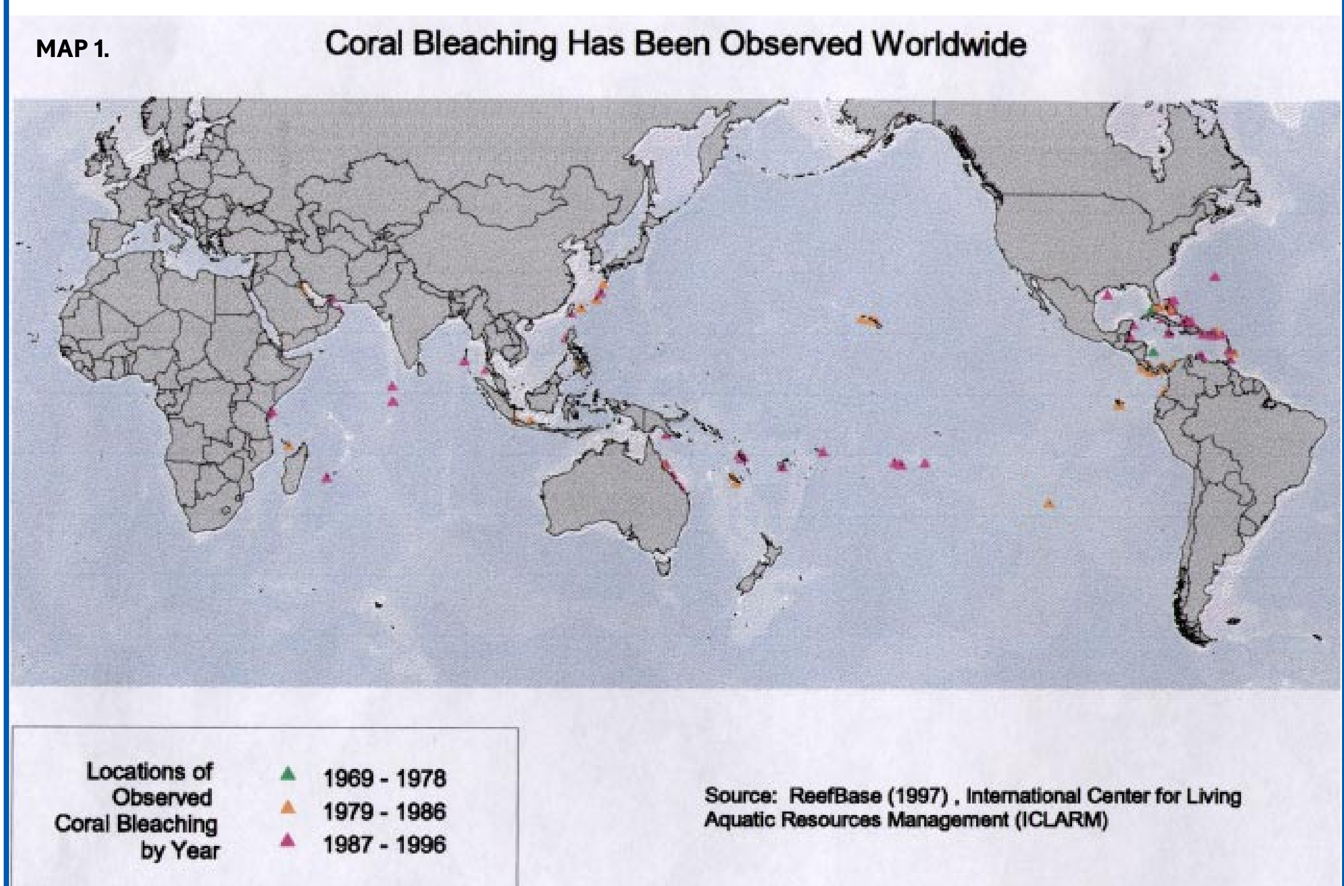
JOHN MCMANUS, ICLARM

Coral bleaching occurs rapidly in response to a wide range of stresses.

When corals undergo certain kinds of stress, much of the zooxanthellae—the symbiotic algae that provide coral polyps with nutrients—are expelled from the coral tissue. Ultimately, weakened corals may die. Bleaching is a frequent symptom of pollution-induced stress, as well as a response to natural factors such as changes in water temperature, salinity levels, and possibly ultraviolet light.[34]

During the El Niño of 1982–83, large areas of coral reef around the world were severely damaged by high water temperatures, which resulted in coral bleaching. Scientific studies have linked bleaching events to temporary "hot spots," local areas of unusually high temperatures caused by changes in atmospheric circulation during the El Niño oceanographic events. *(Map 1 provides a sense of the wide incidence of coral reef bleaching.)* The effects of the severe El Niño that started in 1997 have yet to be documented.[35,36]

MAP 1.



ships pose an unknown, but probably less significant, threat to coral reefs. Studies on the impact of some 8–9 million barrels of oil discharged into the Arabian Gulf during the Iran–Iraq and Gulf Wars found that spills appeared to be related to short-term declines in many fish and other species. In 1986, a major spill off the mouth of the Panama Canal was linked by scientists to significant losses of coral diversity and cover in heavily affected areas. In the longer term, oil spills may leave reef communities more vulnerable to other types of disturbances.[37, 38, 39]

In many cases it is difficult to pinpoint the exact causes of coral reef declines now occurring around the world. Scientists believe that degradation frequently occurs through the interaction of a combination of human-caused factors, which then leaves reef communities less resistant to periodic natural disturbances. Disease, temperature extremes, pest outbreaks, tropical cyclones, and other natural events periodically devastate corals, with resulting ecosystem-wide repercussions. However, healthy reefs are resilient, and will recover with time. The impact of multiple stressors, both natural and human caused, can have a multiplicative effect on reef ecosystems. Evidence, much of it anecdotal, suggests that human-damaged reefs may be more vulnerable to some types of natural disturbances and take longer to recover.[40] For example, some experts believe pollution contributed to the recent die-offs of Florida Key reefs in the United States from white pox disease.[41]

Even where they are not directly affected by human activity, coral reefs may be threatened by the degradation of nearby mangroves, seagrass beds, and other associated habitats, which serve as nurseries for many reef species. In addition, mangroves play an important role in filtering out sediments washed into coastal areas from upstream runoff. In many parts of the world, mangroves are being hacked away for fuel wood, creation of aquaulture ponds, and to make room for coastal development.[42, 43]

One other long-term threat is global climate change. Current models predict that climate change will elevate sea surface temperatures in many places, cause sea levels to rise, and result in greater frequency and intensity of storms. Although regional and local patterns in these changes are harder to model, the effects on coral reefs are likely to include greater physical damage by storms and more frequent instances of coral bleaching. *(See box "Coral Reef Bleaching.")* This increase in "natural" stress levels will leave coral reefs in many parts of the world more vulnerable to human disturbances.[44]

Cyanide Fishing: A Poison Tide on the Reef

The use of cyanide to stun and capture live coral reef fish began in the 1960s in the Philippines to supply the growing market for aquarium fish in Europe and North America, a market now worth more than $200 million a year. Since the late 1970s, the poison has also been used to capture larger live reef fish (primarily grouper species) for sale to specialty restaurants in Hong Kong and other Asian cities with large Chinese populations. Selected and plucked live from a restaurant tank, some species can fetch up to $300 per plate, and are an essential status symbol for major celebrations and business occasions. As the East Asian economy boomed over the past several decades, live reef food fish became a business worth some $1 billion annually.

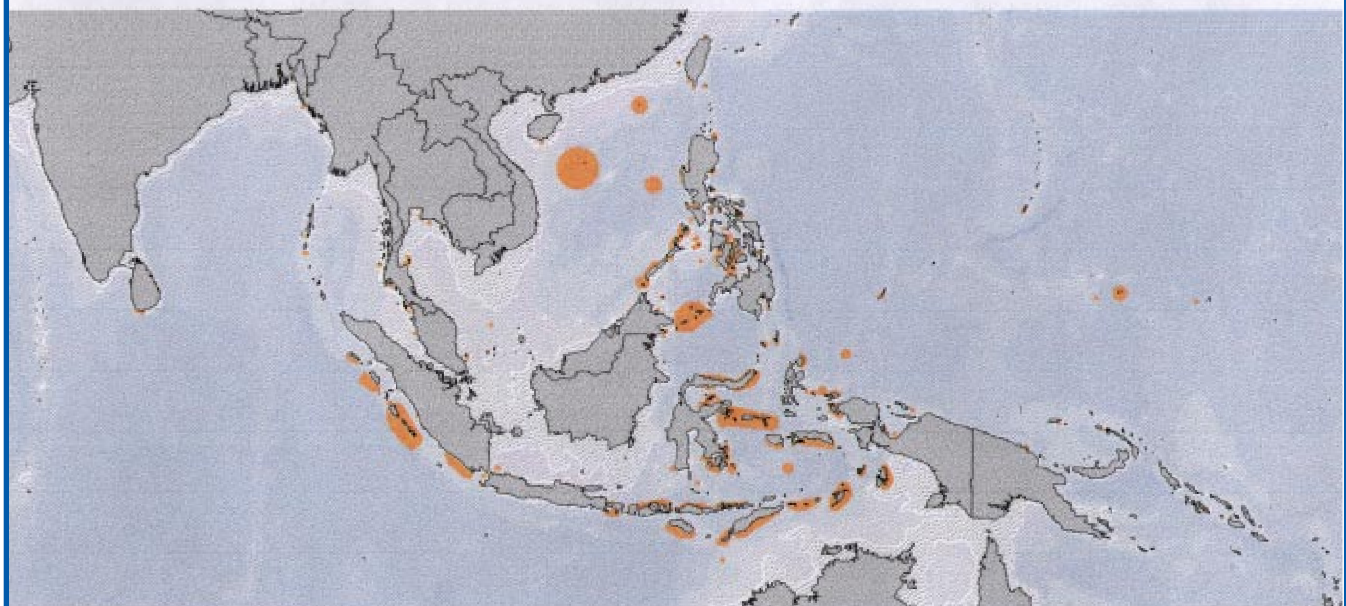
Despite the fact that cyanide fishing is nominally illegal in virtually all Indo-Pacific countries, the high premium paid for live reef fish, weak enforcement capacities, and frequent corruption have spread the use of the poison across the entire region—home to the vast majority of the planet's coral reefs. Since the 1960s, more than one million kilograms of cyanide has been squirted onto Philippine reefs, and the vast Indonesian archipelago now faces an even greater cyanide problem. As stocks in one country are depleted, the trade moves on to new frontiers, and cyanide fishing is now confirmed or suspected in countries stretching from the central Pacific to the shores of East Africa. Sadly, the most pristine reefs, far from the usual threats of sedimentation, coral mining, and coastal development, are the primary target for cyanide fishing operations.

Systematic scientific testing of the impact of cyanide on reefs is scanty, but tests show that cyanide kills corals, and its toxic effects on fish are well known. Anecdotal evidence of the poison's lethal effects on the reef comes from countless scuba-diving operators, field researchers, and cyanide fishermen themselves. The process of cyanide fishing itself indisputably wreaks havoc on coral reefs. The divers crush cyanide tablets into plastic squirt bottles of sea water and puff the solution at fish on coral heads. The fish often flee into crevices, obliging the divers to pry and hammer the reefs apart to collect their stunned prey. Cyanide fishing also poses human health risks: to fishermen, through accidental exposure to the poison and careless use of often shoddy compressed-air diving gear by untrained divers.

Cyanide fishing can be attacked, as experience shows in the Philippines, the only country so far to take concrete action against the problem. That country's Cyanide Fishing Reform

(continued on page 16)

MAP 2. Destructive Fishing is Widespread in Southeast Asia



■ Areas Under High Threat from Destructive Fishing

Note: Areas classifed as threatened by destructive fishing practices are based upon a 20 kilometer radius zone from known occurances of dynamite or cynide fishing as found in ReefBase (ICLARM, 1997) and were revised based upon expert opinion obtained at the two-day Reefs at Risk workshop held in September 1997 in Manila.

Program, a unique partnership between the government and the International Marinelife Alliance (IMA), a local non-governmental organization, has trained thousands of fishermen to use alternatives to cyanide such as fine-mesh barrier nets draped over a reef section to catch aquarium-sized fish and hook-and-line techniques to catch larger fish for the restaurant trade. The government has stepped up enforcement of anti-cyanide fishing laws by establishing a network of cyanide detection laboratories, operated by IMA, that randomly sample fish exports at shipment points throughout the country and monitor all aspects of the trade. New regulations are slated to make testing a requirement for all live fish exports and to tighten controls on import and distribution of cyanide. A public awareness campaign in the media and public schools is helping to educate Filipinos about the value of coral reefs and the threats posed by cyanide and other destructive fishing practices. Cyanide fishing has not ceased in the Philippines, but it has certainly been reduced as a result of these efforts.

Currently, IMA, the World Resources Institute, and other partners are implementing the only on-the-ground program in Indonesia to train cyanide fishermen in alternative capture techniques, and are collaborating in the Indo-Pacific Destructive Fishing Reform Program to assist governments in at least half a dozen countries in Southeast Asia and the Pacific to combat this poison tide sweeping the planet's largest and most diverse expanse of coral reefs.

Adapted from Charles Victor Barber and Vaughan R. Pratt, **Sullied Seas: Strategies for Combating Cyanide Fishing in Southeast Asia and Beyond** ***(Washington D.C.: World Resources Institute and International Marinelife Alliance, 1997).***

JAN C. POST, WORLD BANK

THE REEFS AT RISK INDICATOR

"Reefs at Risk" is an indicator: it flags problem areas around the world where, in the absence of good management, coral reef degradation might be expected, or predicted to occur shortly, given ongoing levels of human activity. Such degradation includes *major* changes in the species composition, relative species abundance, and/or the productivity of coral reef communities, attributable to human disturbance. As noted above, this indicator measures potential risk associated with human activity, not actual reef condition.

Our analysis covers potential threats from (1) coastal development, (2) overexploitation and destructive fishing practices, (3) the impact of inland pollution and erosion, and (4) marine pollution. This assessment does not include likely future threats posed by population growth or climate change, nor does it consider threats resulting from coral diseases, bleaching, and other factors considered largely natural in origin.

Our results are based on a series of distance relationships correlating mapped locations of human activity such as ports and towns, oil wells, coastal mining activities, and shipping lanes ("component indicators"), with predicted risk zones of likely environmental degradation. Detailed subnational statistics on population density, size of urban areas, and land cover type were also incorporated into the analysis. In addition, we used data on rainfall and topography to help estimate potential runoff within watersheds, from inland deforestation (and other land clearing), and from agriculture.

Distance rules defining threat zones were established for each component indicator using information on the known locations of more than 800 reef sites documented as degraded by human activity by one of the four factors (for example, coastal development) considered in this analysis. Minimum distances were established through expert review and input, and by determining the most conservative set of rules that, when taken in aggregation for any one of the four threat categories, assured that we encompassed at least two-thirds of all known degraded sites affected by activities related to that category. Tables 1 and 2 present the component indicators used and the decision rules established to grade any one reef as under "low," "medium," or "high" threat. (A more detailed description of the implementation of the Reefs at Risk Indicator can be found in the Technical Notes at the end of this publication.)

Draft risk maps were revised and vetted at a global workshop attended by coral reef experts from around the

TABLE 1. REEFS AT RISK INDICATOR: DECISION RULES FOR COMPONENT INDICATORS

THREAT FACTOR: COASTAL DEVELOPMENT

Component Indicator	Qualifier	High	Medium
Cities	population over 5 million	within 30 km	30–60 km
Cities	population over 1 million	within 20 km	20–40 km
Cities	population over 100,000, with little sewage treatment	within 10 km	10–25 km
Cities	population over 100,000, with moderate sewage treatment	–	within 10 km
Settlements	any size	–	within 8 km
Airports and military bases	military and civilian airports	–	within 10 km
Mines	any type	within 10 km	–
Tourist resorts	including diving facilities	–	within 8 km

THREAT FACTOR: MARINE POLLUTION

Component Indicator	Qualifier	High	Medium
Ports	large size	within 20 km	within 50 km
Ports	medium size	within 10 km	within 30 km
Ports	small size	–	within 10 km
Oil tanks and wells	any size	within 4 km	within 10 km
"Shipping threat areas"	known major shipping routes with areas of relatively narrow passage	–	defined zone

THREAT FACTOR: OVEREXPLOITATION AND DESTRUCTIVE FISHING

Component Indicator	Qualifier	High	Medium
Population density	coastal population density exceeds 100 persons per sq. km.	within 20 km	–
Population density	coastal population density exceeds 20 persons per sq. km.	–	within 20 km
Destructive fishing	expert-defined areas where blast or cyanide fishing occur	within 20 km	–

THREAT FACTOR: INLAND POLLUTION AND EROSION

Component Indicator	Qualifier	High	Medium
Modeled relative erosion potential (REP)	based on the relative slope, land cover class, and precipitation in an area	scaled to modeled river flow	scaled to modeled river flow

Notes:
Table 1 defines zones for high and medium threat only. Areas not defined as under high or medium threat default to low threat.

Within the coastal development threat factor, areas classified as being under medium threat from any individual component that were also identified as an embayment or lagoon were reclassifed to high threat to reflect the elevated threat to reefs in enclosed waters.

Within the overexploitation threat factor, only countries where the per capita gross national product is less than $10,000 per year or the per capita fish consumption is greater than 50 kilograms per person per year were included.

Further description of the methodology can be found in the Technical Notes at the back of this publication.

world. At that workshop, scientists also mapped areas under high threat from destructive fishing practices, and areas of intense shipping within narrow passages or "shipping threat areas"—two additional data sets incorporated into this analysis. Final draft maps underwent a second series of review by these and other experts. (Experts who helped us with the mapping or otherwise contributed to this study are listed in the acknowledgments.)

Overall, the Reefs at Risk indicator accurately classifies over 80 percent of sites known to be degraded by humans as "at risk."* In some cases, where we know the condition of reefs, those mapped as at risk nevertheless remain relatively healthy due to good planning and management by local governments and people, or because currents, topography, and other factors render these reefs less sensitive to the impact of human activity. In other cases, a review of the literature and expert opinion show that degradation is actually worse than our indicator suggests. (Experts' comments on the final Reefs at Risk Indicator results can be found in the Technical Notes.)

Finally, it is important to note that reefs classified as being at low risk are not necessarily healthy: these sites may be affected by pressures not captured by this indicator (overfishing within remote areas, undocumented by our experts), or by new activities not captured by our base maps and statistics, many of which are already out-of-date (for example, development of a new mine or sedimentation from newly cleared land upstream from a reef). For these reasons, we have likely underreported risk in regions where the availability of recent high-quality data is poor and in areas, such as portions of the Pacific, where many reefs are distant from human settlements. The maps presented here are a static picture of pressures on reefs: sites at low risk today may be under heavy pressure, and as a result be seriously degraded, within the next few years.

* We compared Reefs at Risk results with 800 sites documented within ICLARM's ReefBase (version 2) database as having been degraded by human activity. This analysis showed that 80 percent of the time, our results accurately classified these areas as "at risk" (under medium or high threat).

