Reefs at Risk Revisited:
Technical Notes on Modeling Threats to the World's Coral Reefs

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This paper provides additional technical documentation on the modeling methodology of the *Reefs at Risk Revisited* analysis.

Reefs at Risk Project Purpose

Reefs at Risk Revisited brings together data on the world's coral reefs in a global analysis designed to quantify threats and to map where reefs are at greatest risk of degradation or loss. We incorporated more than 50 data sources into the analysis—including data on bathymetry (ocean depth), land cover, population distribution and growth rate, observations of coral bleaching, and location of human infrastructure. These data were consolidated within a geographic information system (GIS), and then used to model several broad categories of threat from human activities, climate change, and ocean acidification. In the absence of complete global information on reef condition, this analysis represents a pragmatic hybrid of monitoring observations and modeled predictions of reef condition.

Human pressures on coral reefs are categorized throughout the report as either "local" or "global" in origin. These categories are used to distinguish between threats that involve human activities near reefs that have a direct and relatively localized impact, versus threats that affect the reef environment indirectly through the cumulative impact of human activities on the global climate and ocean chemistry.

Local threats addressed in this analysis are:
- Coastal development
- Watershed-based pollution
- Marine-based pollution and damage
- Overfishing and destructive fishing.

Global threats addressed are:
- Thermal stress (warming sea temperatures, which can induce coral bleaching)
- Ocean acidification (driven by increased CO_2, which can reduce coral growth rates).

This is the first *Reefs at Risk* project to incorporate data on these global-level threats. These data allow us not only to estimate current and imminent reef condition, but also to project trends well into the future. For the global-level threats, we did not develop new models, but rather incorporated existing data from partner organizations on past thermal stress, future thermal stress, and ocean acidification. These data have enabled us to consider impacts to date and the potential future effects of ocean warming and acidification on reefs to 2030 and 2050 using climate projection scenarios.

The *Reefs at Risk Revisited* project delivers results as maps showing the distribution of local and climate-related threats to coral reefs. These threats are also consolidated into a single integrated index, which represents their combined impact on mapped reef locations. The analysis draws on a newly compiled global reef map—the most comprehensive and detailed rendition of global coral reef locations created to date—that we compiled into a 500-m resolution grid for modeling.

Through the individual threat indicators and the integrated local threat index, *Reefs at Risk Revisited* estimates the level of human pressure on coral reefs. The index is not a direct measure of reef status or condition; some areas rated as threatened may have already suffered considerable loss or degradation, while others are still healthy. For healthy reefs, a high threat score is a measure of risk, a pointer to likely, even imminent, damage. More typically, however, reefs that are threatened are already showing signs of damage—such as reduced live coral cover, increased algal cover, or reduced species diversity. Even in this case, it is important to realize that reef degradation is not a simple, step-wise change, but rather a cascade of ongoing changes. Even where degradation is already apparent, the models provide a critical reminder that future change will often make matters worse**.**

These technical notes provide a list of the data sources used in the analysis and a detailed description of the modeling methods. Results of the threat analysis are presented in Chapters 4 and 5 of the *Reefs at Risk Revisited* report.

Threat Analysis Method

The four local threats to coral reefs were modeled separately, and later combined in the *Reefs at Risk* integrated local threat index. The modeling approach is an extension and refinement of that used in previous *Reefs at Risk* analyses, and benefited from input from more than 40 coral reef scientists and other experts. For each local threat, sources of stress that could be mapped were identified and combined into a proxy indicator that reflected the degree of threat. These "stressors" include human population density and infrastructure features such as location and size of cities, ports, and hotels, as well as more complex modeled estimates such as sediment inputs from rivers. For each stressor, distance-based rules were developed, such that threat declines as distance from the stressor increases. Thresholds for low, medium, and high threats were developed using available information on observed impacts to coral reefs. Table 1 provides a summary of the approach and limitations for modeling each local threat.

