Sciencexpress Report

One-Third of Reef-Building Corals Face Elevated Extinction Risk from Climate Change and Local Impacts

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The conservation status of 845 zooxanthellate reef-building coral species have been assessed using IUCN Red List Criteria. Of the 704 species that could be assigned conservation status, 32.8% are in categories with elevated risk of extinction. Declines in abundance are associated with bleaching and diseases driven by elevated sea surface temperatures, with extinction risk further exacerbated by local-scale anthropogenic disturbances. The proportion of corals threatened with extinction has increased dramatically in recent decades and exceeds most terrestrial groups. The Caribbean has the largest proportion of corals in high extinction risk categories while the Coral Triangle (western Pacific) has the highest proportion of species in all categories of elevated extinction risk. Our results emphasize the widespread plight of coral reefs and the urgent need to enact conservation measures.

Coral reefs harbor the highest concentration of marine biodiversity. They have high esthetic, recreational and resource values that have prompted close scientific scrutiny, including long-term monitoring (*1*, *2*) and face increasing threats at local and global scales. Globally, rapid build-up of carbon dioxide (and other greenhouse gases) in the atmosphere is leading to both rising sea surface temperatures (with an increased likelihood of mass coral bleaching and mortality) and acidification (*8*). Ocean acidification is reducing ocean carbonate ion concentrations and the ability of corals to build skeletons (*9*). Local threats include human disturbances such as increased coastal development, sedimentation resulting poor land-use and watershed management, sewage discharges, nutrient loading and eutrophication from agrochemicals, coral mining, and over fishing (*1*–*7*). Local anthropogenic impacts reduce the resilience of corals to withstand global threats, resulting in a global deterioration of reef structure and ability of these ecosystems to sustain their characteristic complex ecological interactions (*1*–*8*).

In view of this ecosystem-level decline, we used International Union for Conservation of Nature Red List Categories and Criteria to determine the extinction risk of reef-building coral species. These criteria have been widely used and rely primarily on population size reduction and geographic range information to classify, in an objective framework, the extinction risk of a broad range of species (*10*). Categories range from "Least Concern" with very little probability of extinction to high risk "Critically Endangered" (Table 1). The 'threatened' categories (Vulnerable, Endangered, Critically Endangered) are intended to serve as one means of setting priority measures for biodiversity conservation.

Our assessments of extinction risk cover all known zooxanthellate reef-building corals and include 845 species from the Scleractinia plus reef-building octocorals and hydrocorals (families Helioporidae, Tubiporidae and Milleporidae). Corals have persisted for tens of millions of years, and the many widespread species in particular are not obvious candidates for extinction. However, periods of mass coral extinctions are known from the fossil record (*11*, *12*), so conditions must have persisted that allowed populations to be reduced below sustainable levels. Up to 45% of all coral species went extinct around the Cretaceous-Tertiary boundary with significantly more zooxanthellate than azooxanthellate extinctions (*13*). With reports of current widespread reef destruction (*2*) and unprecedented population declines in particular species (*14*, *15*) we used IUCN Red List Criteria to investigate whether present conditions have placed corals at elevated extinction risk.

Nearly all extinction risk assessments were made with the IUCN criterion that uses measures of population reduction over time (*10*). Most reef-building corals do not have sufficient long-term species-specific monitoring data to calculate actual population trends; consequently we used widely cited and independently corroborated estimates of reef area lost (*2*, *10*) as surrogates for population reduction. These estimates suffer from lack of standardized quantitative methodology, and so we interpreted them conservatively and weighted declines both regionally and by species-specific life history traits, including susceptibility to the threats causing reef area declines (*10*). Therefore, rates of population decline for each species are based on the rate of habitat loss within its range adjusted by an assessment of the species-specific response to habitat loss (so more resilient species have slower rates of decline) (*10*).

Of the 845 reef-building coral species, 141 had insufficient data to complete a Red List assessment (Table 1), and are excluded from subsequent calculations. Of the remaining 704 species, 231 are listed in the threatened categories, while 407 are in threatened and Near Threatened categories combined (Table 1). Species in the families Euphylliidae, Dendrophylliidae, and Acroporidae are particularly at risk with more than or close to 50% of species in a threatened category; the figures are around 40% for Meandrinidae and Oculinidae. *Heliopora coerulea*, the sole extant member of the ancient family Helioporidae, is rated as Vulnerable. The only species that do not fall within threatened categories are those that inhabit deeper, lower reef slopes and those not solely dependent on reef habitats (i.e. inter-reefal species). The Caryophyllidae, Astrocoeniidae, Merulinidae and Fungiidae have the lowest proportions of threatened species.