TABLE 2. CLASSIFICATION RULES FOR RANKING RISK

Data reflecting coral reef locations were initially classified by individual threat factors and finally by the combined (integrated) results for all four threat factors as follows:

Reefs classified as high threat in at least one of the threat factors are assigned **High Threat** overall;

Reefs classified as medium threat in at least one threat factor are assigned **Medium Threat** overall; and

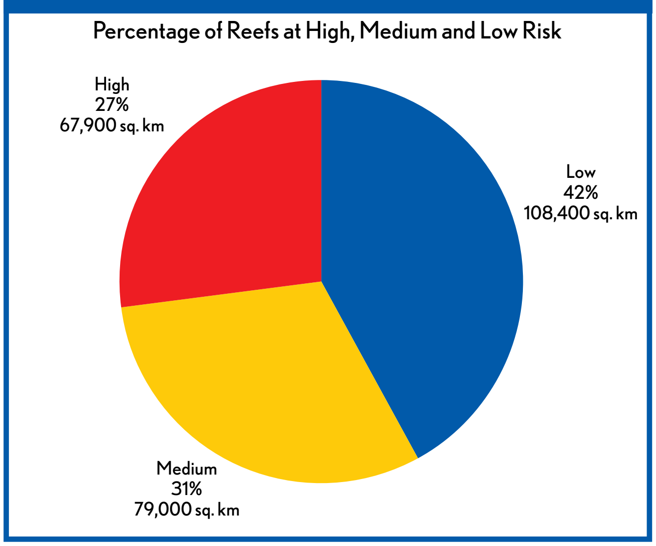
Reefs classified as low threat in all four threat factors are assigned **Low Threat** overall.

JAN C. POST, WORLD BANK

STATUS OF THE WORLD'S CORAL REEFS

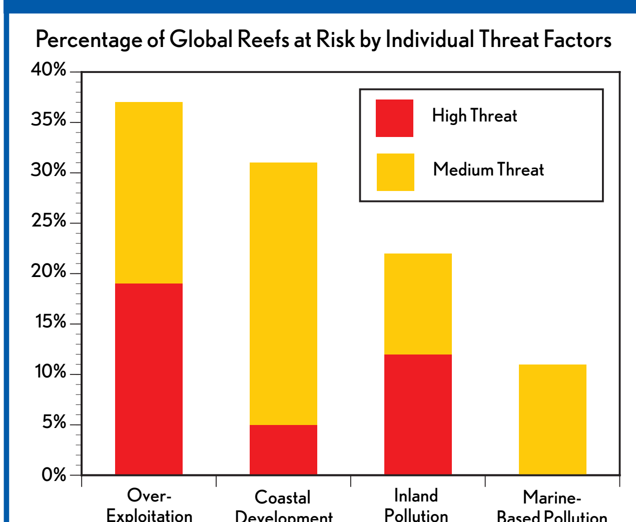
More than a quarter of the world's reefs are at high risk, and just under a third of these habitats are at moderate risk, from human disturbance. Of the four broad categories of potential threat to coral reefs evaluated, overexploitation of marine resources, including destructive fishing practices, and coastal development present the greatest threat. Globally, 36 percent of all reefs were classified as threatened by overexploitation, 30 percent by coastal development, 22 percent by inland pollution and erosion, and 12 percent by marine pollution. When these threats are combined, 58 percent of the world's reefs are at risk (defined as medium and high risk). *(See Figures 2 and 3.)*

FIGURE 2. FIFTY-EIGHT PERCENT OF THE WORLD'S REEFS ARE AT RISK



These figures are tempered by the relatively low threat faced by coral reefs in the Pacific—home to more reefs than any other part of the world. Forty-one percent of reefs in the Pacific are estimated to be at risk. Outside of this region, 70 percent of all reefs are at risk (almost 40 percent at high risk). Figure 4 presents a summary of coral reef area and combined threat classification by region, while Figure 5 shows the same information for several countries. (Definitions for regional groupings can be found in the Technical Notes section.)

FIGURE 3. OVEREXPLOITATION AND COASTAL DEVELOPMENT POSE THE GREATEST THREAT TO REEFS



Note: Figures 2 and 3 are based upon coral reef area totals (equaling 255,000 square kilometers) derived from the World Conservation Monitoring Centre base maps used in this study.

TABLE 3. REEFS AT RISK INDICATOR BY REGION AND COUNTRY

A. Regional Statistics

Region	Reef Area in Square Kilometers By Threat Category[a] Total	Low	Medium	High	Percentages Low	Medium	High	Coastal Population Density[b] (pp/sq.km.)	Marine Protected Areas[c] Number	Area (sq. km.)
Middle East	20,000	7,800	9,200	3,000	39%	46%	15%	24	10	11,845
Caribbean	20,000	7,800	6,400	5,800	39%	32%	29%	63	139	38,914
Atlantic (excl. Caribbean)	3,100	400	1,000	1,700	13%	32%	29%	64	3	368
Indian Ocean	36,100	16,600	10,500	9,000	46%	29%	25%	135	66	15,100
Southeast Asia	68,100	12,300	18,000	37,800	18%	26%	56%	128	57	36,263
Pacific	108,000	63,500	33,900	10,600	59%	31%	10%	98	92	372,809
Global Total	255,300	108,400	79,000	67,900	42%	31%	27%	101	367	475,298

B. Selected Country and Geographic Grouping Statistics

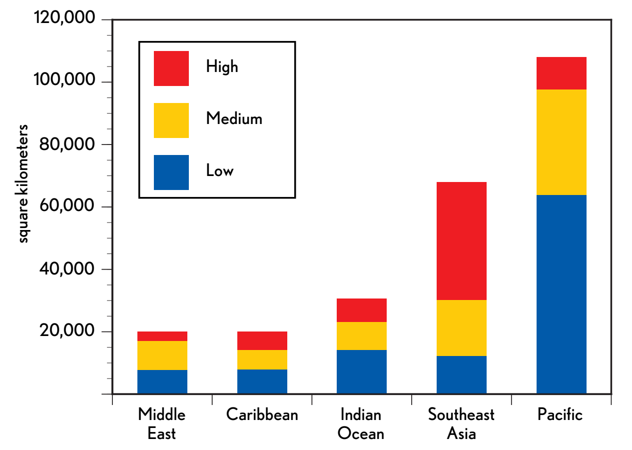
Region	Reef Area in Square Kilometers By Threat Category[a] Total	Low	Medium	High	Percentages Low	Medium	High	Coastal Population Density[b] (pp/sq.km.)	Marine Protected Areas[c] Number	Area (sq. km.)
Australia	48,000	33,700	13,700	600	70%	29%	1%	12	12	374,967
Fiji	10,000	3,300	4,800	1,900	33%	48%	19%	91	1	1
French Polynesia	6,000	4,900	1,100	0	82%	18%	0%	38	1	124
India	6,000	1,400	500	4,100	23%	8%	68%	412	2	288
Indonesia	42,000	7,000	14,000	21,000	17%	33%	50%	93	26	30,405
Lesser Antilles	1,500	0	300	1,200	0%	20%	80%	159	2	253
Maldives	9,000	7,900	1,100	0	88%	12%	0%	NA	NA	NA
Marshall Islands	6,000	5,800	200	0	97%	3%	0%	NA	2	163
New Caledonia	6,000	5,000	800	200	83%	13%	3%	6	5	530
Papua New Guinea	12,000	6,000	4,500	1,500	50%	38%	13%	7	8	2,149
Philippines	13,000	50	1,900	11,050	0%	15%	85%	174	12	458
Saudi Arabia	7,000	2,500	4,100	400	36%	59%	6%	15	1	4,500
Solomon Islands	6,000	3,000	2,500	500	50%	42%	8%	8	0	0
US - Hawaii	1,200	650	450	100	54%	38%	8%	50	2	1,031

a. Reef Area Estimates by Region and Threat Category (sq. km.) and percentages
Reef area estimates are based on WCMC's dataset Shallow Coral Reefs of the World and Spalding and Grenfell (1997).
Estimates of shallow reef area for Australia, Indonesia and the Philippines are significantly smaller than other published estimates.

b. Average Coastal Population Density (pp/sq.km.)
Statistics are for populated areas within 60 kilometers of the coastline. Population data come from Gridded Population of the World data set from the National Center for Geographic Information and Analysis—Global Demography Project.
Data are unavailable for some small island areas.

c. Marine Protected Areas (Number and Area Estimates)
Marine protected area counts and area estimates are summaries of the WCMC dataset Marine Protected Areas of the World, and are incomplete for some countries. Area statistics for protected sites are for the entire protected area, which include non-reef areas and can include substantial land areas.

FIGURE 4. MOST LOW RISK REEFS ARE IN THE PACIFIC



Most disturbing is the status of reefs in Southeast Asia—a global hot spot of coral and fish diversity *(see box "Biodiversity and Reefs at Risk")*. As with tropical rainforests in this region, reef ecosystems are under tremendous threat. More than 80 percent of these ecosystems are potentially at risk, primarily from coastal development, overfishing, and destructive fishing practices.

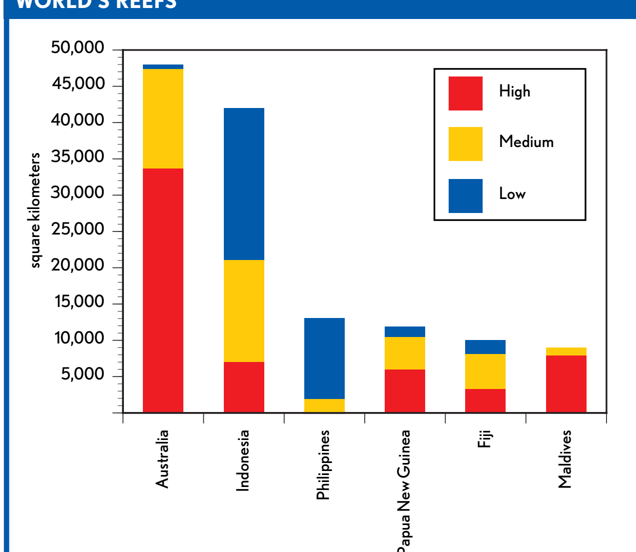
Results from the Reefs at Risk analysis are presented in Table 3 and in the five regional maps included in this report. Regional highlights follow.

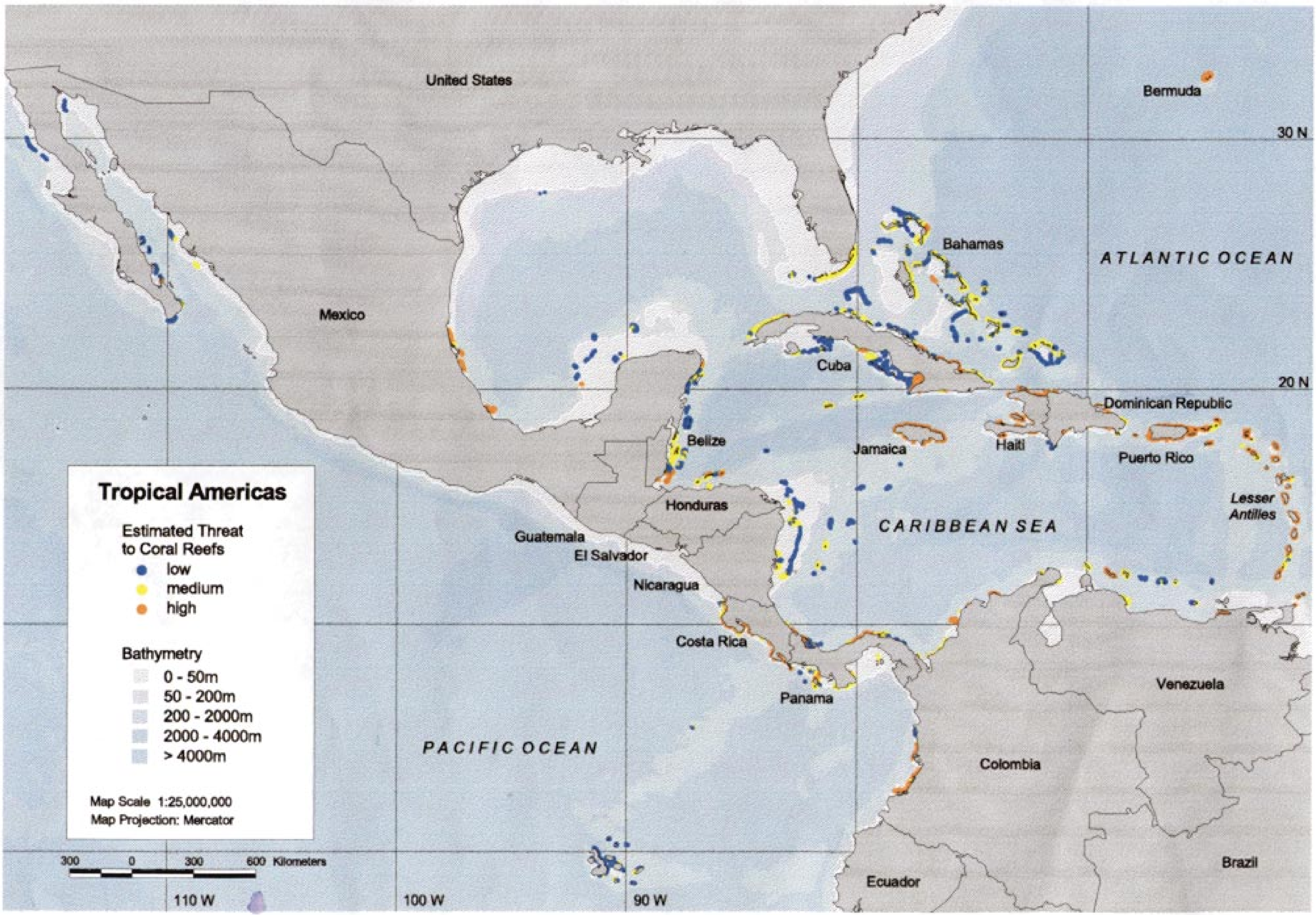
Caribbean and Atlantic Ocean: About 9 percent of the world's mapped reefs are found in this region, most of which are located along the Central American coast and off the Caribbean islands. Our results indicate that almost two-thirds of reefs here are at risk (about one-third at high risk). Sedimentation from upland deforestation, poor agricultural practices, coastal development, pollution, and overfishing are major threats to many reefs here.[45, 46] Most reefs of the Antilles and Lesser Antilles (including Haiti, the Dominican Republic, Puerto Rico, Dominica, and Barbados) are under high potential threat. Virtually all of the reefs of the Lesser Antilles are at risk. Almost all reefs of the Florida Keys are at moderate threat, largely from coastal development, inappropriate agricultural practices, overfishing of target species such as conch and lobster, and pollution associated with development and farming. Those of the Bahamas and the Yucatan Peninsula and the remoter reefs off Belize, Honduras, and Nicaragua are largely at low risk from mapped human activity.

Indian Ocean: Over half of the region's reefs are at risk. Almost all of the reefs off India and Sri Lanka are under high potential threat. Destructive fishing practices, overexploitation, pollution, sedimentation from land clearings, and coral mining for lime have all been blamed for the widespread degradation of Sri Lankan reefs.[47, 48] Off East Africa, most documented damage to coastal habitats occurs near major towns and cities, due to sewage discharge and overexploitation. Blast fishing and agricultural runoff also pose significant threats. Our results indicate that the great majority of reefs of the Chagos Archipelago and Maldive Islands are under low potential threat (according to this study, close to 90 percent of reefs in the Maldives are at low risk). All told, the Indian Ocean accounts for roughly 15 percent of the world's mapped reefs.

Middle East (Red Sea and Arabian Gulf): Although in the past most of the region's reefs have been reported to be in good condition, about 60 percent of these habitats were assessed as at risk primarily due to coastal development, overfishing, and the potential threat of oil spills in the heavily trafficked Arabian Gulf and southern end of the Red Sea. Almost two-thirds of Gulf reefs are at risk, largely because over 30 percent of the world's oil tankers move through this area each year.[49] Industrial pollution and coastal development are threats in some areas. Corals in many parts of the Gulf of Aqaba have been degraded through tourism impact and related development. Reefs in the northern Red Sea and the Arabian Gulf are espe-cially vulnerable to degradation due to limited water circulation and temperature extremes. About 8 percent of the world's mapped reefs are found in the Middle East.