Table 1. *Reefs at Risk Revisited* Analysis Method—Present Threats

Threat	**Analysis Approach**	**Limitations**
Coastal development	• The threat to coral reefs from coastal development was modeled based on size of cities, ports, and airports; size and density of hotels; and coastal population pressure (a combination of population density, growth, and tourism growth).	• Provides a good indicator of relative threat, but is likely to miss some (especially new) tourism locations. • Does not directly capture sewage discharge, but relies on population as a proxy for this threat.
Watershed-based pollution	• The threat to reefs from land-based pollutants was modeled for over 300,000 watersheds (catchments) discharging to coastal waters. • Relative erosion rates were estimated across the landscape based on slope, land cover type, precipitation, and soil type. • Sediment delivery at the river mouth was estimated based on total erosion in the watershed, adjusted for the sediment delivery ratio (based on watershed size) and sediment trapping by dams and mangroves. • Sediment plume dispersion was modeled using a linear decay rate from the river mouth and was calibrated against actual sediment plumes observed from satellite data.	• The model represents a proxy for sediment, nutrient, and pollutant delivery. • Nutrient delivery to coastal waters is probably underestimated due to a lack of spatial data on crop cultivation and fertilizer application. However, agricultural land is treated as a separate category of land cover, weighted for a higher influence. • The model does not incorporate nutrient and pollutant inputs from industry, or from intensive livestock farming, which can be considerable.
Marine-based pollution and damage	• The indicator of threat from marine-based pollution and damage was based on the size and volume of commercial shipping ports, size and volume of cruise ship ports, intensity of shipping traffic, and the location of oil infrastructure.	• Threat associated with shipping intensity may be underestimated because the data source is based on voluntary ship tracking, and does not include fishing vessels. • The threat model does not account for marine debris (such as plastics), discarded fishing gear, recreational vessels or shipwrecks, due to a lack of global spatial data on these threats.

Overfishing and destructive fishing	• Threats to coral reefs from overfishing were evaluated based on coastal population density and extent of fishing areas (reef and shallow shelf areas), with adjustments to account for the increased demand due to proximity to large populations and market centers. Areas where destructive fishing occurs (with explosives or poisons) were also included, based on observations from monitoring and mapping provided by experts. • The threat estimate was reduced inside marine protected areas that had been rated by experts as having "effective" or "partially effective" management (meaning that a level of management is present that helps to guard ecological integrity).	• Accurate, spatially referenced global data on fishing methods, catches, and number of fishers are not available; therefore, population pressure is used as a proxy for overfishing. • The model fails to capture the targeting of very high value species, which affects most reefs globally, but has fewer ecosystem impacts than wider scale overfishing. • Management effectiveness scores were only available for about 83% of the reefs within marine protected areas.

THREAT: Coastal Development

Poorly managed coastal development can threaten coral reefs through dredging, land reclamation, mining of sand and limestone, dumping of waste, and runoff from construction. Sewage discharge from human settlements increases nutrient and bacteria levels in coastal waters and can have an adverse impacts on reef health. In addition, undermanaged tourism can harm coral reefs, both through poorly planned and implemented construction and through careless recreation on reefs.

Analysis Method

A proxy indicator reflecting the threat to reefs from coastal development was developed based on the location and size of cities, ports, and airports, as well as coastal population density (2007), coastal population growth (2000–05), and tourism growth since 2000.

Table 2. Model Rules Implemented for Coastal Development Threat Analysis

Subject/Stressor	Qualifier	High	Medium	Low
Cities	50,000 to 100,000		0–5 km	Areas not classified as medium or high default to low
	100,000 to 250,000	0–5 km	5–10 km	
	250,000 to 500,000	0–10 km	10–15 km	
	500,000 to 1,000,000	0–15 km	15–20 km	
	Over 1 million	0–20 km	20–30 km	
Ports—Threat distance scaled based on harbor size	Large	0–7 km	7–15 km	
	Medium	0–5 km	5–10 km	
	Small	0–2 km	2–5 km	
	Very Small		0– 3 km	
Airports	Military and civilian		0–8 km	
	Military and civilian with population density < 500 within 10 km		0–4 km	
	Other/small		0–4 km	
	Other/small with population density < 500 within 10 km		0–2 km	
Tourism Centers	Areas with hotels > 100 rooms		0–4 km	
	Areas with hotels > 50 rooms		0–2 km	
Coastal Pop Pressure	Coastal population density (people per sq km) was adjusted by population growth and tourism growth	Up to 18 km	Up to 36 km	

Distance buffers based on the rules shown above are calculated for cities (based on population size), ports (based on harbor size), and airports. A separate indicator of "coastal population pressure" is calculated, which integrates population density (2007), coastal population growth (2000–05), and annual tourism growth. These factors are then combined into a single threat layer reflecting estimated threat to coral reefs from coastal development. This threat layer is overlaid with coral reef locations.