In terms of species-specific vulnerability to impacts, approximately 40% of the species are primarily reef-restricted, shallow water corals (<20m depth) (*10*) that are susceptible to general anthropogenic disturbances. The remaining 60% of species can survive on deeper reef (>20m depth), in marginal reef habitat, or in off-reef areas. There are 303 species highly susceptible to bleaching although 102 of these typically grow quickly and populations recover within a few years (*5*). Approximately 52% of the bleaching-susceptible species (mainly in the Acroporidae) are also heavily impacted by disease and predation from the crown-of-thorns seastar *Acanthaster planci*. Acroporid corals account for a high percentage of coral cover on reefs (*11*, *12*) and for a high proportion of the threatened species (Table. 1). Eighty species are considered resistant to bleaching and include mostly members of the genera *Favia* and *Porites*.

Our results indicate that the extinction risk of corals has increased dramatically over the past decade (Fig. 1). Using the values from previous reports of the Global Coral Reef Monitoring Network (*16*) it is possible to determine extinction risk levels prior to the 1998 massive bleaching events (10). Before 1998, 671 of the 704 data-sufficient species would have been categorized as of Least Concern, 20 as Near Threatened and only 13 included in threatened categories. Although an estimated 6.4% of reefs recovered from the 1998 bleaching event approximately 5 years after it occurred, 16% were considered irreversibly destroyed after subsequent monitoring (*2*). Another study shows an increasing rate of coral cover loss in the Indo-Pacific of 1-2% per year since 1997 (*7*).

The proportion of threatened (not including Near Threatened) coral species exceeds that of most terrestrial animal groups apart from amphibians, particularly because of corals' apparent susceptibility to climate change (*10*). At slightly elevated sea surface temperatures corals expel their symbionts, often resulting in colony death if the heat stress persists (*5*). Adult reef-building corals are restricted to well-lit tropical waters and are sessile, not having the option to move to cooler water. This also makes them susceptible to localized disturbances that can magnify the stress on a system already impacted by warming seas.

Regionally, Caribbean reefs (Fig. 2) have been devastated by population declines of two key species, *Acropora cervicornis* (staghorn coral) and *A. palmata* (elkhorn coral) (*14*, *15, 17*), which were recently listed as Threatened under the US Endangered Species Act. They were spatial dominants and primary framework builders during the Pleistocene and Holocene, their loss having had a major ecological impact (*14*, *15*). Another major Caribbean reef-builder, *Montastraea annularis*, has been listed as Endangered because of a rapid population decline over the last decade; on many reefs it is no longer dominant (*10*). It is the largest coral species in this region, has very slow recruitment (*18*), and is also highly susceptible to disease that can kill 500 year-old colonies within months, with recovery unlikely for decades.

In the eastern tropical Pacific, a high proportion of corals have been impacted by warming events. However, subsequent monitoring has shown reefs are recovering in most areas across the region (*19*). Indian Ocean corals were the most impacted by the 1998 warming event with two subsequent bleaching events in some places. Many of the shallow reefs have lost their 3-dimensional rugosity, with cascading trophic and ecological effects including subsequent loss of fish populations (*20*). Other reefs are recovering their structure, but the time to complete recovery may range to decades, and will be highly dependent on future climatic and local disturbance regimes.

The epicenter of marine biodiversity in the Indo-Malay-Philippine Archipelago, the 'Coral Triangle' (*11*, *21*) has the highest proportion of Vulnerable and Near Threatened coral species (Fig. 2c,d). The chronic nature of anthropogenic disturbance in many parts of this region is compounded by the effects of climate change.

Corals in oceanic islands of the Pacific generally have the lowest proportion of threatened species (Fig 2) and Hawaiian reefs have been spared extensive coral loss from bleaching or disease (*22–25*). However, Hawaii is an isolated archipelago with high levels of endemism (*23*) and several rare endemic species may prove especially vulnerable to future threats. Our analysis indicates that the extinction risk for many corals is now much greater than it was prior to recent massive bleaching events. Whether corals actually go extinct this century (*12*) will depend on the continued severity of climate change, extent of other environmental disturbances, and the ability of corals to adapt. If bleaching events become very frequent, many species may be unable to re-establish breeding populations before subsequent bleaching causes potentially irreversible declines, perhaps mimicking conditions that led to previous coral extinctions (*13*). If corals cannot adapt, the cascading effects of the functional loss of reef ecosystems will threaten the geologic structure of reefs and their coastal protection function, and have huge economic effects on food security for hundreds of millions of people dependent on reef fish. Our consensus view is that the loss of reef ecosystems would lead to large-scale loss of global biodiversity.