FIGURE 5. SIX COUNTRIES CONTAIN OVER HALF OF THE WORLD'S REEFS




Tropical Americas
Estimated Threat to Coral Reefs
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Belize
Jamaica
Haiti
Puerto Rico
Honduras
Lesser Antilles
CARIBBEAN SEA
Guatemala
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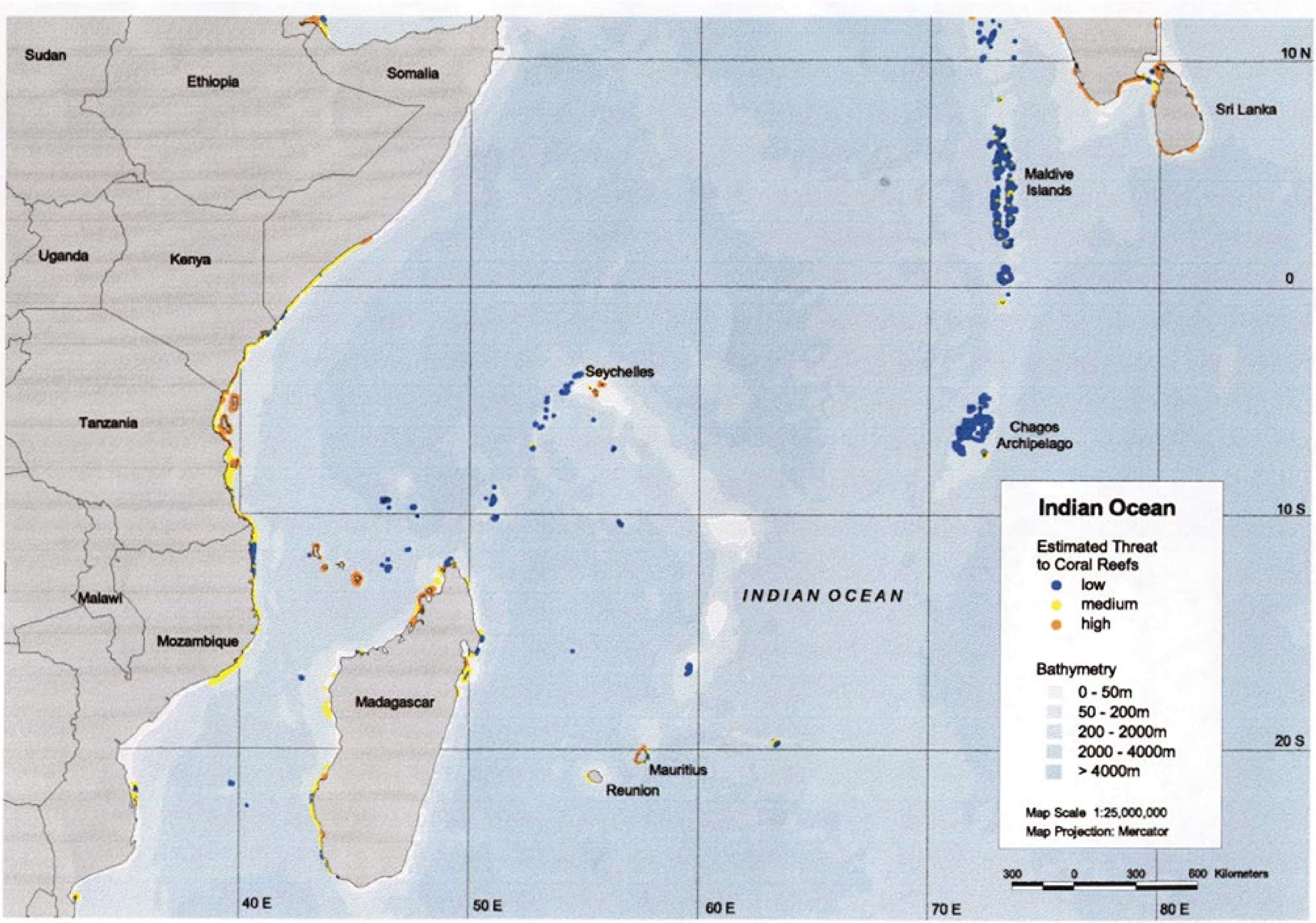
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Kenya
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Malawi
Mozambique
Madagascar
Seychelles
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Sri Lanka
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Mauritius
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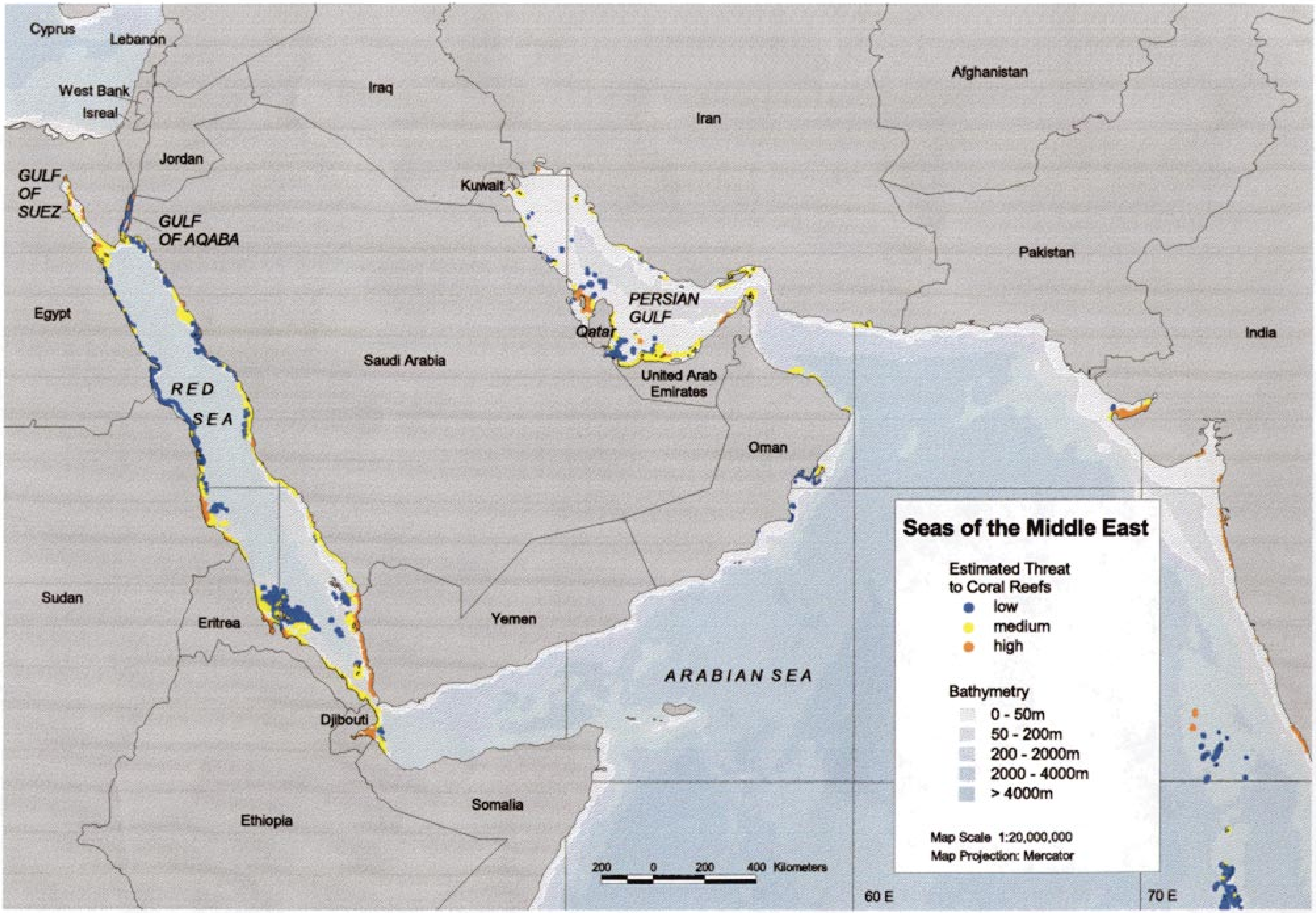
Seas of the Middle East
Estimated Threat to Coral Reefs
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Bathymetry
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Map Projection: Mercator
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Lebanon
West Bank
Isreal
Jordan
Iraq
Iran
Afghanistan
Pakistan
India
Kuwait
PERSIAN GULF
Qatar
United Arab Emirates
Oman
Saudi Arabia
GULF OF SUEZ
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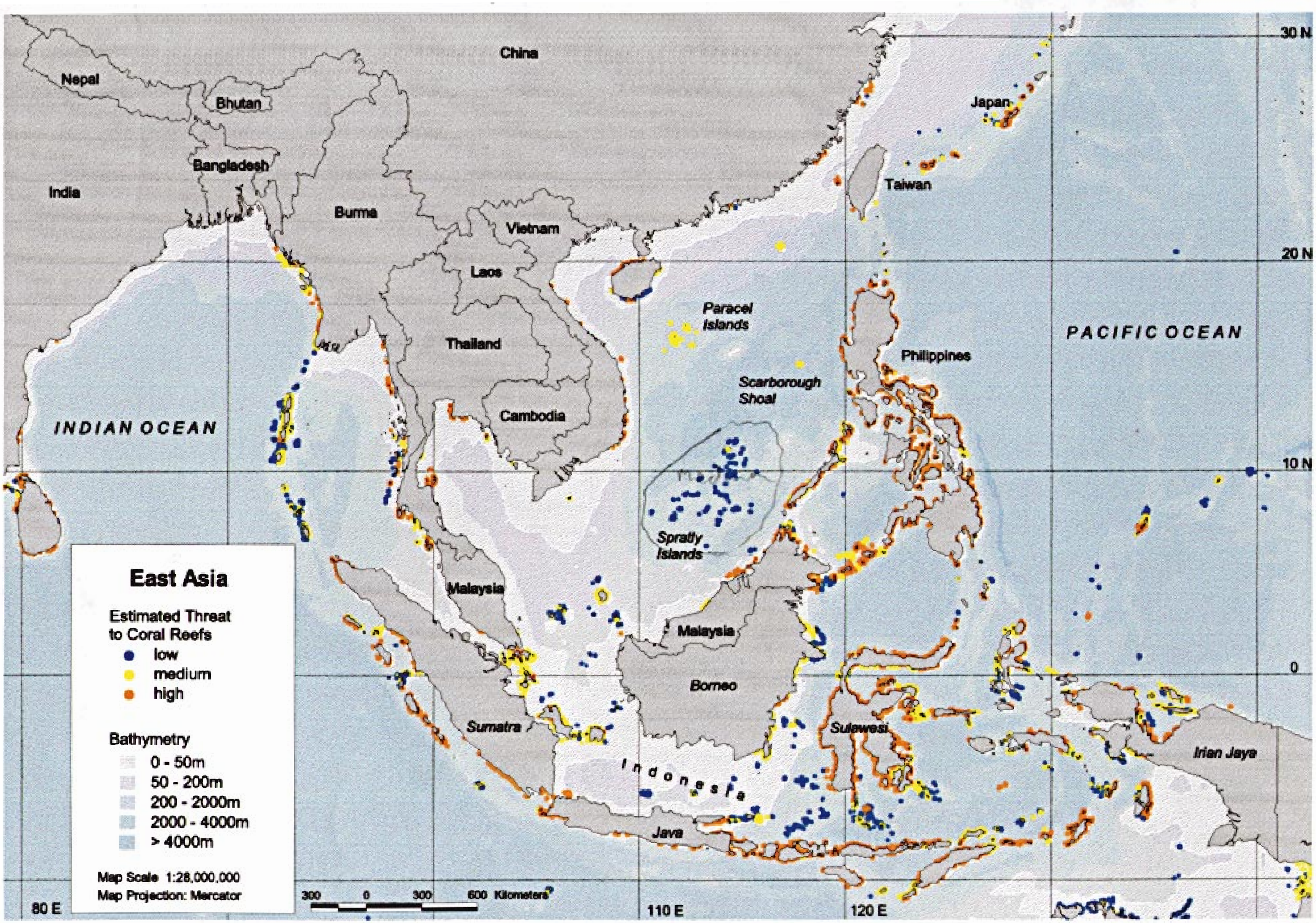
Eritrea
Yemen
Djibouti
Ethiopia
Somalia
ARABIAN SEA



China
Nepal
Bhutan
Bangladesh
India
Burma
Vietnam
Laos
Thailand
Cambodia
Japan
Taiwan
Paracel Islands
Scarborough Shoal
Philippines
PACIFIC OCEAN
INDIAN OCEAN
Spratly Islands
Malaysia
Malaysia
Borneo
Sumatra
Sulawesi
Indonesia
Java
Irian Jaya
30 N
20 N
10 N
0
80 E
110 E
120 E
East Asia
Estimated Threat to Coral Reefs
low
medium
high
Bathymetry
0 - 50m
50 - 200m
200 - 2000m
2000 - 4000m
> 4000m
Map Scale 1:28,000,000
Map Projection: Mercator
300 0 300 600 Kilometers

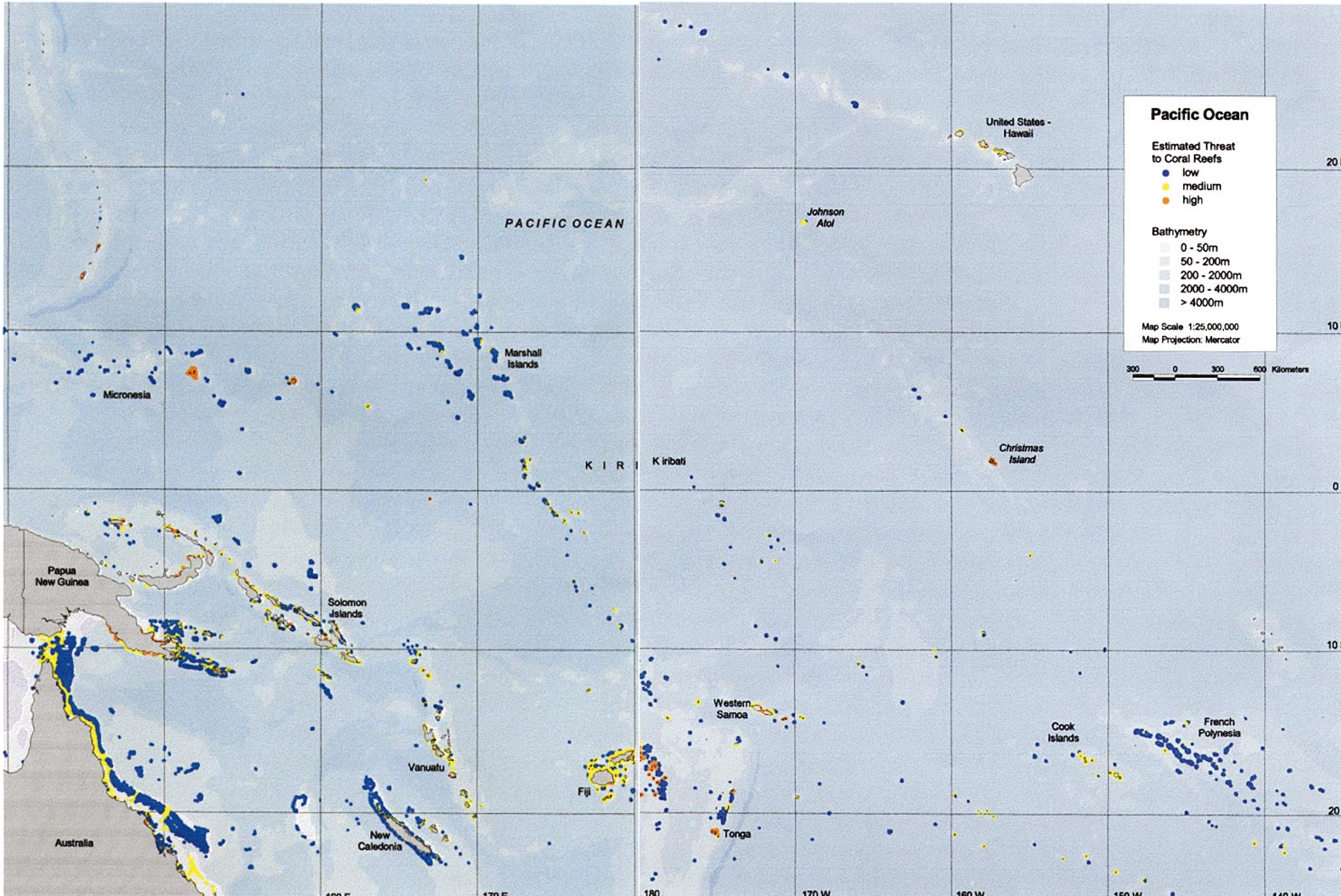
Southeast Asia: Over 80 percent of the reefs in this region are at risk, and over half (56 percent) are at high risk. Most of the coral reefs of the Philippines, Sabah, Eastern Sumatra, Java, and Sulawesi were assessed at high potential threat from disturbance. More than 70 percent of the region's people live within the coastal zone, putting heavy pressure on nearby marine resources.[50] Overfishing, destructive fishing practices, sedimentation, and pollution associated with coastal development are the biggest threats.[51]

SOURCE: COREL PHOTO CD

Southeast Asia contains one-quarter of the world's mapped reefs. Indonesia and the Philippines account for a major portion of these habitats. Reefs in both countries are noted for extraordinarily high levels of diversity, each containing at least 2,500 species of fish.[52] Studies suggest that only 30 percent of reefs off both countries are in good or excellent condition (as measured by live coral cover).[53, 54] Our results, which include threats from overfishing, indicate that virtually all of Philippine reefs, and 83 percent of Indonesia's reefs, are at risk. Because of the reef area they contain, coastal zone policy and management decisions made by these two countries will have a major impact on the global heritage of coral reef diversity for future generations.

Pacific: Reefs here appear to be in the best shape of any region: almost 60 percent were assessed at low risk. About 40 percent of the world's mapped reefs are found in the Pacific, many of which are located around remote atolls and within the Great Barrier Reef tract. Although reef communities in many uninhabited areas remain in good condition, others have been affected by the long-term impacts of historic nuclear testing and other military activities and by poaching of rare species.[55] Several areas, particularly those near population centers, face significant human pressures. These include many of the reef communities off southeastern Papua New Guinea, the Solomon Islands, Vanuatu, Fiji, and Hawaii. Almost half of the Hawaiian and Solomon Island reefs (the latter noted for their high biodiversity) are potentially threatened. Two-thirds of the reefs off Fiji are at risk. Overfishing, coastal development, logging, and agricultural erosion are documented threats to these ecosystems. Fiji's reefs are an important tourist draw and, according to a 1992 estimate, a major source of food for local people, generating close to $200 million annually in fisheries and tourism revenues alone.[56]

Seventy percent of Australia's reefs are at low risk. Although some parts of the inner Great Barrier Reef are potentially threatened, good management has largely maintained these as healthy ecosystems *(see section titled "Protecting the Health of Coral Reef Ecosystems")*.


Pacific Ocean
Estimated Threat to Coral Reefs
low
medium
high
Bathymetry
0 - 50m
50 - 200m
200 - 2000m
2000 - 4000m
> 4000m
Map Scale 1:25,000,000
Map Projection: Mercator
300 0 300 600 Kilometers
PACIFIC OCEAN
United States - Hawaii
Johnson Atol
Christmas Island
Marshall Islands
Micronesia
K I R I K iribati
Papua New Guinea
Solomon Islands
Vanuatu
Fiji
Western Samoa
Tonga
Cook Islands
French Polynesia
New Caledonia
Australia
20 N
10 N
0
10 S
20 S
160 E
170 E
180
170 W
160 W
150 W
140 W

Biodiversity and Reefs at Risk

Some threatened reefs stand out as particularly important from a biodiversity perspective. As part of this analysis, we worked with collaborators at the University of York in England, and Ocean Voice International in Canada to integrate data on reef fish species diversity with our data on potential threats to coral reefs. This allows for analysis of the likely degree of threat in areas of high reef fish richness—those having species counts in the top 20 percent of values found around the world. As noted below, our results are rudimentary, given the incompleteness of the fish species dataset.

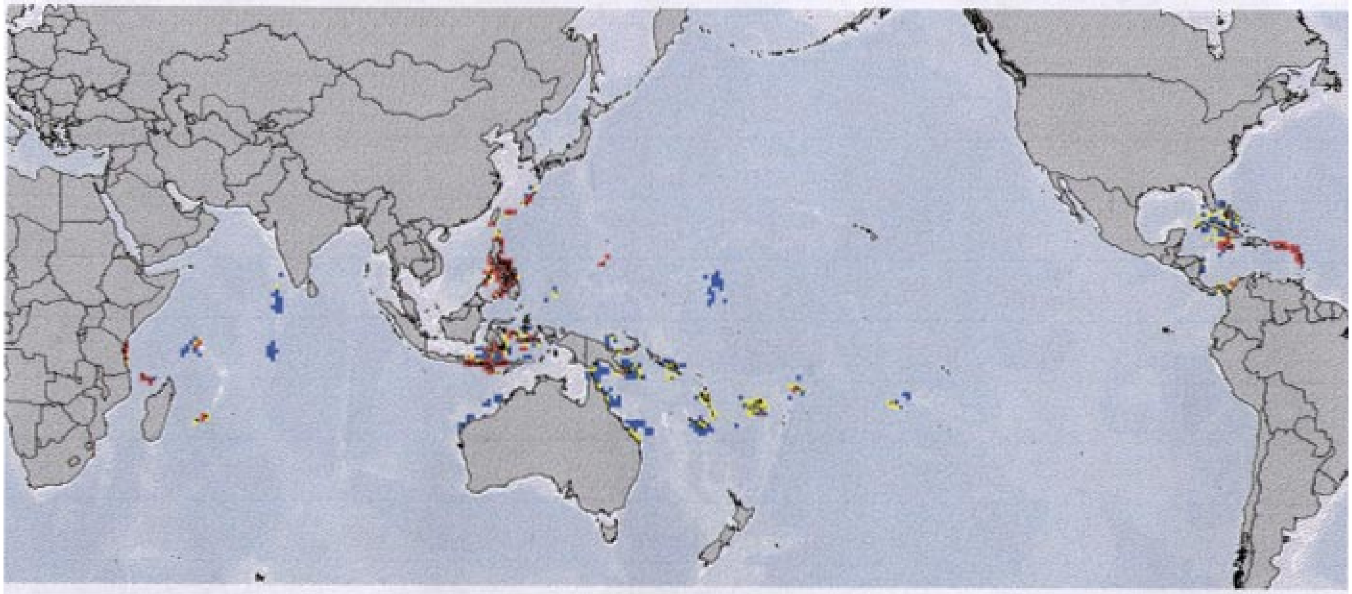
At least 11 percent of the world's reefs qualify as "biodiversity hot spots": areas of high species richness that are also under high threat. As Map 3 shows in red, most of these sites are located in Southeast Asia (almost a quarter of this region's reefs classify), especially in waters off the Philippines, Indonesia, and Japan. As a proportion of total reef area, the Caribbean emerges as another large hot spot: about 18 percent of Caribbean reefs exhibit high coral reef fish species counts, and are at high risk. This includes most of the coral communities of Jamaica, Puerto Rico, and the Lesser Antilles (Guadeloupe, Dominica, Martinique, and other islands).* Additional hot spot areas were identified off the Comoros, Tanzania, and Fiji.