"Coastal Population Pressure" was estimated as follows:

a) Coastal population density within 10 km of the coast was extracted from the 1km resolution LandScan 2007 gridded data set. These population density data were grouped into 10 population density classes, which serve as the basis for the later adjustments. (Class 1 (least impact) are areas with between 100 and 300 people per sq km. Class 10 (highest impact) have over 20,000 people per sq km.)

b) Population growth within smoothed 3 km by 3 km grid cells between 2000 and 2005 was converted to a continuous variable ranging between 1 and 2. 1 reflects areas with no population growth over the period. 2 reflects areas where the population doubled (or more) over that period.

c) Annual growth in tourism (by country) was also included as an adjustment. Areas with significant growth received a factor as high as 1.5, while areas with no growth have a factor of 1.0.

These three elements (population density, population growth, and tourism growth) combine to constitute the population density threat factor. The units were chosen to allow for direct multiplication:

1) PD = Population density (1–10) (factor of 10)
2) PG = Population growth (1.0–2.0) (factor of 2)
3) TG = Tourism growth (1.0–1.5) (factor of 1.5)
4) Scaling factor of 1500 (converts the number to a distance in meters)

These are combined (multiplied) to get a population density pressure indicator (POP_PRESS).

POP_PRESS = PD * PG * TG * 1500

The POP_PRESS factor in each 1 km resolution coastal grid cell is used as the distance (in meters) for the medium threat buffer. For medium threat distances of 4,000 m or greater, half the distance was used to identify areas of high threat.

The components described above were combined into an aggregate coastal development threat estimate.

Data Sets Used in the Analysis of Coastal Development Threat:

- **Population density (2007)**—LandScan (2007)^{TM} High Resolution global Population Data Set copyrighted by UT-Battelle, LLC, operator of Oak Ridge National Laboratory under Contract No. DE-AC05-00OR22725 with the United States Department of Energy.
- **Population growth**—Derived at WRI from LandScan (2007) and Global Rural-Urban Mapping Project (GRUMP), Alpha and Beta Versions: Population Density Grids for 2000 and 2005. GRUMP is a product of the Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI); the World Bank; and Centro Internacional de Agricultura Tropical (CIAT). Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University.
- **Tourism data (tourist arrivals in millions)**—Development Data Group, the World Bank. World Development Indicators 2000 to 2006. Washington, DC: World Bank.
- **City size and location**—Gridded Rural-Urban Mapping Project (GRUMP), 2005 (see above).

- **Ports**—Compiled at WRI from National Geospatial Intelligence Agency, World Port Index, 2005; and GeoNames for select countries. Available at www.geonames.org. Downloaded at WRI, April 2010.
- **Airports**—Compiled at WRI from Digital Aeronautical Fight Information File (DAFIF), a product of the National Geospatial-Intelligence Agency (NGA) and the United States Department of Defense (DOD), 2002; and GeoNames for select countries. Available at www.geonames.org. Downloaded at WRI, April 2010.
- **Hotels and resorts**—Compiled at WRI from HotelbyMaps (www.hotelbymaps.com**)**, 2009, Global hotel locations and size (number of rooms); and GeoNames for select countries. Available at www.geonames.org. Downloaded at WRI, April 2010.

THREAT: Watershed-based Pollution

Agriculture and other land-use activities can have an adverse impact on coral reefs through the increased delivery of sediment and pollution to coastal waters. A watershed-based analysis of sediment and pollution was implemented to develop an estimate of this threat.

Analysis Method

Watersheds are an essential unit for analysis, since they link land areas with their point of discharge to the sea. The analysis of the impact of sediment and pollution on reefs incorporates land cover type, slope, soil characteristics, and precipitation for all land areas, using a simplified version of the Revised Universal Soil Loss Equation (RUSLE) (USDA, 1989) in order to estimate relative erosion rates for each 1 km resolution grid cell. These relative erosion estimates are summarized by watershed. Since not all erosion makes its way to the river mouth, sediment delivery ratios (based on watershed size, dam locations, and mangroves) were applied in order to estimate relative sediment delivery at the river mouth. It should be noted that relative erosion rates and sediment delivery are being used as a proxy for both sediment and pollution delivery.

Sediment plumes from the watershed discharge point were estimated on the basis of relative sediment delivery and distance from the river mouth. Any given location can have contributions from multiple rivers. Model results were calibrated using data on river discharge, sediment delivery, and observations of plumes from MODIS Aqua satellite data. The model for plume dispersion was implemented by a consultant affiliated with the University of California, Santa Barbara, in collaboration with WRI.