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26. We thank Tom Haas and the New Hampshire Charitable Foundation, Conservation International, Esmée Fairbairn Foundation, and the Royal Caribbean Cruises Ocean Fund for their generous support of the IUCN Coral Red List Assessment. We also thank the following for help and support: Moonyeen Alava, Jonathan Baillie, Deb Bass, Hector Reyes Bonilla, Thomas Brooks, Hubert Froyalde, Peter Glynn, Scott Henderson, Cleve Hickman, Michael Hoffmann, Danwei Huang, Roger McManus, Mike Palomar, Caroline Pollock, Rodolfo Quicho, Michael Smith, Muhammad Syahrir, Romeo Trono, Mariana Vera, Dana Zebrowski, Charles Darwin Foundation, Conservation International Philippines, Darwin Initiative, First Philippine Conservation Incorporated, Gordon and Betty Moore Foundation, Walton Family Foundation, and the Zoological Society of London.

Supporting Online Material
www.sciencemag.org/cgi/content/full/1159196
Materials and Methods
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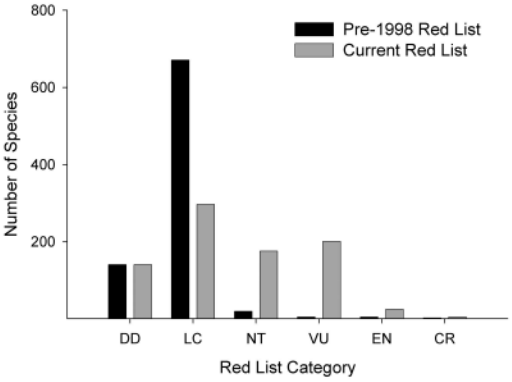
16 April 2008; accepted 24 June 2008
Published online 10 July 2008; 10.1126/science.1159196
Include this information when citing this paper.

Fig. 1. Comparison of current Red List Categories for all reef-building coral species to hypothetical Red List Categories back-cast to pre-1998. (CR=Critically Endangered, EN=Endangered, VU=Vulnerable, NT=Near Threatened, LC=Least Concern, DD=Data Deficient).

Fig. 2. a) Critically Endangered species as percent of total species in area, **b**) Critically Endangered and Endangered species as percent of total species in area, **c**) species in all Threatened categories (Critically, Endangered and Vulnerable) as percent of total species in area, and d) species in Threatened and Near Threatened categories as percent of total species in area. Calculations are based on a cell size of 10 km^2.

Table 1. Current Red List Categories for reef-building coral species by family. Percentages in Threatened Categories (Thr) include all non-Data Deficient species listed as VU, EN, CR, while Near Threatened and Threatened (NT + Thr) includes all non-Data Deficient species listed as NT, VU, EN, and CR. (CR=Critically Endangered, EN=Endangered, VU=Vulnerable, NT=Near Threatened, LC=Least Concern, DD=Data Deficient).

Family	DD	LC	NT	VU	EN	CR	Total species	NT+Thr	Thr
Acroporidae	81	54	42	85	7	2	271	71.6%	49.5%
Agariciidae	3	26	5	11			45	38.1%	26.2%
Astrocoeniidae	4	9	1	1			15	18.2%	9.1%
Caryophylliidae		3					3	0.0%	0.0%
Dendrophylliidae	1	4	3	7			15	71.4%	50.0%
Euphylliidae	3		5	9			17	100.0%	64.3%
Faviidae	5	43	57	22	3		130	65.6%	20.0%
Fungiidae	2	32	5	5	2		46	27.3%	15.9%
Helioporidae				1			1	100.0%	100.0%
Meandrinidae	3	4		2	1		10	42.9%	42.9%
Merulinidae	1	7	3		1		12	36.4%	9.1%
Milleporidae	2	8	1	2	2	1	16	42.9%	35.7%
Mussidae	7	21	12	11	1		52	53.3%	26.7%
Oculinidae	6	3	3	4			16	70.0%	40.0%
Pectiniidae	5	12	6	5	1		29	50.0%	25.0%
Pocilloporidae	2	15	5	7	2		31	48.3%	31.0%
Poritidae	10	40	20	25	5	1	101	56.0%	34.1%
Rhizangiidae		1					1	0.0%	0.0%
Siderastreidae	6	15	6	4		1	32	42.3%	19.2%
Trachyphyliidae			1				1	100.0%	0.0%
Tubiporidae			1				1	100.0%	0.0%
Total	141	297	176	201	25	5	845		