What does this imply, in terms of priorities for immediate protection? Some scientists advocate taking a "portfolio approach" to selecting new sites for protection as parks and reserves.[57] They say that planners and managers should protect important biodiversity sites that are threatened *and* sites where human pressure and human disturbance are low—where it is easier to create and maintain parks and reserves. About 17 percent of the world's reefs exhibit high coral reef fish species richness, and are presently classified at low risk from human activities. More than half of these low-risk, high-diversity sites *(shown in blue on the map)* are located in the central and western Pacific, especially within waters off Australia and Papua New Guinea. Large tracts of qualifying reefs occur off the Maldives, Chagos Archipelago, Cuba, the Bahamas, Belize, and southern Mexico.

It should be noted that there are many ways to define important biodiversity areas beyond simply looking at total species count (species richness). These include endemism (the proportion of species found nowhere else), the number and percentage of rare species found, and protection of unique types of coral reef communities (ecosystem representation), among others. An ideal assessment would examine conservation importance at both the species level (examining endemics and total species) and the ecosystem level (examining unique habitats). This analysis considers only total species count for one taxonomic group—coral fish species—and not the total count of all species. In choosing priorities for protection, many planners also consider nonbiological criteria, such as identifying sites to protect on the basis of economic and social values.[58] One major consideration in identifying conservation priorities is the degree to which sites are already protected as parks and reserves. Unfortunately, the data and maps used for this analysis were too coarse to allow detailed examination of protected area gaps (existing marine protected area data are also incomplete and/or are not adequately spatially referenced). Map 4 provides an idea of some of the possible gaps in protection in Southeast Asia. Many areas in the Philippines and Indonesia have high species diversity, are highly threatened, and are not protected.

*It should be noted that the analysis of areas of high reef fish biodiversity is biased in favor of coral reef areas that are more intensively surveyed. For example, the analysis suggests that there are no hot spots in the Middle East, but, in fact, levels of biodiversity in parts of the Red Sea reach similar levels to the hot spots in the Caribbean. Because a greater proportion of species present in the Caribbean were sampled relative to other areas, these areas achieve relatively high species counts, warranting inclusion in this analysis. Several other areas likely to have comparable diversity that were not included are the reefs off the coast of Vietnam and the Spratly Islands.

MAP 3. Most Areas With High Reef Fish Species Diversity Are Threatened ....



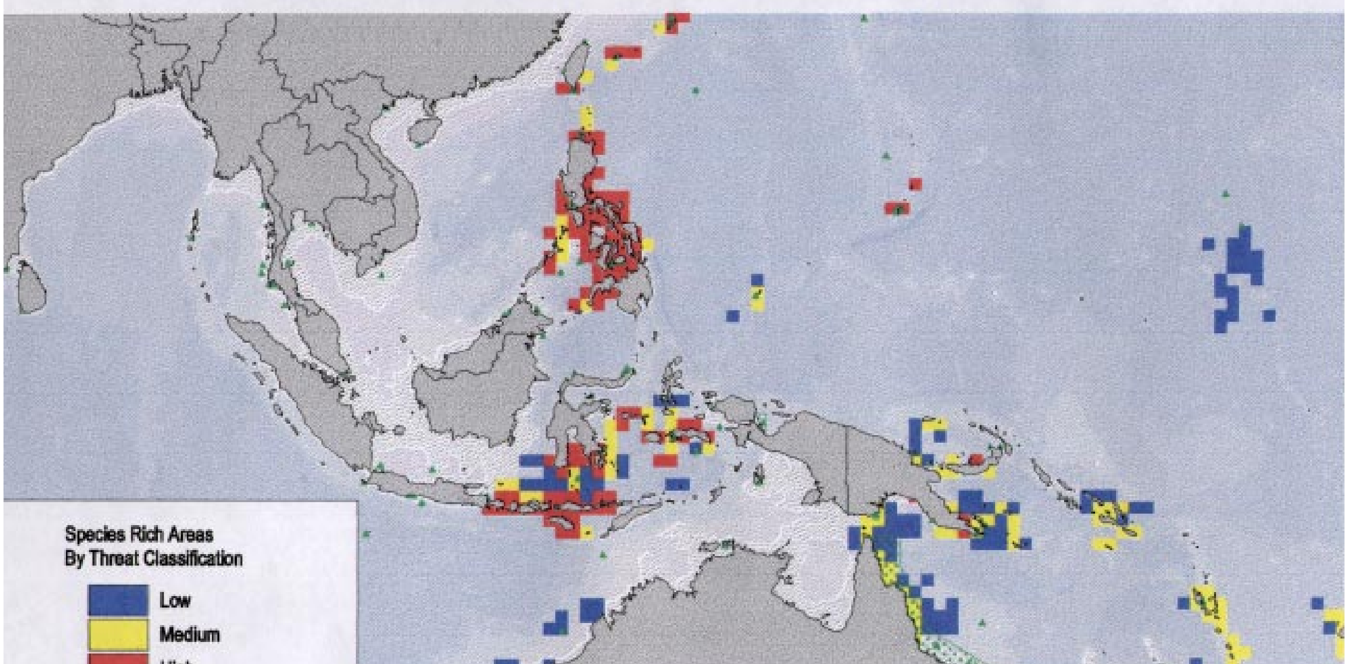
Species Rich Areas
by Threat Classification

- Low
- Medium
- High

Data Sources: Data on coral reef fish species diversity come from the University of York (U.K) and Ocean Voice International (Canada). The classification of potential threat to coral reefs was developed as part of the Reefs at Risk analysis at the World Resources Institute, using a data set reflecting the location of shallow coral reefs of the world from the World Conservation Monitoring Centre (U.K.).

Note: This map shows areas of known high reef fish species diversity (areas in excess of 210 species), classified by estimated threat to rooks in that area.

MAP 4. ... And Most Areas With High Reef Fish Species Diversity Are Not Protected



Species Rich Areas
By Threat Classification

- Low
- Medium
- High

Marine Protected Area Locations

Great Barrier Reef Marine Protected Areas

Data Sources: Data on coral reef fish species diversity come from the University of York (U.K) and Ocean Voice International (Canada). The classification of potential threat to coral reefs was developed as part of the Reefs at Risk analysis at the World Resources Institute, using a data set reflecting the location of shallow coral reefs of the world from WCMC. Marine Protected Area locations also come from WCMC.

TWELVE REEFS AT RISK

The following profiles, contributed by some of the experts who helped us with this assessment, illustrate the types of threats faced by reefs around the world and what is at stake should these ecosystems continue to be degraded.

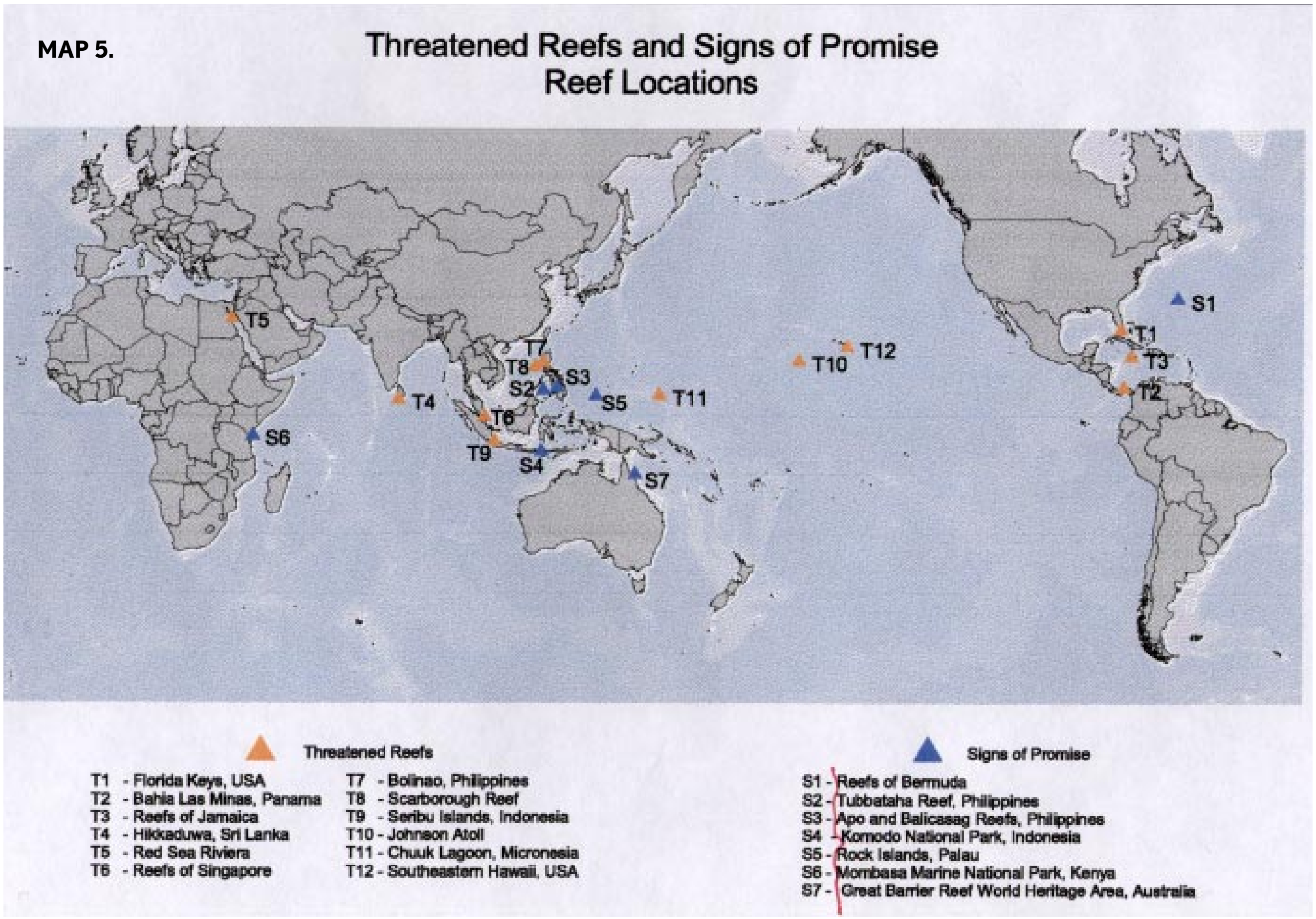
Reef name: **FLORIDA KEYS REEFS**
Location: Southeastern United States

Description: These reefs extend from Miami to the Dry Tortugas, near Key West. Outside of those of the Bahamas and Bermuda, they are the northernmost reefs found within the western Atlantic. The Florida Keys are probably home to more marine fish species than any other coastal region of the mainland United States.[59] Reefs here are a major tourism draw—over one million divers visit this area each year. Commercial and recreational fisheries are an additional and important source of income for local communities. For example, the spiny lobster catch generated $10 million in 1980 alone.[60]
Threats: The coral reefs of the Florida Keys exemplify the complexity of threats to reef resources. They naturally lie near the temperature limits for reef building. Strong winter cold fronts have episodically killed *Acropora* thickets throughout the Keys. Florida reefs have been repeatedly stressed in the past 25 years by bleaching events in 1973, 1983, 1987, 1991, and 1997. Disease is an even more serious problem: two of the most important reef-builder species (*Acropora palmata* and *A. cervicornis*) are now relatively uncommon due to white-band disease, while others have proved particularly susceptible to black-band disease. New coral diseases are being reported each summer.

The two major threats to these reefs are polluted waters from Florida Bay and anthropogenic nutrients from storm runoff, discharge from sewage-laden groundwaters, and from agricultural sources. Even distant sources are involved: waters from the heavily polluted Mississippi River periodically reach the Keys while Saharan dust has been implicated as an origin of nutrients and possibly disease spores particularly during El Niño years. Finally, direct human activity is damaging reef resources here. Activities such as boating, fishing, and diving individually cause minimal damage, but because of sheer numbers of participants result in chronic stress. The all too frequent groundings of large vessels have resulted in loss of significant percentages of individual reefs. Aside from boating activities and despite years of research, it is difficult to lay blame for damage on specific anthropogenic stresses. However, it is clear that human activity compounds the natural regional vulnerability of Florida's reefs, thereby severely threatening the future integrity of these ecosystems.

Reef name: **REEFS OF BAHIA LAS MINAS**
Location: Caribbean Panama

Description: Bahia Las Minas forms part of one of Panama's most extensive stretches of coral reef and mangrove along the Caribbean coast. These ecosystems provide an important source of food fish for local communities.[61]
Threats: A major crude oil spill occurred in April 1986 from a ruptured storage tank at a local refinery just east of the Caribbean entrance to the Panama Canal. Oil slicks from the refinery landfill and from mangroves (whose soils retained oil from the original spill) are still common there after 10 years. The spill affected a wide range of reef community species. The cover, size, and diversity of live corals decreased greatly on oiled reefs (for example, total coral cover declined by 76 percent in waters three meters deep). The species *Acropora palmata*, a major Caribbean reef-building coral, was practically eliminated. Sublethal but long-term consequences for corals include decreased growth, reproduction, and recruitment, which suggest little prospect for rapid recovery. The spill also damaged nearby sea grass and mangrove communities.[62, 63, 64]



Reef name: **JAMAICA'S REEFS**
Location: Jamaica, Caribbean

Description: The entire island is surrounded by reefs, although those of the north coast once contained the most coral cover and are the most diverse. Reefs are an integral part of the Jamaican economy, supporting fishing, and tourism, the country's most important industry.[65]
Threats: Virtually all reef communities here have been affected by human and natural causes. Overfishing in particular, as well as pollution from sewage disposal, industry and agricultural runoff, siltation due to poor land use practices, and tourism-related activities, have seriously degraded Jamaica's reefs. Storm damage from hurricanes, coral reef bleaching due to periodic high sea water temperatures, and, with the decline of sea urchins and other algae grazers, the unchecked algal overgrowth of corals have compounded the problem. The reefs surrounding Montego Bay are perhaps the most seriously degraded, even though they are protected, in part, by a marine park. The original park, established in 1966, was too small and was completely unmanaged. Although reestablished and expanded in 1990, with a financial base and staff that works closely with town authorities, reefs in the park continue to be affected by poaching, pollution from the nearby city and airport, and runoff from inland agricultural activity.

Reef name: **HIKKADUWA REEFS**
Location: The Hikkaduwa Marine Sanctuary and the surrounding reef, located in southwestern Sri Lanka, Indian Ocean

Description: Hikkaduwa is one of the most densely developed tourism sites in Sri Lanka and encompasses the first national marine sanctuary, established in 1979. Coastal tourism is a mainstay of the country's economy. With 80 percent of all tourism infrastructure in coastal areas, the industry generates about $200 million each year. The tourism economy of Hikkaduwa is almost entirely dependent on the quality of the beach and coral reef along its five-kilometer beach front. Gross annual revenue from about 150 tourism establishments is more than $30 million.
Threats: The coastal environment is increasingly degraded from development's impacts. Poor environmental planning, inadequate law enforcement, and lack of consideration of sociocultural issues are the

primary underlying causes. Longtime residents of the area have stated that "entire sections" of the reef have been destroyed over the last 20 years. The most important threat to the area is the unregulated operations of a large number of glass-bottomed boats. These vessels hit the corals, anchors are dropped, and tourists stand and walk on the reefs. Anchoring and dumping of oil by fishing boats is also a problem. Additional threats include polluted water from fish holds and waste oil dumped directly in the sanctuary, and sediments stirred up by boat traffic. Coral reef mining occurs within a kilometer of this protected area, and many of the nearby reefs are devastated. The government and local community are finally taking steps to limit boating activity, to require hotels to stop dumping wastewater into the ocean, and to patrol the reef in order to prevent trampling of corals and illegal fishing.[66, 67, 68]

Reef name: **RED SEA RIVIERA**
Location: Coral reefs in the Gulf of Aqaba off Jordan, Israel, and Egypt plus the reefs of the Egyptian Red Sea

Description: The coral reefs along the Red Sea Riviera are high-value resources for attracting European (primarily German and Italian) tourists seeking diving adventures. They provide habitat for many commercially important fish that are consumed in local hotels and restaurants. The extensive fringing reefs also help consolidate desert shorelines and protect them (and coastal property) from storms.
Threats: The Red Sea Riviera is a good example of an area that presently is only partially threatened, but where the potential exists for large-scale degradation. Overfishing and physical damage from excessive diving threaten reefs in an area overlapping Jordan and Israel—a region where tourism is expected to quadruple by the year 2000.[69] In Egypt, where the number of hotel beds (a measure of tourism demand) is expected to increase over 1000 percent by the year 2005, the Environmental Affairs Agency (EAA) has been able to manage the resort development process along the south Sinai with a measurable degree of effectiveness via a network of coastal protectorates. However, off Hurghada, tourism development proceeded without an active management system in place and degradation (coastal sedimentation, physical damage from anchoring and overdiving, and overfishing) is clearly evident.[70, 71] In 1997, more than 250 mooring buoys were installed off Hurghada and EAA assigned rangers to patrol the Elba Protectorate. EAA is working to expand its system of marine protected areas to include reefs located north of Hurghada and stretching to the Sudan border. The Tourist Development Agency is attempting to better design new tourist villages to ensure the sustainable use of valuable coral reef resources. Time will tell whether Red Sea Riviera governments will take the necessary actions to preserve their coral reefs in the face of economic needs and rapid development.

Reef name: **REEFS OF THE SOUTHERN ISLANDS (SINGAPORE)**
Location: Singapore

Description: Most of Singapore's reefs lie off the Southern Islands. This area is home to at least 197 species of hard corals.[72] The area supports a growing tourism industry, as well as some subsistence and sport fishing.[73]
Threats: The Southern Islands reefs lie within the port limits of the world's busiest harbor, while the islands themselves support oil refineries, petrochemical industries, and slop-treatment plants. Thirty years of massive land reclamation programs compounded with regular dredging of shipping channels, has resulted in the widespread sedimentation of coral communities, posing the biggest threat to this area. Underwater visibility has been reduced from 12 meters in the 1960s to two meters today. The active growth zone of corals is now confined to the upper five meters of reef slopes. The news is not all bad: thanks to careful sewage and industrial treatment practices, these coral communities still survive despite their proximity to one of the most densely populated places on earth.