Data Sets Used in the Analysis of Watershed-based Pollution:

- **Watershed boundaries**—Based on HydroSHEDS (15 arc-second/500 meter resolution) produced by the World Wildlife Fund in partnership with the U.S. Geological Survey (USGS), the International Centre for Tropical Agriculture (CIAT), The Nature Conservancy (TNC), and the Center for Environmental Systems Research (CESR) of the University of Kassel, Germany. Available at: http://hydrosheds.cr.usgs.gov. For Pacific Islands: derived at WRI from NASA/NGA, Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (3 arc-second/90 meter resolution).
- **Land cover data**—ESA/ESA GlobCover Project, led by MEDIAS-France, 2008 coupled with agricultural areas from Global Land Cover Database (GLC2000), EU Joint Research Centre 2003.
- **Precipitation**—Data are from Berkeley/CIAT/Rainforest CRC (www.WorldClim.org), Average Monthly Precipitation 1950–2000, version 1.4, 2006.
- **Soil porosity**—FAO/IIASA/ISRIC/ISS-CAS/JRC. Harmonized World Soil Database (version 1.0). FAO, Rome, Italy, and IIASA, Laxenburg, Austria, 2008.
- **Dams**—Global Water System Project. Global Reservoir and Dam (GRanD) Database, 2008.
- **Mangroves—** Spalding, M. D., M. Kainuma, and L. Collins. 2010. *World Atlas of Mangroves*. London: Earthscan, with International Society for Mangrove Ecosystems, Food and Agriculture

Organization of the United Nations, UNEP World Conservation Monitoring Centre, United Nations Scientific and Cultural Organisation, and United Nations University.

- **Great Barrier Reef plumes**—Devlin, M., P. Harkness, L. McKinna, and J. Waterhouse. 2010. *Mapping of Risk and Exposure of Great Barrier Reef Ecosystems to Anthropogenic Water Quality: A Review and Synthesis of Current Status*. Report to the Great Barrier Reef Marine Park Authority. Townsville, Australia: Australian Centre for Tropical Freshwater Research.

Model Implementation

Step 1) The first step of the analysis involves estimating likely relative erosion rates for each 1 km resolution grid cell using a modified, simplified form of the Revised Universal Soil Loss Equation (RUSLE) (USDA, 1989).[a] Information on slope, land cover type, precipitation, and soil porosity were integrated to develop an indicator of relative erosion potential (REP) for all land areas.

REP relies upon the following input data sets (see above for full citations of data sets):

- **Percent slope** derived from watershed boundaries.
- **Relative erosion rate** by land cover type. Land cover data were reclassified to relative erosion rates, ranging from 15 (for forest) to 220 for barren land (see Table 3). These relative erosion rates are based on published work involving conversion factors[b] (1 km resolution).
- **Precipitation** for the peak rainfall month (mm) based on the long-term average monthly precipitation. This variable was chosen instead of mean annual precipitation because it is more indicative of the extreme rainfall events and because it captures more of the rainfall variability in the area.
- **Soil porosity.**
- **Dams** (geo-referenced point locations).

Table 3. Land Cover and Associated Relative Erosion Rates

Land Cover Category	Relative Erosion Rate
Water Bodies	5
Closed Forest	15
Open Forest	50
Woody Savanna	60
Grass / Forest Mosaic	80
Regularly flooded areas	80
Grassland / Savanna	100
Crops in mosaic, mostly natural	120
Flooded croplands	130
Crops in mosaic, mostly agriculture	160
Cropland	200
Sparse Vegetation	200
Urban areas	210
Bare areas	220

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[a] See http://www.iwr.msu.edu/rusle/.

[b] Estimates of erosion from different land cover types (Table 3) are based on (a) Berner, E., and R. Berner. 1987. *The Global Water Cycle: Geochemistry and Environment* (pp. 183–189). Yale University: Prentice-Hall International; and (b) Nyborg, Petter A. 1995. *Assessment of Soil Erosion in Sierra Leone*. Washington, DC: World Bank.

REP Equation:

REP (by 1 km grid cell) = percent_slope^0.65 * Landcover_erosion_rate * Precip_mm * porosity / 100,000

Within this analysis, slope is the most influential input variable, even when dampened by the fractional exponent. Land cover, precipitation, and soil porosity follow in order of influence. The most influential areas in the landscape in terms of high relative erosion rates are steep slopes with land converted to agriculture, or bare landscape.