800
600
400
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Number of Species
Pre-1998 Red List
Current Red List
DD
LC
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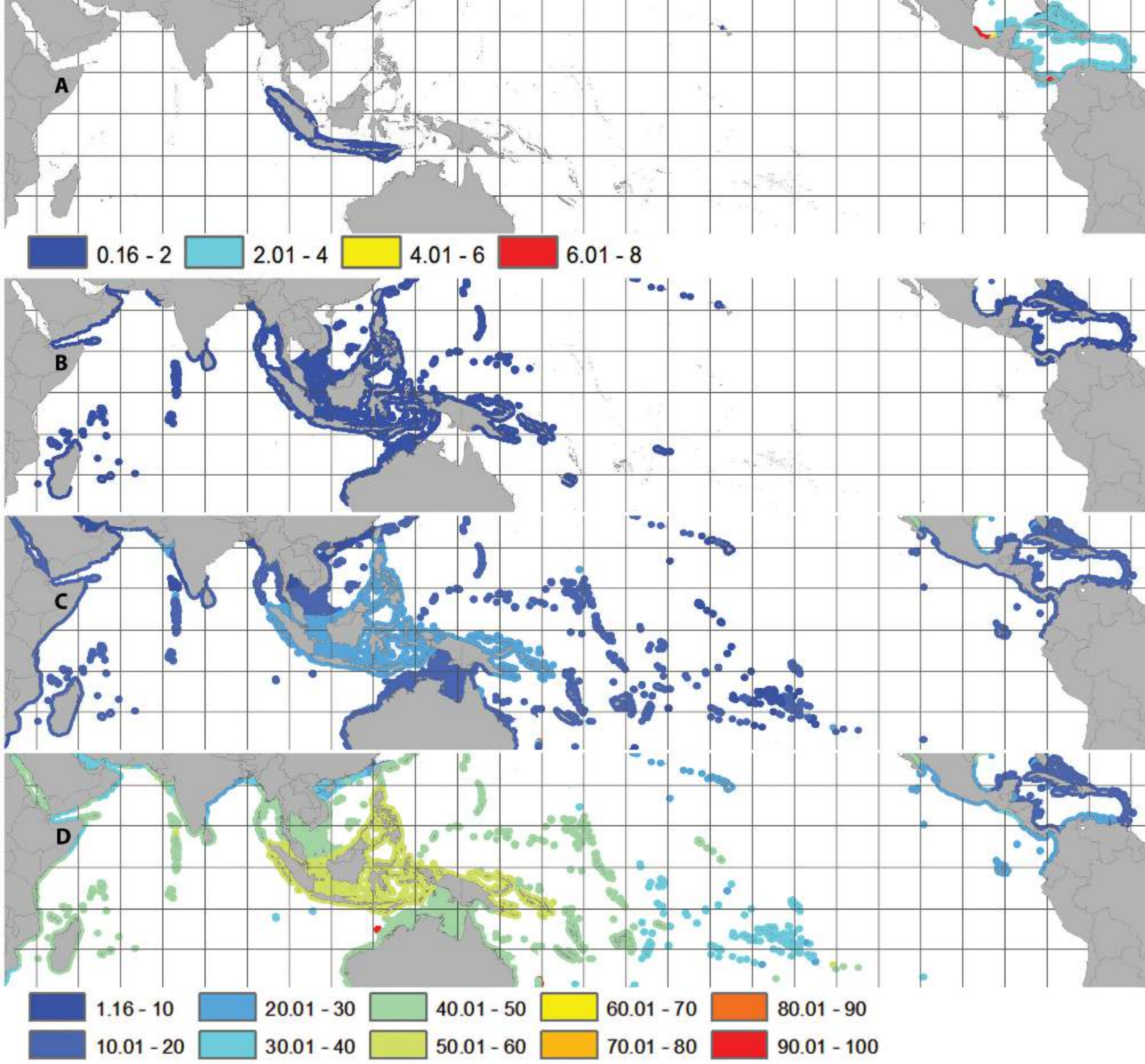
CR
Red List Category


A
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70.01 - 80
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