JOHN MCMANUS, ICLARM

Trampling of reefs by tourists is a threat at this Red Sea resort.

Reef name: **THE BOLINAO REEF COMPLEX**
Location: Fringing reefs on western Luzon Island in the Philippines

Description: The 200-square-kilometer complex includes reefs from the municipalities of Anda and Bolinao. Of approximately 50,000 people in Bolinao, only a few thousand actually fish the reefs, but the reefs support about 20,000 people who are either workers in fishery-related occupations (fish sales, shell craft, etc.) or are dependent family members.
***Threats*:** As farmlands across the Philippines have become finely divided and overutilized, increasing numbers of people have migrated into reef areas such as Bolinao to join in harvesting fish and other reef resources, contributing to their dramatic decline. Competition for these resources led to the proliferation of blast and cyanide fishing. In the late 1980s one could hear an average of 10 blasts per hour from fishers targeting schools of fish and clumps of coral. The bottom cover of reef-building coral diminished from roughly 40 percent to about 15 percent over a period of about 15 years. Target fish were 10 centimeters in length and less. While fishers of more pristine reefs in Papua New Guinea are able to harvest up to 30 kilograms of fish per day, the Bolinao fishers have had their catches reduced to an average of about one kilogram per day on reefs that were once ecologically very similar.

Beginning in 1986, programs were established by the University of the Philippines and collaborators to help the Bolinao municipality. Various projects to introduce small-scale mariculture of seaweed and invertebrates were supplemented by community organizing activities. Public education and improved law enforcement have led to a reduction in blast fishing. Coral cover and fish abundances seem to be increasing. In 1997, the municipality approved an integrated coastal management plan that reflected the concerns of all major sectors. Marine protected areas are being established and fishery regulations are being revised. However, the reef remains in a critical state. The proliferation of fish pens is causing problems with pollution, water stagnation, and public access to reef resources. Incomes in the area remain low, and many resources on land and sea are seriously overutilized by the dense human population. Ultimately, the greatest challenges may be yet to come—the population of Bolinao is expected to double in the next 30 years.

Coral has encrusted this World War II bomb at Scarborough Reef.

JOHN MCMANUS, ICLARM

Reef name: **SCARBOROUGH REEF**
Location: A large atoll in the eastern South China Sea

Description: Scarborough Reef is noted for high levels of biodiversity. The populations of organisms on the reefs of the South China Sea are believed to be linked through the exchange of the free-swimming life stages that characterize most reef species. Being highly isolated, Scarborough Reef may play a particularly crucial role as an "outpost" in this exchange of genetic material and in the restocking of overfished fringing reefs in the Philippines and China.
Threats: Like the Spratly Islands to the southwest, Scarborough Reef is the subject of ownership disputes. The reef is claimed by the Philippines, mainland China, and Taiwan. Fishers from all three areas regularly fish the reef. However, the unclear ownership and lack of regulation exacerbate competition for the resources. Fishers stock up on blasting devices and cyanide to fish the reef in short, destructive trips. The reef is a major site for shark fishing with gill nets and for the capture of large fish for the live fish trade using cyanide. Ships load their holds with coral to sell as decorations for store windows and aquariums.

The U.S. military used the reef for bombing practice during the 1990 confrontation with Iraq, complicating matters. Large and unique underwater dunelike structures of organ-pipe coral tens of meters long were used as targets. Substantial areas of coral were torn apart by the explosions. Many of the bombs failed to explode, littering the lagoon with live ordinance. It is reportedly common for a fisher to drop a small explosive charge in a beer bottle, only to set off a massive explosion. Visitors to the reef over the years have reported increasing levels of degradation from the combination of abuses to the reef.

JIM MARAGOS, EAST-WEST CENTER

Achilles Tangs are one of the many reef fish species found on Johnston Atoll in the Pacific.

Reef name: **JOHNSTON ATOLL**
Location: Line Islands, Central Pacific, an island possession of the United States

Description: Johnston is a small ancient atoll (80 million years old) and is perhaps the most isolated reef in the world, being 800 kilometers southwest of Hawaii, its nearest island neighbor, and 1,500 kilometers north and east of the Northern Line Islands and the Phoenix Islands, respectively. These reefs are important for biodiversity, serving as a biological stepping stone between Hawaii and the island groups to the south and west. The 30 species of coral have close affinities to the coral biota of Hawaii, and corals, reef fishes, seabirds, and green turtles flourish on the reefs and islands of the atoll. The atoll is a national wildlife refuge, jointly administered by the U.S. Fish and Wildlife Service and the U.S. Department of Defense.
Threats: Beginning about 1960, the United States established Johnston as an above-ground atmospheric nuclear and missile testing range. Massive dredging and filling destroyed many reefs in a process to expand the size of main islands and to build an airport, deep draft port, and entrance channel. Some Thor missile launches failed, with one scattering plutonium on the island and nearby reef. Later thousands of drums of Agent Orange, a defoliant used during the Vietnam War, were shipped to Johnston where they were stockpiled for years out in the open. Eventually a floating incinerator ship destroyed the defoliant, but not before many of the drums leaked, discharging dioxins and other toxic substances into the groundwater. In 1970, explosively configured chemical munitions, including blister agent and nerve gases, were removed from Okinawa and stockpiled at Johnston. Rapid deterioration of the munitions prompted the U.S. Army in the mid-1980s to construct a high-technology incinerator to destroy them. The plant is still incinerating the munitions today, subject to various safeguards of the U.S. government.

Reef name: **SERIBU ISLANDS REEFS**
Location: Java Sea, north of Jakarta, Indonesia

Description: The Seribu Islands reefs cover 108,000 hectares, along a chain of more than 100 small islands. The area is noted for its abundance of attractive beaches and coral reefs. In 1995, the islands were declared a marine national park. Tourism has grown rapidly from one operator on a single island in 1982 to 11 operators working out of 18 islands in 1992. There were approximately 8,000 visitors in 1991. Some islands have long been inhabited by villagers who depend on reef and island resources. However, the tourism industry employs less than 5 percent of the local population.
Threats: Domestic sewage, industrial effluent, and urban runoff from Jakarta threaten the southernmost portion of this area. Floating garbage is a problem, depending on prevailing winds. Ballast water discharges from boats result in tar being washed up on local beaches. Blast fishing, although outlawed nationally since 1920, still occurs as well as heavy ornamental fish collecting and major subsistence exploitation of marine resources. The islands are under pressure from developers seeking more tourism and recreational facilities to service greater Jakarta. There is no strategy to promote environmentally and economically sound expansion of this industry. Boat anchoring and diving have already damaged coral reefs. To encourage protection of the area, local residents, few of whom currently benefit from existing recreational development, need more economic options and increased participation in park activities (such as employment servicing the resorts). Oil and gas exploration, taking place within kilometers of the park, could pose a potential future threat.

Reef name: **CHUUK LAGOON (TRUK LAGOON)**
Location: Central Caroline Islands, western Pacific, Federated States of Micronesia

Description: Chuuk Lagoon is the largest single barrier reef in Micronesia, enclosing reefs and a lagoon with 26 volcanic islands and 22 low coral islets. It is also the largest urban center and the capital of Chuuk State in

Micronesia, home to nearly 50,000 residents living mostly on several of the larger volcanic islands. The atoll is noted for an exceptional diversity of fish, marine invertebrates, and coral species (about 300 species of stony corals were recently cataloged here). Chuuk is also a significant cultural center having been continually occupied by Micronesians over the past several thousand years. During World War II, nearly 70 Japanese naval vessels were sunk during a 1944 battle, Operation Hailstone. During the past half century the wrecks have been colonized by fish, sponges, seaweeds, and soft corals. The shipwrecks of the lagoon are now one of the premier sport diving destinations in the world due to luxuriant reef growth and the historic significance of the wrecks. Several dive operations and most of the subsistence fishermen rely on the reefs and lagoon for their catch.

Threats: Japanese military construction and Operation Hailstone were the first major insults to Chuuk's coral reefs. After the war the human population expanded rapidly, placing ever increasing demands on marine food resources (reef fish and shellfish). Fishers have removed explosives from the residual World War II munitions on the atoll, making them into bombs and using them to blast reefs to stun, kill, and collect fish. Blast fishing is still a serious threat to reefs, especially in the more remote western lagoon, beyond the watchful eyes of villagers and government enforcement. Blasting has damaged about 10 percent of the reefs in the lagoon according to a 1994 survey. Heavy urbanization, especially on Tonowas and Weno, has spurred dredging and filling for land expansion and development, while sewage discharges into the lagoon from the islands has reduced water quality and subsequently underwater visibility at many of the dive sites. Reef fish populations are being depleted from heavy fishing pressure, and nesting sea turtle populations have nearly been eliminated from the area. Rubbish is haphazardly dumped into mangrove areas on the most populated islands, further degrading water quality.

JIM MARAGOS, EAST-WEST CENTER

Military debris have become substrate for coral at Chuuk Lagoon.

Reef name: **REEFS OF THE WINDWARD SOUTHEASTERN HAWAIIAN ISLANDS**
Location: Main Hawaiian Islands (USA), tropical Pacific

Description: The eight volcanic islands are generally large (100 to 16,000 square kilometers), with the four smallest (Lanai, Molokai, Niihau, and Kahoolawe) sparsely settled and the largest (Oahu, Maui, Hawaii, and Kauai) supporting rapidly growing urban populations. The Hawaiian Islands reefs are not noted for high levels of coral, fish, and other reef species. However, about 25 percent of their fauna consists of endemic (unique) species, a manifestation of near continuous geographic isolation over a long time period.

Threats: During the past century, plantation agriculture, ranching, and feral livestock introduced to the islands reduced natural ground cover, increased soil erosion, and subjected reefs to heavy sedimentation especially off Oahu, south Molokai, northeast Hawaii, east Kauai, and Maui. Military, and more recently tourism development since World War II has led to dredging and filling of many reefs, and coastal sedimentation and heavy use of some reef sites. However, the most serious threats relate to rapid population growth and urbanization, leading to sewage discharges, additional construction, overuse, overfishing, industrial discharges, and port development and operations. A spate of government environmental laws and regulations and coastal planning now controls many but not all of these influences, and overfishing and water quality degradation from nonpoint sources and sewage will continue to be serious if not growing threats to the reefs. Reefs within embayments, such as Kaneohe (off Oahu), are particularly vulnerable to urban-related development.

IMPROVING OUR KNOWLEDGE BASE

The Reefs at Risk indicator presents our best estimate of likely threats to coral reefs from human activities, but it is only an estimate. Our results confirm that there is a critical need for detailed monitoring and assessment of reef habitats in order to better document where and how coral reefs are threatened and to understand what measures are needed to safeguard them. Scientists and managers have only rudimentary, incomplete data on the status and health of coral reef ecosystems. For example, we still lack a complete global map depicting reef location, and the vast majority of coral reefs are unassessed. This and other basic information is essential for informed decision making by resource management agencies, fishers, the tourism industry, and other sectors economically dependent on reef resources. The public, non-governmental organizations and scientists need such data to better understand and advocate for the protection and stewardship of coral reefs.

These data gaps are not for lack of tools. There are a range of techniques for assessing and monitoring coral reefs, each with advantages and limitations. Generally, these entail tradeoffs between cost and detail, and range from the use of satellite imagery to map reef location (relatively low cost, but low detail) to running underwater transects to measure reef health (high cost, high detail). The optimal approach is through multilevel sampling, where information obtained from limited, detailed high-resolution sampling is extrapolated to large areas based on low-resolution data of wide coverage. The goal is to use as much information as possible and available to improve assessments at national, regional, and global scales. The box titled "Tools and Techniques for Monitoring and Mapping Coral Reefs" describes some of the technological options at hand for assessing reefs.

As of 1998, several major new initiatives were underway to collect new data and synthesize existing information so as to build a picture of the status of reefs worldwide. These include:

Global Coral Reef Monitoring Network (GCRMN): GCRMN will rely on governments and local communities to regularly assess the health of coral reefs and their fish populations in about 80 countries of the world. Permanent transects are to be established on many reefs. The data will be fed into ReefBase *(see below)*. GCRMN is coordinated by the Australian Institute for Marine Sciences and the International Center for Living Aquatic Resources Management and is a joint program of the International Oceanographic Commission, the World Conservation Union (IUCN), and the United Nations Environment Programme.

Reef Check Program: Through this volunteer effort, hundreds of diving groups around the world are organizing annual field trips to gather transect data on selected coral reefs. The Reef Check protocol (methodology) is simple, requiring only a few hours to explain, but is dependent on the involvement of coral reef scientists to supervise site selection and data gathering. Three hundred reefs in 30 countries were surveyed between June and August 1997.

ReefBase Aquanaut Method: The ReefBase Aquanaut Method has been developed to empower divers to conduct highly reliable surveys independent of scientists. Professional scuba instructors teach the four-day training course as an advanced specialty course. In addition to volunteers, park rangers and members of governmental and private sector groups tasked with coral reef management also use the training. In the Reef Check and Aquanaut systems, data exchange and dissemination are facilitated through ReefBase *(see below)*.

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Reef surveys by scientific teams and by recreational divers in volunteer programs are improving our knowledge of the condition of coral reefs around the world.

Other volunteer programs: Throughout the world, increasing numbers of volunteers are conducting coral reef surveys with organizations such as Reef Watch, Reef Keeper, REEF, Frontier, and Coral Cay Conservation. Efforts are underway to coordinate this work. In many cases, volunteer surveys have had substantial impact on coral reef management and public awareness.

ReefBase: ReefBase was initiated in late 1993 to consolidate and disseminate information useful in managing coral reefs.[74] This database, produced by ICLARM, is the most comprehensive source of information on reefs available, providing ecological and socioeconomic data on sites around the world. It includes digital maps of coral reefs provided by the World Conservation Monitoring Centre (WCMC), space shuttle and satellite images contributed by the National Atmospheric and Space Administration (NASA) and others, and photographs of reefs contributed by volunteers. ReefBase is currently distributed yearly on CD-ROMs, and major portions are available through a Web site **(www.reefbase.org)**.

Bringing scientists together: The International Coral Reef Symposia (ICRS) are held approximately every four years, and serve as a primary focal point for the analysis and official release of information on coral reef status (the next session will be held in 2000 in Bali, Indonesia). In November 1998, a new series of conferences will be initiated, focused particularly on management concerns. The first International Tropical Marine Ecosystem Management Symposium, to be held in Australia, will provide a forum for the evaluation of the success of the International Coral Reef Initiative in the three and a half years since the first global workshop. Other periodic conferences of importance in the release and critical evaluation of reef information include the regional meetings of the International Society for Reef Studies, the Pacific Science Congresses, the West-Pac Conferences, and many others.

Most available data collection is focused on the biological and physical dimensions of reefs: species found within these ecosystems, the location of these habitats, degree of degradation, etc. Socioeconomic and political information can help managers, scientists, and others better understand the direct and underlying factors that result in changes in reef condition (for example, subsidies and laws that result in overfishing). Information that can be used to quantify the direct and indirect values derived from coral reef ecosystems is important input for weighing development and management options. Collection of such policy-relevant data should be a priority in future monitoring and assessment efforts.

Tools and Techniques for Monitoring and Mapping Coral Reefs

Satellite-based sensors: Satellite imagery can be used for low-cost, albeit coarse-scale mapping of coral reefs, and as such is probably the most effective way to build a comprehensive picture of where the world's reefs are located. Satellite data can also provide information on sea-surface temperatures, wave height and direction, and primary production in upper waters. They may also be useful for distinguishing living from dead coral in very shallow waters. Military agencies have more comprehensive satellite data, often at a much finer resolution; however, these data are rarely available for public use.[75, 76]

Aerial photography and sensors: Photos and data from overflights of reefs can provide a more detailed picture of reef location, and can yield bathymetric data to depths of several tens of meters.[77] However, aerial surveys and the analysis of their products are far more costly than those derived from satellite information and are difficult or impossible to conduct legally in many countries because of security concerns. These data can determine living from dead coral, but only within very shallow water.[78] Costs have been reduced by using ultralight aircraft,[79] balloons, kites,[80] and other devices. With improvements in computer technology, it will be possible to survey reefs with remote-controlled aircraft, further cutting costs.[81, 82, 83, 84]

Ship and boat-based sensors: Research vessels carry a range of sensors useful for detailed mapping of coral reefs. Various types of sonar can be used to produce three-dimensional images of coral and distinguish between different types of bottom substrate. Passive acoustic analysis, along with sonar in some instances, can distinguish between live and dead reefs. Research vessels play a vital role in surveying and mapping coral reef habitats. However, they are costly to operate (generally ranging around $10,000 per day). One way to reduce costs, and better utilize existing research vessel fleets, is to conduct reef surveys during the course of other oceanographic and fishery investigations.[85, 86]

Submersibles: Manned and unmanned submarines play an essential role in assessing coral reefs in waters below a 30-meter depth—beyond the practical working limits for scuba diving. Although the technological capacity available for exploring the world's oceans is highly developed, there are very few submersibles in the world that are available for undersea research. Promising new technologies are coming on line for conducting transect surveys, distinguishing live from dead coral cover using laser-line sensing devices, and conducting rapid, large area assessments at various depths including shallower waters accessible by scuba divers.[87, 88]

Diving surveys: Scuba-diving scientists are the main source of information on reefs in shallower waters today (down to 30 meters in depth). However, the specific objectives, taxa of focus, and sampling approaches severely limit the comparability of the data among regions and over time. In addition, scuba-based assessments and monitoring are limited by the number of scientists available for this work and the small area that can be covered by one individual. Survey protocols are being developed so that recreational divers and others can help gather data, often on a volunteer basis. This offers tremendous potential for gathering new information on reefs, since there are several million scuba divers in the world and several times as many people proficient at skin diving with mask or goggles. Similarly, residents of coastal communities can be recruited to evaluate their reefs through participatory resource mapping. This low-tech approach is particularly relevant in developing countries, where few can afford expensive scuba equipment. Here, villagers are trained to gather general information on the coverage of various ecosystems, supplemented with descriptions of simple factors such as hard coral cover, and then transfer the data to a map using a simple compass. Work on this type of approach is underway through various programs, such as the Coastal Resource Management Program in the Philippines.[89]

PROTECTING THE HEALTH OF CORAL REEF ECOSYSTEMS

Maintaining the biological diversity, condition, resources, and values of coral reefs and related ecosystems is a matter of global urgency. While the majority of countries which have coral reefs are developing countries, there are many reefs in the waters of developed countries. This unites the developed and developing countries and should command the attention of the international community. Coral reef survival depends upon the world community acquiring and maintaining the knowledge and capacity to conserve and sustainably use coral reefs and related ecosystems. This requires that all uses and impact be brought within and maintained at levels which do not exceed these systems' natural capacity for production and regeneration.