Step 2) Watersheds link land areas with a point of discharge to the sea. We used the Hydrosheds 15 arc-second resolution (~500 m) watershed data for the majority of the global analysis, supplemented with watersheds derived by WRI from 3-arc-second (~90 m) SRTM data for Pacific islands.

Step 3) Two indicators indicative of erosion within the watershed were calculated for each watershed: mean REP for the basin (an indicator of average erosion rates for the basin) (**REP_MEAN),** and total relative erosion within the basin **(REP_SUM).**

Step 4) Dams are important as a sediment trap. An indicator of relative sediment trapped behind a dam was estimated by deriving the catchment area of the dam based on hydrology, including the flow direction, flow accumulation, and dam location within a watershed. **TRAP_AREA** represents the catchment area above the dam. **TRAP_PCT** is the amount of REP behind a dam as a fraction of the REP_SUM for the basin. **REP_SUM_TR** is the total REP for the basin, adjusted by the amount trapped behind the dam.

Step 5) An indicator of relative sediment delivery at the river mouth **(SED_MOUTH)** was estimated by multiplying total relative erosion in the basin (**REP_SUM_TR)** by the sediment delivery ratio **(SDR)** for the basin, which is a function of watershed size. **SDR = 0.41 * basin area (in sq km)**$^{-0.3}$. This factor comes from published research on watersheds in the western Caribbean.[a]

Step 6) Mangroves serve as a natural sediment trap when located along major river channels and at the mouths of rivers. Global mangrove and flow accumulation data were used to adjust sediment delivery within a watershed. Mangrove density was calculated for the area of the watershed containing the top 5% of flow accumulation, which represents the lowest portion of a river at the mouth and varies in size as a function of the watershed size. Sediment delivery **(SED_MOUTH)** was reduced between 0.1% and 18% **(PCT_MNG_TR)** for a watershed, with higher reductions given proportionately to watersheds with a higher density of mangroves in the areas near the river mouths. **SED_MO_MNG** is the sediment delivery estimate at the mouth, after factoring in the adjustment for mangroves.

Step 7) Sediment plumes were estimated using a diffusive cost-based model that allows a linear dispersion around headlands and islands to replicate the dispersion of sediment from the river mouth, but does not account for currents. The model, written in Python, was run within the GRASS GIS system. Relative sediment dispersion was based on the sediment delivery estimates at the river mouth and the distance from the river mouth (see equations below). The model used a decay function that assigns a fixed amount of sediment (in this case, 0.3%) in the initial cell, then removes that amount from the remaining amount to be distributed, and repeats the process until no quantifiable amount of sediment remains. River discharge and sediment delivery measurements for large rivers, as well as MODIS Aqua satellite observations of river plumes, were used to calibrate the decay function.

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[a] Thattai, D., B. Kjerfve, and W.D. Heyman. 2003. "Hydrometeorology and variability of water discharge and sediment load in the inner Gulf of Honduras, Western Caribbean." *Journal of Hydrometeorology* 4: 985-995.

Plume modeling equations:

d: distance in cells from source
S: Sediment load at pour point
D: percent distributed
c_d: valid/null cell ratio at distance d
E_d: amount distributed at distance d
X_d: per-cell distributed at distance d

$$E_d = (S - \sum_{i=0}^{d-1} E_i) \cdot D$$

$$X_d = \frac{E_d}{c_d \cdot d^2}$$

Step 8) Thresholds for level of threat were established based on the estimated relative amount of sediment for a particular grid cell. Plume grid cells with a value of 60 or greater were classified as high threat, cells with a value of 18 to 59 were classified as medium threat, and cells with a value of less than 18 were classified as low threat.