—from the International Coral Reef Initiative Framework for Action

Reefs at Risk demonstrates that coral reefs around the world face threats from overfishing, coastal development, and other human activity. In most places these pressures will grow as economies develop and coastal populations swell. Despite these sobering trends, the news is not all bad. Careful planning and management can assure healthy reefs while meeting the needs of local people. Increased concern about, and interest in, coral reef issues is translating into action at local, national, and international levels to protect and conserve reef resources. As we illustrate at the end of this section, promising efforts are under way in many parts of the world.

This report, because it is an indicator analysis, does not list policy recommendations, or provide a comprehensive overview of management approaches and initiatives to protect and conserve reef ecosystems. Instead, we provide a few examples of the types of efforts under way to address threats to these habitats.

The box "International Agreements and Initiatives" outlines some of the global activities that are helping to focus attention on coral reefs and, in some cases, to mobilize governments and people to better monitor and manage these habitats. The section titled "Improving Our Knowledge Base" details some of the data collection efforts under way worldwide to track the health of reef ecosystems.

The most important actions for promoting healthy coral reef ecosystems are taken at local and national levels. These depend on efforts by local governments, community groups, environmental organizations, the private sector, and others. Successful approaches are often based on cross-sectoral planning and management at a landscape scale to assure, for example, that agricultural policies within inland watersheds do not impact reef-dependent fisheries and tourism along the coast. Some of the actions that can best protect reefs are not directly linked to conservation. They range from building sewage and industrial waste treatment facilities to minimize pollution of coastal habitats to removing the host of subsidies and incentives—in the agricultural, forestry, development, fisheries, and other economic sectors—that result in degradation of water quality, direct destruction of reef habitats, and overexploitation of reef species.

For these approaches to work, legislation backed up by enforcement of these laws and regulations must be in place to protect reef resources. Restrictions alone will not work. Successful management approaches address the underlying causes of reef degradation by promoting economic development while protecting coral reef habitats. Examples include providing alternative livelihoods for people engaged in destructive activities through economic necessity, training fishers to use less destructive fishing methods, and regulating access and use of reef resources by establishing community ownership over reef fisheries and through other approaches. Environmental education plays an important role in building public support for better reef management.

One of the most effective approaches for combating threats to reefs is through a well-managed, representative marine protected area system *(see box "Reefs and Marine Protected Areas")*. Marine parks, sanctuaries, and reserves can protect reef ecosystems and species while generating tourism dollars and maintaining the vitality of nearby fisheries. The World Conservation Union has called on countries to protect 10 percent of all habitat types. However, with one or two exceptions (such as Australia), countries protect a far lower percentage of their coral reefs, and all have a long way to go in order to meet a recently proposed global target of protecting 20 percent of the oceans. Protection alone, however, cannot safeguard reefs from the sedimentation, pollution, and other threats that originate outside the boundaries of parks and reserves.

Around the world, governments and people are taking steps to conserve and restore coral reef ecosystems. Seven examples, most contributed by experts who helped us with the Reefs at Risk assessment, are profiled below.

Reef: **BERMUDA'S CORAL REEFS**
Location: Bermuda, Atlantic Ocean
Signs of progress: Catch levels of grouper and snapper, two important reef species, declined significantly from the mid-1970s, apparently due to overharvesting. Total grouper catch per fishing pot (a fish trap commonly used to catch reef species) dropped from 1.8 to 0.65 kilos between 1975 and 1985, with smaller fish increasingly predominating. Meanwhile, fish traps and boat anchoring by fishers and recreational boats were damaging reef structure.[90] Under pressure from hotel owners, dive operators, and other businesses, the government closed the $2 million pot fishing industry in 1990, compensating fishers for the cost of their gear and lost revenue. In doing so, Bermuda recognized the importance of its lucrative reef-based tourism and recreational industries—valued at over $9 million in 1988—while benefiting reef biodiversity in the process.[91, 92]

Reef: **TUBBATAHA REEF**
Location: Sulu Sea, Philippines
Signs of progress: In the late 1980s, overfishing and destructive fishing practices were rampant here, with coral cover reduced by 50 percent over a five-year period ending in 1989.[93] The 33,200-hectare area is now a national marine park (the only one in the Philippines) and was declared a UNESCO World Heritage Site in 1994. Non-governmental organizations and the government have worked together to manage the park since its establishment in 1988. The navy, with assistance from NGOs, is patrolling the area to stop illegal fishing. In 1997, all fishing activities were halted within the park and a ranger station was constructed. In 1998, a park management board was put into place. Environmental education materials have been disseminated to stakeholders in the area, and the dive tourism industry is helping to install anchor buoys and regulate the activities of divers on the reefs. The condition of the coral reef substrate has improved remarkably since 1989 and the diversity of fish is exceptionally high.[94]

Reef: **APO AND BALICASAG ISLAND REEFS**
Location: Central Visayas, Philippines
Signs of progress: In the late 1970s, blast and cyanide fishing, as well as other destructive fishing practices, threatened these and other reefs in Central Visayas. Thanks to a community-based marine management program, put in place in the mid-1980s, these practices ceased by 1997. Under this program, Silliman University staff helped organize local people into marine management committees. These groups then set up marine reserves that included no-fishing sanctuaries on one portion of the reef. With the aid of municipal governments, residents have continued to prevent reef damage from fishermen and divers, both within and outside the sanctuaries. A growing tourism industry catering to scuba divers is providing much needed revenue to local communities. In 1992, surveys indicated that live coral cover and fish populations within the sanctuaries had increased substantially along with fish yields per unit area off Apo Island.

Reef: **KOMODO NATIONAL PARK REEFS**
Location: Off the coast of Flores, eastern Indonesia
Signs of progress: The park (which is also a Man and Biosphere Reserve and a World Heritage Site) covers 1,320 square kilometers of water and adjacent land areas. Reefs here exhibit exceptionally high fish species diversity (home to an estimated 900 to 1,000 fish species). The area is also home to many types of corals, sponges, and marine mammals. Fishing and tourism are major income generators in the area around the park. However, these resources have been under serious threat due to destructive fishing practices.

JIM MARAGOS, EAST-WEST CENTER

The coral reefs of Palau support exceptional species diversity.

To combat overfishing and destructive fishing practices, The Nature Conservancy and the Komodo National Park Authority developed a marine resource management plan, which is now in the early phase of implementation. Along with beefing up law enforcement, they are working with local communities to promote alternative livelihood programs, and have initiated training and awareness-building and other projects. These activities are paying off. For example, dynamite fishing went down from an average of more than 10 blasts per month in early 1996 to around one blast per month in late 1996 when routine park patrols were started. Fishermen are being encouraged, successfully, to shift their efforts to catching deeper-water species, keeping them off the reefs.

Reef: **PALAU ROCK ISLANDS**
Location: Palau (southern lagoon of main islands), western Pacific
Signs of progress: The 500 rock islands located in the southern lagoon are renowned for their beauty. The lagoon supports the largest hawksbill sea turtle populations in Micronesia, although nesting adults are being seriously overharvested. Palau also boasts exceptional species diversity of reef life and supports other marine mammals and reptiles, such as dugongs and saltwater crocodiles, not found elsewhere in Micronesia. Urban and resort development pose the most serious threats to this area. The Nature Conservancy and the Palau Conservation Society are successfully working with local communities and the government to protect the Palau reefs.

Reef: **MOMBASA MARINE NATIONAL PARK**
Location: Kenya
Signs of progress: The Mombasa Marine National Park is adjacent to the most heavily populated tourist beach along the Kenyan coast. The reefs are threatened by overfishing, destructive fishing from beat seining and spear fishing, organic pollution and sedimentation, and tourist damage from trampling. The reduction of predatory fish led to increases in burrowing sea urchins, whose excavations began to reduce the reef framework to rubble. In 1989, the area was officially gazetted by the Kenya government as a marine park. Management activities include patrolling, beach cleaning, regulation of tourist activities (including glass bottom boat excursions), and maintenance of moorings. Surveys carried out since 1988 have shown a major increase in fin fish size, abundance, and diversity; recorded coral cover has increased from 8 to 30 percent; and sea urchin numbers have decreased steadily throughout the survey period. The number of sea turtles recorded nesting in the area has also increased.

Reef: **GREAT BARRIER REEF WORLD HERITAGE AREA AND MARINE PARK**
Location: Australia
Signs of progress: The Great Barrier Reef actually consists of about 3,000 individual reefs spread over at least 350,000 square kilometers. The largest reef in the world, it still remains in generally good condition, although runoff of silt, nutrients, and contaminants from agricultural, urban, and industrial areas may pose localized threats in some places. The marine park embraces the

total reef area. Mining is banned, but most of the area is open to fishing and diving and, in some locations, to the development of tourism infrastructure. About 20 percent of the reef is zoned as "no take" areas, where fishing is off-limits. Commercial prawn trawling is taking its toll, however, on sea floor structure and biodiversity. These effects, and those of line fishing, are subject to scientific assessment through large-scale

Reefs and Marine Protected Areas

The development of a global system of marine protected areas (MPAs) lags far behind that of the terrestrial biosphere in both the extent and the effectiveness of its coverage. Nonetheless, it is increasingly apparent that MPAs can play a vitally important role in protecting marine habitats, particularly when forming part of a wider program of measures for coastal and marine management. Many coral reef scientists and managers promote the inclusion of small reserves in planning at the scale of the municipality, while large reserves are the necessary supplement to ensure sustainability and to provide for the needs of species requiring large areas to forage.

Based on what is probably the most comprehensive list currently available,* we estimate that there are at least 400 MPAs including coral reefs in more than 65 countries and territories. *(See Map 6.)* Although important as it currently stands, this list clearly does not represent anything like a global network, although it does provide a framework for one. There are at least 40 countries with no formal protection for their coral reefs, and there are significant regional gaps in this network. The Indian Ocean region, the west coast of the Americas, Solomon Islands, Fiji, French Polynesia, and the Philippines, for example, are all underrepresented. With the exception of a few very large sites such as the Great Barrier Reef, the Florida Keys National Marine Sanctuary, and the Ras Mohammed Park Complex in Egypt, the great majority of protected coral reefs are very small indeed: more than 150 of the MPAs mentioned are less than one square kilometer in size. Outside of the largest sites just mentioned, it is likely that less than 3 percent of the world's coral reefs are protected.

MPAs provide some of the great points of hope for coral reefs. The Great Barrier Reef, the world's second-largest protected area (after northeast Greenland!), is a model of integrated and multiple-use management, allowing sustainable utilization of the reef by a wide range of users with numerous and often conflicting needs. Bonaire Marine Park in the Caribbean is one of the first self-funding protected areas, supported entirely from tourist revenues (which also bring in half of that country's total gross domestic product). Apo Island, in the Philippines, is a tiny fishing reserve that, in the years since its designation, has allowed stocks to recover sufficiently so that local fishermen operating in the surrounding areas are reporting major increases in fish yields. Such cases provide overwhelming support for the economic, social, and political arguments to protect coral reefs.

However, many existing MPAs exist only as "paper parks" where legislation is not enforced, resources are lacking for protecting these areas, or management plans are poorly conceived. In other MPAs, management safeguards are in place, but pressures outside parks and reserves undermine the integrity of protected marine habitats. This was documented in a recent global study, where of 383 MPAs assessed for management effectiveness, conservation objectives were achieved at less than a third (117) of these sites (that is, management effectiveness was ranked as "high").[95]

Johnston Atoll serves as one example of this problem *(see section titled "Twelve Reefs at Risk")*. Probably among the earliest designations of a coral reef protected area, this site has been subjected to massive military development, high atmospheric nuclear testing, chemical waste disposal, and other threats. Elsewhere, external influences beyond the control of the management agencies undermine protected marine habitats. Reefs are highly dynamic and open systems. They cannot be fenced off and are dependent on the flow of currents carrying nutrients, circulating water and oxygen, and transporting larvae and other materials. But it is these same water movements that carry pollutants and sediments into protected areas, while overfishing upstream of a reef may cut off the vital supply of new recruits of coral and fish to the reef community.

In this assessment, we found that reefs within many MPAs are under high potential threat. These include the Gulf of Mannar National Park in India; Bunaken, Bali Barat, Komodo, and Kepulauan Togian National Parks in Indonesia; Mochima National Park in Venezuela; Iriomote and Okinawa Kaigan National Parks in Japan; Pulau Tiga and Turtle Islands in Malaysia; Corals del Rosario in Colombia; and others. Protected areas can play a vital role, and act as flagships for the protection of coral reefs, but cannot be designated in isolation. The need for a more concerted and broadly based management regime, in many cases crossing national boundaries, will be essential for the ultimate protection of many reefs.

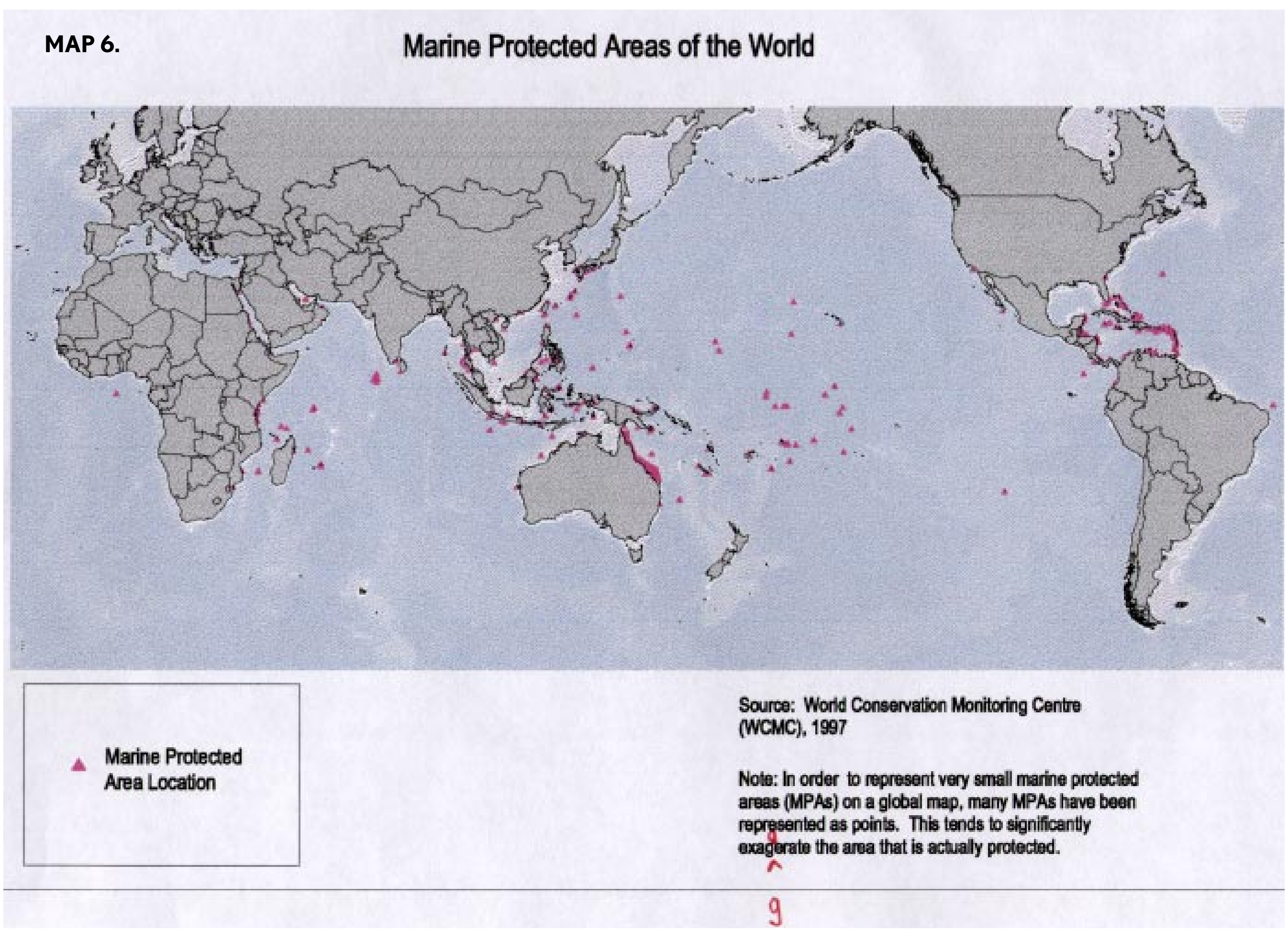
*Taken from the World Conservation Monitoring Centre's Protected Areas Database, a global database managed in collaboration with the IUCN's World Commission on Protected Areas, which houses information on more than 30,000 sites, including more than 3,000 marine protected areas.

investigations. Strong stakeholder involvement, education programs, and enforcement are all combined to achieve compliance with, and support for, park regulations and management plans. The Great Barrier Reef World Heritage Area is a classic and often cited example of how management can be applied successfully to conserve entire ecosystems.

JIM MARABGOS, EAST-WEST CENTER

Protection and proper management can allow damaged reefs to recover.

The International Coral Reef Initiative's Framework for Action *(see box "International Agreements and Initiatives")* outlines the broad types of local and national efforts needed to assure the integrity of reef ecosystems. These include, but are not limited to, involving stakeholder groups at all levels of decision making; integrated coastal zone management; educating the public, policy-makers, and others about reef issues and how these habitats should be managed; strong environmental laws; encouraging micro-enterprise development; promoting environmentally sound land use practices; cracking down on illegal fishing and promoting sustainable fisheries management; developing disaster strategies to minimize threats to reefs when oil spills and unforeseen events occur; and developing an effective network of marine protected areas. If implemented, these steps would help ensure that reefs at risk today are maintained as healthy ecosystems in the future.



International Agreements and Initiatives

Although there are no internationally binding conservation targets or treaties related *specifically* to coral reefs, a range of existing initiatives and agreements are in place that have helped focus attention on these ecosystems. These include:

The International Coral Reef Initiative (ICRI): This effort was first launched in 1995, under the sponsorship of eight countries (the United States, Philippines, Japan, Australia, Jamaica, France, Sweden, and the United Kingdom). ICRI seeks to promote the sustainable management and use of coral reefs and related ecosystems (mangroves and sea grass beds) through a range of activities that have included regional workshops to identify area-specific issues and priorities and opportunities for collaboration between countries.

The Framework for Action: A major outcome of the first ICRI workshop was the production of a Framework for Action, which was subsequently agreed to by representatives of at least 80 governments and a variety of non-governmental organizations and funding agencies. This framework includes actions to be taken in the areas of management, capacity building, research and monitoring, and review. For the framework to be effective, it must be strongly supported and accepted as the standard guideline for the implementation of improved coral reef management.

The International Year of the Coral Reef: As part of an international awareness-raising campaign under ICRI, 1997 was declared the "Year of the Reef." Environmental organizations, museums and aquaria, research institutions, and other groups hosted activities to promote public education, data collection and assessment, and reef management around the world.

The International Year of the Ocean: The United Nations declared 1998 the "Year of the Ocean" to help maintain media and public attention on coral reefs and other marine habitats.

Protected area targets: The World Conservation Union (IUCN), a nonprofit organization with a broad government and non-governmental organization membership, proposed, in 1992, that countries protect a minimum of 10 percent of their ecosystems, a target that has since gained wide endorsement.[96] More recently, at an American Association for the Advancement of Science special symposium on marine protected areas held in Seattle in 1997, Dr. Jane Lubchenco called for the setting aside of 20 percent of the surface area of the world's oceans as no-take protected reserves by the year 2020. Within no-take areas, all fishing is prohibited. The 20-percent-by-2020 goal is supported by a number of scientists and other experts, who recommend that it be a major focus of activities beyond the International Year of the Reef.[97]

The Convention on Biological Diversity: This 1992 binding agreement requires countries to develop and implement strategies for the sustainable use and protection of biodiversity, including that of marine ecosystems. Many of the signatory nations have developed national-level strategies and action plans to this end. Marine issues are specifically addressed in the convention's 1995 Jakarta Mandate on Coastal and Marine Biodiversity.[98] To date, however, few concrete actions have been taken to implement this workplan.

Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES): This binding agreement, which came into force in 1975, prohibits most international trade of certain species (Appendix I species) and regulates that of others through a permit system (Appendix II species). All stony corals and black corals are listed as Appendix II species, and as such receive some protection, although currently it is difficult to track their trade due to nonstandardized reporting protocols.[99] CITES could be a more effective treaty for protecting coral reef biodiversity if there were adequate data on the status of marine species (without proof that a species is threatened, there are no grounds for limiting its trade).

There are a range of other international agreements and initiatives covering marine pollution, land-based pollution, fisheries, and protected areas relevant to coral reefs. They offer both mechanisms for reducing human impact on reef ecosystems (for example, the United Nations Conference on the Protection of the Marine Environment From Land-Based Activities and the Convention for the Prevention of Pollution from Ships) and means for better protecting coral reefs (for example, World Heritage Convention, Ramsar Convention, and the UNESCO Man and Biosphere Programme).[100]

TECHNICAL NOTES

Implementation of the Reefs at Risk Indicator

Reefs at Risk is a global assessment of likely threats to coral reefs from four separate threat factors: coastal development, marine-based pollution, overexploitation of marine resources, and inland pollution, including sedimentation. Zones of high, medium, and low threat were estimated for each of the threat factors, and were combined (through spatial overlay analysis) with a data set reflecting the location of coral reefs. Coral reefs are represented by a four-kilometer resolution data set (55,168 cells) reflecting shallow coral reefs of the world from the World Conservation Monitoring Centre. This data set was classified as follows:

- Reefs classified as under high threat in at least one of the individual threat factors were classified as under high threat overall;
- Reefs classified as under medium threat in at least one threat factor were classified as under medium threat overall; and
- Reefs classified as under low threat in all four threat factors were classified as under low threat overall.

Details of the individual threat factors follow.

Implementation of the Coastal Development Threat Factor

Proxies were developed to reflect the likely threat from pollution and sedimentation associated with coastal development. Stressors within the threat factor are cities with a population of more than 100,000, settlements of any size, airports (including some military bases), mines, and tourist resorts. Both the rationale for inclusion of each of these stressors and the details of implementation are described below.

Cities: Cities were differentiated based both upon size and upon likely level of sewage treatment, as both are important factors relating to the potential threat a city presents to nearby coral reefs. All cities with a population of 100,000 or more were differentiated as to likely level of sewage treatment based upon income level. Additionally, large cities (above one million and five million person thresholds) were assumed to have larger zones of potential effect than smaller cities, regardless of income level.

Cities with populations of more than 100,000 come from the World Cities Data Base by Birbeck College.

The World Bank's classification of income level was used as a means of differentiating likely degree of treatment of sewage for all cities with a population of more than 100,000. Cities in low-income and lower-middle-income countries were assumed to have little treatment of sewage, while those in upper-middle and high-income countries were assumed to have at least moderate treatment.*

Areas were classified as being under high threat if within 10 kilometers of a city assumed to have little sewage treatment. Areas were classified as being under medium threat if within 10 kilometers of a city assumed to have at least moderate sewage treatment or within 25 kilometers of a city assumed to have little sewage treatment.

The additional threat associated with large cities was implemented for two population sizes. Areas were classified as being under high threat if within 20 kilometers of a city of one million or more, or within 30 kilometers of a city of five million or more. Areas were classified as being under medium threat if within 40 kilometers of a city of one million or more, or within 60 kilometers of a city of five million or more.

Settlements: Population centers of less than 100,000 can also present a significant threat to coral reefs. The Populated Place data set from the Digital Chart of the World (DCW) by the U.S. Defense Mapping Agency (DMA) and the Environmental Systems Research Institute (ESRI) was used to reflect settlements of any size. There are more than 206,000 settlement locations represented, with about 60,000 of these within the 60-kilometer coastal zone. Areas were classified as being under medium threat if within 8 kilometers of a settlement.

Airports and Military Bases: Airports and military bases are potential stressors to coral reefs directly, as a result of

**Low and lower-middle income countries* include Algeria, Angola, Bangladesh, Benin, Cambodia, China, Colombia, Congo, Cuba, Dominican Republic, Egypt, Ghana, Guyana, India, Indonesia, Iran, Iraq, Jamaica, Lebanon, Morocco, Mozambique, Nigeria, Pakistan, Panama, Peru, Philippines, Republic of Korea, Saudi Arabia, Senegal, Sri Lanka, Sudan, Tanzania, Venezuela, Vietnam, and Yemen. *Upper-middle and high income countries* include Australia, Brazil, Chile, Curacao, Gabon, Guam, Hong Kong, Japan, Malaysia, Mexico, New Zealand, Puerto Rico, Saint Lucia, Singapore, South Africa, St. Thomas, Taiwan, Thailand, Trinidad, United Arab Emirates, and the United States.

construction, renovations, and emissions, and also indirectly, through the increased activities associated with the transit of people and goods. The 8,235 military and civilian airports from the DCW were used for this analysis, supplemented by military bases that were added to the maps at the two-day Reefs at Risk workshop held in September 1997 in Manila. Areas were classified as being under medium threat if within 10 kilometers of an airport or military base.

Mines: Sedimentation and pollution associated with mining can present a significant threat to coral reefs. The DCW data set on mines, including 8,515 mines that are undifferentiated by type, served as the base data set. This was supplemented by eight mine locations added to maps at the expert workshop. Areas were classified as being under high threat if within 10 kilometers of a mine.

Tourist Resorts: Tourism represents threats to coral reefs—and their potential salvation. Types of tourism and resorts vary widely. The philosophies of the owner and guests, the resort design, and the care taken in implementation all affect whether a tourist site or resort will be a benefit or harm to nearby coral reefs.

The data set used to evaluate areas likely to be under threat from tourism is based upon resort and dive facility locations and areas of known impact to coral reefs from tourism. A data set of 628 locations was assembled from ReefBase's Lodging Facilities (232) and Dive Facilities (207) data sets, ReefBase's known locations of reefs impacted by tourism (131), and additional resort locations that were added to maps at the expert workshop (58).

Areas were classified as being under medium threat if within 8 kilometers of a tourist resort or location of known impact.

Embayments: Pollution and sediment entering enclosed areas such as bays and lagoons will not flush out as easily as in open areas and can result in an elevated threat to coral reefs. A data set of 650 embayments in areas near coral reefs was developed. Areas classified as being under medium risk from any of the above coastal development stress factors that were also identified as an embayment were reclassified as being under high threat.

Implementation of the Marine-based Pollution Threat Factor

Proxies were developed to reflect the likely threat associated with pollution from oil rigs, tanks, and wells and from ports, as well as the threat to reefs from shipping.

Ports: Large- and medium-sized ports, as defined by the U.S. Defense Mapping Agency's World Port Index (1994) were used in this analysis. Additionally, a number of ports were added based upon input from our reef experts at the Manila workshop. These additional ports were treated as small ports in the analysis. There were 125 large, 288 medium, and 61 small ports.

Areas were classified as being under high threat if within 20 kilometers of a large port or 10 kilometers of a medium-sized port. Areas were classified as being under medium threat if within 50 kilometers of a large port, 30 kilometers of a medium-sized port, or 10 kilometers of a small port.

Oil-related Threats: Information on oil wells and oil tanks come from the DCW. The locations of several additional oil wells were added by experts at the workshop. There were 794 oil wells and 134 oil tanks in the DCW data sets, while 13 points representing oil well locations were added.

Areas were classified as being under high threat if within four kilometers of an oil tank or well and under medium threat if within 10 kilometers of an oil tank or well.

Shipping-related Threats: Areas of intense shipping traffic pose threats to reefs from discharges, spills, and potential groundings. Although most of the world's oceans are crisscrossed at one time or another by vessels, many areas experience a much heavier volume of traffic, and this can be particularly acute in areas of narrow passage or narrow channels.

Areas were defined as "shipping threat areas" if they are along known shipping routes and have relatively narrow areas for passage or have adjacent shallow reefs. These areas, as revised by reef experts at the Manila workshop, were classified as being under medium threat.

Implementation of the Overexploitation Threat Factor

Proxies were developed to reflect the likely threat from population-driven overfishing and destructive fishing practices (dynamite fishing, fishing using poisons, and trawling).

Overfishing: Only countries where the per capita gross national product is less than $10,000 per year or the per capita fish consumption is greater than 50 kilograms per year were considered. (In considering coastal countries with or near coral reefs, Australia, the

Bahamas, Hong Kong, Israel, New Zealand, Singapore, and the United States were excluded. Japan was not excluded because the per capita fish consumption exceeds 50 kilograms per year.)

For all other countries, high threat areas were identified as being within 20 kilometers of coastal areas where the population density exceeds 100 persons per square kilometer, and medium threat areas were identified as being within 20 kilometers of coastal areas where the population density exceeds 20 persons per square kilometer. The medium-resolution global data set Gridded Population of the World, from the National Center for Geographic Information and Analysis–Global Demography Project, was used to represent population density.

Destructive Fishing Practices: The original estimation of areas under high threat from destructive fishing was defined as being within a 20-kilometer radius of a known occurrence of dynamite or cyanide fishing, as reflected in ReefBase. This estimate has since been revised (both expanded and reduced in a few areas) based upon expert input, obtained at the Manila workshop. These revised areas were classified as under high threat.

Implementation of the Inland Pollution and Erosion Threat Factor

The inland pollution threat factor is analytically more complicated than the other factors. Hydrologic modeling and geographic overlay analysis were used to incorporate information on topography, land use, and precipitation. There are three main steps to the method.

In the first step of the analysis, a surface reflecting relative erosion potential (REP) was developed based upon slope, land-cover type, and mean monthly precipitation for the peak rainfall month. The variable reflecting land cover type was reclassified based upon a relative erosion rate derived from the literature and applied as follows to the land cover classes used by the International Geosphere-Biosphere Program (IGBP). *(See Table 4.)*

Table 4. IGBP Land Cover Categories With Associated Relative Erosion Rates

Category	Relative Erosion Rate
Water body	0.5
Evergreen broadleaf forest	1.0
Evergreen needleleaf forest	1.5
Deciduous needleleaf	2.0
Closed shrub land	4.0
Open shrub land	5.0
Woody savanna	6.0
Savannas	8.0
Permanent wetlands	8.0
Croplands/natural mix	12.0
Grasslands	12.5
Croplands	21.0
Urban and built up	21.0
Barren or sparsely vegetated	21.0

The analysis was performed at one-kilometer resolution for small islands and at three-kilometer resolution for continental areas. The formula for REP is:

$$\text{REP} = \text{Slope}^{1.5} * \text{Relative\_Erosion\_Rate} * \text{Precipitation} / 1000$$

Slope is in percent slope, Relative Erosion Rate is defined in Table 4, and Precipitation reflects mean monthly precipitation for the peak rainfall month during the year in millimeters.

In the second part of the analysis, the REP surface was aggregated by watershed through the use of a summary statistic for the watershed. Mean REP for the watershed was used to classify watersheds as low, medium, or high REP. For coastal watersheds, this classification defines the level of threat from sedimentation.

In the third part of the analysis, the relevant zone of effect for sediment delivery was estimated.* Flow accumulation within the watershed, weighted by rainfall for the peak rainfall month, was estimated for each watershed and was used as a proxy for flow (discharge) at the coastal pour point. This flow estimate was the basis for scaling the circular buffers reflecting zone of effect.† Information on plume distances for 20 rivers of the world was used as the basis for this scaling. The estimated plume area for each river was classed according to the threat classification from step 2.

To summarize the implementation of the inland pollution threat factor: At coastal river mouths, a zone of

*As the range of nutrient plumes into the marine realm is far beyond the range of effects of sedimentation (Hallock, Muller-Karger and Halas, 1993, National Geographic Research and Exploration, 9:358–78) this method might underestimate the zone of effect.

†It is recognized that it would be ideal to take ocean currents into account when estimating the sediment plume, or zone of effect, but this was not possible within this global-scale analysis due to the lack of a sufficiently detailed global data set on ocean currents. Not including ocean currents in the analysis will serve to overestimate the zone of effect, but mostly offshore, where reefs typically do not occur. As such, exclusion of this variable should not significantly affect the classification of threat to reefs.

potential impact from inland (upstream) land-use activities was developed based upon the relative estimate of flow within the watershed, while the degree of threat (low, medium, or high) is based upon the mean estimate of REP for the watershed. The REP itself is a function of slope, land cover, and mean precipitation for the peak rainfall month for that area.

There were 3,260 pour points (discharge points) in the global analysis. The mean REP for the watersheds above these pour points was 41.7, the median was 12.5, and the maximum was 1,412. REP is a unitless value reflecting the *relative* erosion potential for a land surface area.

- watersheds with a mean REP of less than 5 were classified as under low threat;
- watersheds with a mean REP between 5 and 45 were classified as under medium threat; and
- watersheds with a mean REP above 45 were classified as under high threat.

River flow estimates are also in unitless, relative terms. The river flow estimate for coastal pour points have a mean of 566, a median of 40.8, and a maximum (for the Amazon) of 204,600.

Table 5 summarizes the modeled river flow estimates and the associated plume distances (zone of effect) implemented.

Table 5. River Flow Estimates and Associated Plume Distances

River Flow (000)	Plume (km)	Number of Occurrences
0–10	15	544
10–20	25	569
20–30	40	296
30–100	50	838
100–200	60	366
200–400	70	244
400–1,000	80	206
1,000–2,000	90	88
2,000–5,000	100	57
5,000–20,000	120	30
20,000–40,000	140	8
40,000–100,000	160	7
over 100,000	200	1

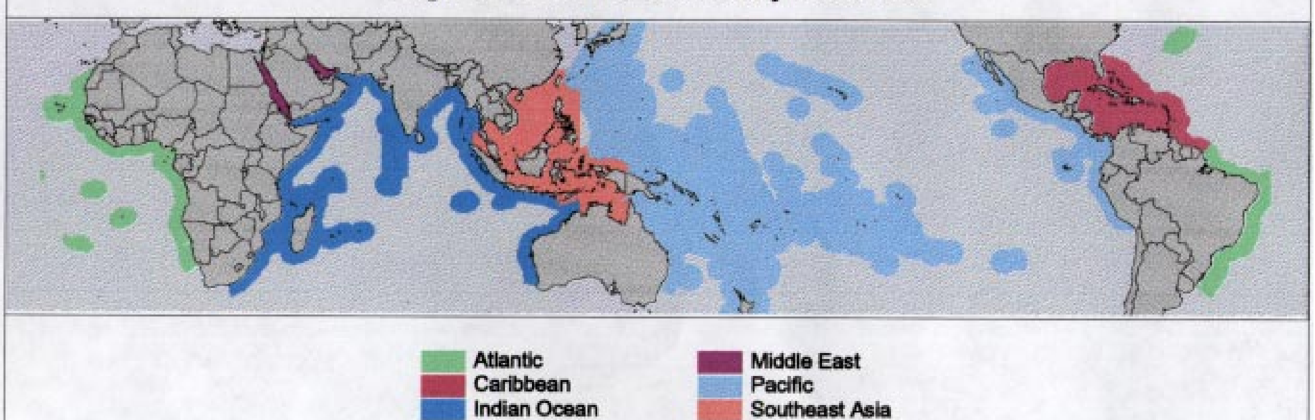
Accuracy Issues

The Reefs at Risk indicator was implemented using the best available global data sets. (The 14 data sets used are described above.) The data sets are of varying spatial accuracy and completeness, and reflect slightly different time periods. For example, the data sets from the DCW reflecting settlements, oil wells, and mines were developed during the 1970s and 1980s, and were largely revised during the late 1980s. Recently developed oil wells or mines would be missing from the data sets. Information on tourist resorts from ReefBase is part of an ongoing data development effort and, as such, is not comprehensive. Additionally, the spatial accuracy of these data sets varies from better than one kilometer for the data sets from the DCW, the land cover and topographic data sets, to up to several kilometers for some of the data in ReefBase, the World Cities Data Base, and the population density data. The spatial accuracy issues associated with using this range of data sets is mitigated through aggregating all data to a standard four-kilometer resolution grid, consistent with the four-kilometer resolution data set reflecting shallow coral reefs from the World Conservation Monitoring Centre. The analysis was implemented at four-kilometer resolution.

Regional Groupings

Within the Reefs at Risk analysis, regional summary statistics were based on the regional groupings as presented in the map below.

MAP 7. Regions Used for Summary Statistics



Comments on the Reefs at Risk Indicator

The Reefs at Risk analysis reflects modeled estimates of threats to coral reefs and is driven by data sets reflecting population density, human population centers, infrastructure and activities, and our derived estimates of threats from inland pollution and sedimentation. These estimates should not be taken to reflect current reef condition, nor should they be taken to reflect all known threats to coral reefs. Estimation of threats to reefs was particularly difficult for remote areas in the Pacific, which are less visited and for which global data sets tend to be less complete.

During review of these final threat classifications, coral reef experts provided the following observations:

Tropical Americas

1. The Florida Keys reefs are classified as under medium threat from marine pollution and coastal development. This is regarded as a potential underestimate of threat.

2. The reefs off southern Belize are classified as being under high threat, largely from inland pollution and erosion. This is regarded as a potential overestimate of threat, relative to other reefs in that region.

3. The reefs off western Costa Rica were estimated to be under high threat from coastal development and inland pollution and erosion. One researcher suggested that this overestimates threat in that area.

4. Bermuda's reefs are classified as being under high threat from overexploitation. This is an overestimate of current threat since the pot fishing industry was closed in 1990.

Indian Ocean

The reefs in the northeastern Seychelles around Mahé and Curieuse Islands were estimated to be under medium and high threat. This is a potential overestimation of threat.

Seas of the Middle East

1. Within the Gulf of Aqaba, reefs were estimated to be approximately 70 percent under low threat and 30 percent under high threat, largely from coastal development. This is regarded as a potential underestimate due to the threats posed by tourism and shipping.

2. Along the coast of Yemen, most reefs were estimated to be under high threat from overexploitation. This is regarded as a potential overestimation of threat, relative to other reefs in the region.

East Asia

The Spratly Islands have been classified predominantly as under low threat. This is probably an underestimate due to blast fishing, fishing with poisons, and shark fishing in that area.

Pacific Ocean

1. New Caledonia's reefs are estimated to be predominantly under low threat. This was noted to be a potential underestimate for the reefs of the main island due to deforestation and mining contributing to sedimentation.

2. The reefs of Christmas Island were classified as being under high threat. Medium was suggested as a more appropriate estimate of threat for this atoll.