Note: Based on expert opinion received during the external review process, we found that the model likely significantly underestimated sediment input to Australia's Great Barrier Reef. A limitation of using a globally consistent model is that unique physical characteristics of certain areas cannot be captured and accounted for in the modeling process. To facilitate the extensive comment and create a more accurate portrayal of the existing extent of watershed-based pollution for northeastern Australia, we used data from a recently completed scientific study of watershed-based pollution on the Great Barrier Reef to update the Reefs at Risk model. (Citation: Devlin, M., P. Harkness, L. McKinna, and J. Waterhouse. 2010. *Mapping of Risk and Exposure of Great Barrier Reef Ecosystems to Anthropogenic Water Quality: A Review and Synthesis of Current Status*. Report to the Great Barrier Reef Marine Park Authority. Townsville, Australia: Australian Centre for Tropical Freshwater Research). Data for plumes of total suspended solids (TSS) and dissolved inorganic nitrogen (DIN) were added to the existing *Reefs at Risk* watershed-based pollution plumes such that the highest threat level between the two data sets would apply. Plumes from this study were already categorized into low, medium, and high categories, similar to the *Reefs at Risk* model. When integrating this data into the existing watershed model, plume grid cells were categorized as high threat if the threat was high for either TSS or DIN, or both. Plume grid cells were categorized as medium if either TSS or DIN were medium, or both; and categorized as low if both TSS and DIN were low.

THREAT: Marine-based Pollution and Damage

Marine-based activities threaten coral reefs through pollution from ports, oil discharge and spills, ballast and bilge discharge, dumping of garbage, and direct physical impacts from groundings and anchor damage.

Analysis Method

Threats to coral reefs from marine-based pollution and damage were evaluated on the basis of distance to ports stratified by size, intensity of shipping in the area, and distance to oil rigs.

Table 4. Model Rules Implemented for Marine-Based Pollution Threat Analysis

Subject / Stressor	Qualifier	High	Medium	Low
Ports: Threat distance scaled based on shipping volume (2003)	Very Large	0–30 km	30–60 km	Areas not classified as high or medium default to low.
	Large	0–20 km	20–40 km	
	Medium	0–10 km	10–20 km	
	Small	0–5 km	5–10 km	
	Very Small	0 km	0–5 km	
	Tiny	0 km	0–2 km	
Cruise Ports: Threat distance scaled based on expected annual ship visitation and passenger volume (2009–10)	Very Large	0–10 km	10–20 km	
	Large	0–6 km	6–12 km	
	Medium	0–4 km	4–8 km	
	Small	0–2 km	2–5 km	
	Very Small	0 km	0–3 km	
Shipping Intensity	Commercial and Research Vessels		Highest 5 percentile intensity	
Oil Infrastructure	Offshore oil rigs and associated infrastructure		0–4 km	

The above components were combined into an aggregate threat estimate, with coral reefs overlaid and classified.

Data Sets Used in the Analysis of Marine-Based Pollution and Damage:

- **Port volume, commercial shipping activity**, and **oil infrastructure** data provided by Halpern, et al. 2008. "A Global Map of Human Impact on Marine Ecosystems." *Science* 319: 948-952. Original sources are as follows:
  - **Ports**—National Geospatial Intelligence Agency, World Port Index, 2005.
  - **Commercial shipping lanes**—World Meteorological Organization Voluntary Observing Ships Scheme, 2004–05.
  - **Oil infrastructure**—Stable Lights of the World data set prepared by the Defense Meteorological Satellite Program and National Geophysical Data Center (NGDC) within the National Oceanic and Atmospheric Administration (NOAA), 2003; and supplemented with point locations of oil fields, rigs, tanks, pipeline terminals, and pumping stations near coral reefs from GeoNames, Oil infrastructure for select countries. Available at www.geonames.org. Downloaded at WRI, April 2010.
- **Cruise port and visitation intensity** data provided by Clean Cruising (www.cleancruising.com.au) based on compiled booking and departure information for all major cruise lines for July 2009 to June 2010.

THREAT: Overfishing and Destructive Fishing

Overfishing can be a major pressure on coral reef systems, reducing levels of biodiversity and typically resulting in shifts in fish size, abundance, and species composition, altering the ecological balance on the reef. Overfishing occurs as a result of a combination of an overabundance of fishers and overcapitalization of the fishing fleet relative to the available fish stock.

Analysis Method

Threats to coral reefs from overfishing were evaluated on the basis of population density up to 30 km of a coral reef (with emphasis on nearby population), adjusted by the shallow fishing area (both shelf up to 30 m depth and area of coral reefs) within 30 km of the reef location, and adjusted by distance to market centers and large population centers. The analysis was calibrated using data on fish occurrence derived from Reef Check surveys.