3. Within Micronesia, the reefs of Majuro and Kwajalein were classified as being under low threat, which may be an underestimate of the threat from coastal development activities.

Analysis of Species Diversity and Threats to Coral Reefs

Work on mapping the distribution of coral reef fish species is ongoing. This analysis draws on work by the University of York and Ocean Voice International, which mapped the ranges of approximately 1,677 coral reef fish species from 29 families. Species ranges were identified using a broad array of data from more than 350 monographs, scientific literature, museum records, and field collection. These data were entered as map points (over 33,000 points) and have been summarized into equal-area grid cells (4,500 distinct areas) covering approximately 50,000 square kilometers each. This sample represents about 40 percent of all known coral reef fishes.

The surveying and sampling of coral reef fish species is uneven across the globe. For example, a greater proportion of species have been sampled in the Caribbean relative to the Red Sea, some parts of Southeast Asia, and remote areas of the Pacific. This sampling bias favors the inclusion of well-sampled areas. As such, several areas likely to have species diversity comparable to areas in the Caribbean were not included in the analysis, including the reefs off the coast of Vietnam, the Spratly Islands, and parts of the Red Sea.

In order to reduce the sampling bias in the identification of areas with high coral reef fish species diversity, interpolated, smoothed species ranges which summarize the number of species within an approximately 400-kilometer radius were used. Areas in the top 20 percent for species diversity (with at least 210 coral reef fish species) were identified. These areas were then classified according to the estimate of potential threat to coral reefs from human activity (the Reefs at Risk indicator) for all reefs within each area.

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ENDNOTES

1 Don McAllister, "Status of the World Ocean and Its Biodiversity," *Sea Wind* 9, no. 4 (1995), 14.

2 Clive Wilkinson, "Coral Reefs Are Facing Widespread Devastation: Can We Prevent This Through Sustainable Management Practices?" in *Proceedings of the 7th International Coral Reef Symposium* 1 (Guam, 1993), 11–21.

3 Elizabeth Pennisi, "Brighter Prospects for the World's Coral Reefs?" *Science* 277 (July 25, 1997), 492.

4 Robert Costanza et al., "The Value of the World's Ecosystem Services and Natural Capital," *Nature* 387 (May 15, 1997), 256.

5 Gustav Paulay, "Diversity and Distribution of Reef Organisms," in *Life and Death of Coral Reefs,* ed. Charles Birkeland (New York: Chapman and Hall, 1997), 303–4.

6 David Malakoff, "Extinction on the High Seas," *Science* 277 (July 25, 1997), 487–88.

7 Elliot Norse, ed., *Global Marine Biological Diversity: A Strategy for Building Conservation into Decision Making* (Washington, D.C.: Island Press, 1993), 14.

8 United Nations Environment Programme (UNEP) and World Conservation Union (IUCN), *Coral Reefs of the World. Volume 1: Atlantic and Eastern Pacific* (Gland, Switzerland: IUCN, 1988), xvi.

9 Mark Spalding and A. M. Grenfell, "New Estimates of Global and Regional Coral Reef Areas," *Coral Reefs* (1997) 16:225–230.

10 Clive Wilkinson and Robert Buddemeier, *Global Climate Change and Coral Reefs: Implications for People and Reefs* (Gland, Switzerland: IUCN, 1994), 6.

11 James E. Maragos, M. P. Crosby, and John W. McManus, "Coral Reefs and Biodiversity: A Critical and Threatened Relationship," *Oceanography* 9, no. 1 (1996), 87.

12 Les Kaufman and Paul Dayton, "Impacts of Marine Resources Extraction on Ecosystem Services and Sustainability," in *Nature's Services: Societal Dependence on Natural Ecosystems,* ed. Gretchen Daily (Washington, D.C.: Island Press, 1997), 275.

13 Stephen C. Jameson, John W. McManus and Mark D. Spalding, *State of the Reefs: Regional and Global Perspectives* (Washington, D.C. ICRI., U.S. Department of State, 1995), 24.

14 Donald Hinrichsen, "Requiem for Reefs?" *International Wildlife* (March/April 1997), 8.

15 Herman Cesar, *Economic Analysis of Indonesian Coral Reefs* (Washington, D.C.: World Bank, 1996), 4, 16.

16 Charles Birkeland, ed., *Life and Death of Coral Reefs* (New York: Chapman and Hall, 1997), 5.

17 William Fenical, "Marine Biodiversity and the Medicine Cabinet: The Status of New Drugs from Marine Organisms," *Oceanography,* 9, no. 1 (1996), 23–24.

18 Maragos, Crosby, and McManus, "Coral Reefs and Biodiversity," 85–7.

19 Birkeland, *Life and Death of Coral Reefs,* 4.

20 Jameson, McManus, and Spalding, *State of the Reefs,* 24.

21 Herman Cesar, *Economic Analysis of Indonesian Coral Reefs* (Washington, D.C.: World Bank, 1996).

22 Robert Richmond, "Coral Reef Resources: Pollution's Impacts," *Forum for Applied Research and Public Policy* 9, no. 1 (Spring 1994), 55–56.

23 Mats Bjork, Salim Mzee Mohammad, Marie Bjorkland, and Adelaida Semesi, "Coralline Algae, Important Coral Reef Builders Threatened by Pollution," *Ambio* 24, nos. 7–8 (December 1995), 502–4.

24 Barbara Brown, "Disturbances to Reefs in Recent Times," in *Life and Death of Coral Reefs,"* ed. Charles Birkeland (New York: Chapman and Hall, 1997), 370–72.

25 Global Environment Facility, *The Hashemite Kingdom of Jordan: Gulf of Aqaba Environmental Action Plan* (Washington, D.C.: World Bank, 1996), 5.

26 James Bohnsack, "The Impacts of Fishing on Coral Reefs," in *Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History* (University of Miami, 1993), 196–98.

27 Simon Jennings and Nicholas Polunin, "Impacts of Fishing on Tropical Reef Ecosystems," *Ambio* 25, no. 1 (February 1996), 44–46.

28 Callum Roberts, "Effects of Fishing on the Ecosystem Structure of Coral Reefs," *Conservation Biology* 9, no. 5 (October 1995), 989–92.

29 Pennisi, "Brighter Prospects."

30 Gomez, Alino, Yap, and Licuanan, "A Review of the Status of Philippine Reefs," *Marine Pollution Bulletin* 29, nos. 1–3 (1994), 65–66.

31 Jorge Cortes, "A Reef Under Stress: A Decade of Degradation," in *Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History* (University of Miami, 1993), 240–45.

32 L. Talaue–McManus and K. P. N. Kesner, "Valuation of a Philippine Municipal Sea Urchin Fishery and Implications of Its Collapse," in *Philippine Coastal Resources Management Under Stress,* eds. M. A. Juinio–Menez and G. F. Newkirk (Quezon City: Coastal Resources Research Network and Marine Sciences Institute, University of the Philippines, 1995), 229–39.

33 R. E. Johannes and M. Riepen, *Environmental, Economic and Social Implications of the Live Fish Trade in Asia and the Western Pacific* (Bonnet Hill, Tasmania, Australia; RE Johannes Pty Ltd and Wellington, New Zealand: Fisheries Development Associates, 1995).

34 Brown, "Disturbances to Reefs," 365.

35 C. M. Eaken, "Where Have all the Carbonates Gone?

A Model Comparison of Calcium Carbonate Budgets Before and After the 1982–1983 El Niño," *Coral Reefs* 15, no. 2 (1 *Aqaba Environmental Action Plan* (Washington D.C., World Bank, 1996), 996), 109–19.

36 P. W. Glynn, "Coral Reef Bleaching: Facts, Hypothesis and Implications," *Global Change Biology* 2, no. 6 (1996), 495–509.

37 Callum Roberts, Nigel Downing and Andrew Price, "Oil on Troubled Waters: Impacts of the Gulf War on Coral Reefs," in *Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History* (University of Miami, 1993), 132–37.

38 UNEP/IUCN, *Coral Reefs of the World. Volume 2: Indian Ocean, Red Sea and Gulf* (Gland, Switzerland: IUCN, 1988), xxi.

39 Brown, "Disturbances to Reefs," 373–4.

40 Brown, "Disturbances to Reefs," p. 376.

41 Joby Warrick, "Coral Reef off Florida Keys Caught in Wave of Deadly Disease," *Washington Post,* February 9, 1997, A3.

42 Rodney Salm, "The Status of Coral Reefs in the Western Indian Ocean with Notes on Related Ecosystems," working paper prepared for the International Coral Reef Initiative Workshop, Seychelles, March 1996.

43 Mark Spalding, Francois Blasco, and Colin Field, eds., *World Mangrove Atlas* (Okinawa: International Society for Mangrove Ecosystems, 1997), 11.

44 Wilkinson and Buddemeier, *Global Climate Change,* 40, 103.

45 S. C. Jameson, J. W. McManus and M. M. Spalding, *State of the Reefs: Regional and Global Perspectives* (Washington, D.C.) I.C.R.I., U.S. Department of State, 1995), 6–7.

46 Jorge Cortes, "Status of the Caribbean Coral Reefs of Central America," in *Proceedings of the 8th International Coral Reef Symposium* (Balboa, Panama, Smithsonian Tropical Research Institute, 1997), 339.

47 Rajasuriya, De Silva, and Ohman, "Coral Reefs of Sri Lanka: Human Disturbance and Management Issues," *Ambio* 24, nos. 7–8 (December 1995), 428–29.

48 Arjan Rajasuriya, "Present Status of Coral Reefs in Sri Lanka," in *Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History* (University of Miami, 1993), 411.

49 Callum Roberts, Nigel Downing, and Andrew Price, "Oil on Troubled Waters: Impacts of the Gulf War on Coral Reefs," in *Proceedings of the Colloquium on Global Aspects of Coral Reefs: Health, Hazards and History* (University of Miami, 1993), 136.

50 Peter Weber, "Reviving Coral Reefs" in *State of the World 1993* (Washington, D.C.: WorldWatch Institute, 1993) 48.

51 Clive Wilkinson, personal communication. Reporting on results from the 1996 International Coral Reef Symposium.

52 Ewald Lieske and Robert Myers, *Coral Reef Fishes: Caribbean, Indian Ocean and Pacific Ocean Including the Red Sea* (Princeton, N.J.: Princeton University Press, 1996), 7.

53 Cesar, *Economic Analysis,* 25.

54 Gomez, Alino, Yap, and Licuanan, "Philippine Reefs," 64.

55 J. E. Maragos and C. Payri, "The Status of Coral Reef Habitats in the Insular South and East Pacific," in *Proceedings of the 8th International Coral Reef Symposium* (Balboa, Panama: Smithsonian Tropical Research Institute, 1997), 311.

56 Leon Zann, "The Status of Coral Reefs in South Western Pacific Islands," *Marine Pollution Bulletin* 29, nos. 1–3 (1994), 53–55.

57 E. Dinerstein, D. M. Olson, D. J. Graham, A. L. Webster, S. A. Primm, M. P. Bookbinder and G. Ledec, *A Conservation Assessment of the Terrestrial Ecoregions of Latin America and the Caribbean* (Washington, D.C.: World Bank and the World Wildlife Fund, 1995).

58 Nels Johnson, *Biodiversity in the Balance*: *Approaches to Setting Geographic Conservation Priorities* (Washington, D.C.: Biodiversity Support Program, 1995), 9.

59 William Smith-Vaniz, James Bohnsack, and James Williams, "Reef Fishes of the Florida Keys," in *Our Living Resources: A Report to the Nation on the Distribution, Abundance, and Health of U.S. Plants, Animals and Ecosystems* (U.S. Department of Interior), 279.

60 UNEP/IUCN, *Coral Reefs of the World. Volume 1*, 311–15.

61 Ibid., 251–52.

62 H. M. Guzman, J. B. C. Jackson, and E. Weil, "Short–term Ecological Consequences of a Major Oil Spill on Panamanian Subtidal Reef Corals," *Coral Reefs* 10 (1991), 1–12.

63 H. M. Guzman and I. Holst, "Effects of Chronic Oil–sediment Pollution on the Reproduction of the Caribbean Reef Coral Siderastrea Sidera," *Marine Pollution Bulletin* 26 (1993), 276–82.

64 H. M. Guzman, K. A. Burs, and J. B. C. Jackson, "Injury, Regeneration and Growth of Caribbean Coral Reef Communities After a Major Oil Spill in Panama," in *Marine Ecology Program Series* 105 (1994), 231–41.

65 UNEP/IUCN, *Coral Reefs of the World. Volume 1*, 177.

66 K. Nakatani, A. Rajasuriya, A. Premaratne, and A. T. White, eds., *The Coastal Environmental Profile of Hikkaduwa, Sri Lanka* (Colombo, Sri Lanka: Coastal Resources Management Project, 1994).

67 A. Rajasuriya and A. T. White, "Coral Reefs of Sri Lanka: Review of Their Extent, Condition and Management

Status," *Coastal Management* 23 (1995), 77–90.

68 A. T. White, V. Barker, and G. Tantrigama, "Using Integrated Coastal Management and Economics to Conserve Coastal Tourism Resources in Sri Lanka," *Ambio* 26, no. 6 (1997), 335–44.

69 Jameson, McManus, and Spalding, *State of the Reefs,* 10.

70 Stephen Jameson and David Smith, "Coral Reef Management on the New Red Sea Riviera," *Proceedings of Coastal Zone 1997* 2 (1997), 784–86.

71 Jameson, McManus, and Spalding, *State of the Reefs,* 10.

72 L. M. Chou, "The Status of Southeast Asian Coral Reefs," in *Proceedings of the 8th International Coral Reef Symposium* (Balboa, Panama: Smithsonian Tropical Research Institute, 1997), 317.

73 UNEP/IUCN, *Coral Reefs of the World. Volume 2*, 307–9.

74 J. W. McManus and M. C. Ablan, eds., *ReefBase: A Global Database on Coral Reefs and Their Resources. User's Guide. Version 2.0* (Makati City, Philippines: International Center for Living Marine Aquatic Resources, 1997).

75 P. J. Mumby, E. P. Green, A. J. Edwards, and C. D. Clarke, *Coral Reef Habitat Mapping: How Much Detail Can Remote Sensing Provide?* (in press).

76 D. L. B. Jupp, "Background and Extensions to Depth Penetration Mapping in Shallow Coastal Waters," paper presented at the Symposium on Remote Sensing of the Coastal Zone, Gold Coast, Queensland, Australia, 1988.

77 Mumby, Green, Edwards, and Clark, *Coral Reef Habitat Mapping.*

78 D. Hopley and P. C. Catt, "The Use of Infrared Aerial Photography for Monitoring Ecological Changes to Coral Reef Flats on the Great Barrier Reef," in *Proceedings of the 6th International Coral Reef Symposium* (Townsville, Australia, 1988), 503–8.

79 J. W. McManus et al., "Coral Reef Fishery Sampling Methods," in *Stock Assessment: Qualitative Methods and Applications for Small–Scale Fisheries*, eds. V. F. Galluci et al. (New York: CRC Lewis Publishers, 1996).

80 D. Hopley, Aerial Photography and Other Remote Sensing Techniques. In *Coral Reefs: Research Methods*, eds. D.R. Stoddard and R.E. Johannes (Paris: UNESCO), 231–50

81 Mumby, Green, Edwards, and Clarke, *Coral Reef Habitat Mapping.*

82 Hopley and Catt, "Use of Infrared Aerial Photography."

83 Hopley, "Aerial Photography."

84 McManus et al., "Coral Reef Fishery Sampling Methods."

85 D. C. Rhoads, J. A. Muramoto, and R. Ward, *A Review of Sensors Appropriate for Efficient Assessment of Submerged Coastal Habitats and Biological Habitats,* Technical Report EL–96 (Vicksburg, Miss.: U.S. Army Corps of Engineers, 1996).

86 R. D. McCaughley, "The Sounds of Coral Reefs" *Joint Conference on Science, Management and Sustainability in the 21st Century.* Abstracts. (Townsville, Australia: James Cook University of North Queensland, 1994), 49.

87 Rhoads, Muramoto, and Ward, *Review of Sensors.*

88 Charles H. Mazel, personal communication.

89 Alan White, personal communication.

90 James Butler, James Burnett–Herkes, John Barnes, and Jack Ward, "The Bermuda Fisheries: A Tragedy of the Commons Averted?" *Environment* 35, no. 1 (1993), 8–13.

91 Birkeland, *Life and Death of Coral Reefs,* 428.

92 Butler, Burnett–Herkes, Barnes and Ward, "The Bermuda Fisheries," 7–32.

93 Yasmin Arquize and Alan White, *Tales from Tubbataha: Natural History, Resource Use, and Conservation of the Tubbataha Reefs Palawan Philippines* (Bandillo ng Palawan Foundation, Philippines, 1994).

94 Alan White and V. P. Palaganas, "Philippine Tubbataha Reef National Marine Park: Status, Management Issues and Proposed Plan," *Environmental Conservation* 18, no. 2 (1991), 148–57.

95 Great Barrier Reef Marine Park Authority, World Bank, and World Conservation Union, *A Global Representative System of Marine Protected Areas. Volume II: Wider Caribbean, West Africa and South Atlantic,* eds. Graeme Kelleher, Chris Bleakley and Sue Wells (Washington, D.C.: World Bank, 1995), 7.

96 World Conservation Union (IUCN), "Parks for Life, A New Beginning" IUCN Bulletin 23, no.2 (1992), 10.

97 Will Hildesley, "Marine Protected Areas: WWF's Role in Their Future Development," draft WWF International discussion document (Gland, Switzerland, February 1998).

98 A. Charlotte de Fontaubert, David Downes, and Tundi Agardy, *Biodiversity in the Seas: Implementing the Convention on Biological Diversity in Marine and Coastal Habitats* (Gland, Switzerland: World Conservation Union, 1996).

99 National Oceanic and Atmospheric Administration's Reporter's Coral Reef Tip Sheet, June 2, 1997.

100 David Downes and A. Charlotte de Fountaubert, "Biodiversity in the Seas: Conservation and Sustainable Use Through International Cooperation," CIEL Brief (Center for International Environmental Law, no. 4, October 1996), 5.

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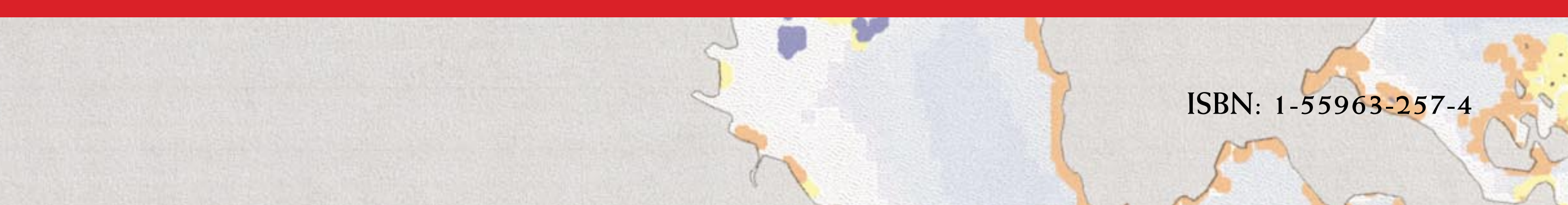

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