Data Sources Used in the Analysis of Overfishing Threat:

- **Population density (2007)**—LandScan (2007)^{TM} High Resolution global Population Data Set copyrighted by UT-Battelle, LLC, operator of Oak Ridge National Laboratory under Contract No. DE-AC05-00OR22725 with the United States Department of Energy.
- **Shelf area**—Derived from GEBCO Digital Atlas published by the British Oceanographic Data Centre on behalf of IOC and IHO, 2003.
- **Coral reef area**—IMaRS/USF, IRD, UNEP-WCMC, The World Fish Center and WRI, 2011. Global coral reefs composite data set compiled from multiple sources by UNEP-WCMC, the World Fish Center, and WRI incorporating products from the Millennium Coral Reef Mapping Project prepared by the Institute for Marine Remote Sensing, University of South Florida (IMaRS/USF), and Institut de Recherche pour le Développement (IRD/UR 128, Centre de Nouméa).
- **Population centers/market centers**—Gridded Rural Urban Mapping Project (GRUMP), Center for International Earth Science Information Network (CIESIN), Columbia University; and Centro Internacional de Agricultura Tropical (CIAT), 2005.

Developing a coastal population adjusted for shelf area:

Our indicator of overfishing pressure is based on human coastal population within 30 km of a coral reef adjusted by the coastal shelf and coral reef area within 30 km of the reef, as well as the additional incentive provided by proximity to markets.

Steps:

1. Human population was identified within 10 km of the coastline, and excluded if above 500 m elevation. (The assumption is that highland populations are much less likely to fish.)
2. This lowland, coastal population was used in estimates of population within 5km, 10km, and 30 km “neighborhoods” around each coral reef. These three data layers were reclassified into categories reflecting the population within the 5, 10, or 30km distance, as follows:

Code	Maximum population size
0	0
1	1–50
2	51–100
3	101–200
4	201–400
5	401–800
6	801–1,600
7	1,601–3,000
8	3,001–6,000
9	6,001–12,000
10	12,001–20,000
11	20,001–40,000
12	40,001–80,000
13	80,001–150,000
14	150,001–300,000
15	300,001–600,000
16	600,001–1,000,000
17	1,000,001–2,000,000
18	2,000,001–4,000,000
19	4,000,001–8,000,000
20	> 8,000,000

3. These categorical classifications of population within 30, 10, and 5 km of a reef were combined by adding the categorical values, as follows: 2 x the 30km value + 1 x the 10km value + 1x the 5 km value. (This approach favors the total population within 30 km of each reef, while acknowledging that much fishing happens much closer to population centers.)

4. Population centers were treated as markets, which provide an additional incentive for fishing. Small markets were defined as those points with a minimum population of 45,000 in 2000 (in GRUMP), supplemented with several important provincial capitals from the ESRI Cities database. Medium-sized markets were defined as those with a minimum population of 200,000 in 2000 in GRUMP. Only points within 12 km of the coast were considered. The “cost distance” from the settlement point was computed, to estimate the distance across water from both small and large markets to a maximum of 300 km from the market center. The following scheme was applied to both the small market and medium market surfaces, and the average was taken. Hence, medium-sized markets exert twice the influence of small markets. Areas within 50 km of a medium sized market, for example, are assigned a 50% increase in pressure; areas within 50 km of a small market will only get a 25% increase. Areas between 250 and 300 km of a medium market get a 5% increase in pressure.

If within (km)	Level of increase based on proximity to medium-sized markets:	Level of increase based on proximity to small-sized markets:
50	50%	25%
100	40%	20%
150	30%	15%
200	20%	10%
250	10%	5%
300	5%	2%

5. An additional adjustment to the coastal population indicator is based on coral reef and shallow shelf area within 30 km available for fishing. Areas with a large shelf and reef area in the vicinity are assumed to have lower fishing pressure per unit area. The population pressure indicator is adjusted downward in these areas.
    a. Both coral reef area and shallow shelf area (to 30 m depth) were summarized for a 30km neighborhood.
    b. The reef and shallow areas were converted to categories (see below) and added together. Areas with a large shallow shelf and large reef area score 12.

Category	Sq km of shelf area within 30 km	Sq km of reef area within 30 km
0	beyond 30 km	beyond 30 km
1	1–50	1–75
2	50–200	75–125
3	200–500	125–200
4	500–1,000	200–300
5	1,000–1,500	300–500
6	over 1,500	over 500

The grade of 0–12 was multiplied by 4.2 to create a range of 0–50. This was used as a percentage reduction applied to the population pressure indicator.

6. The resulting grid ranged in value from 0 to 109. Thresholds were selected for medium and high threat based on comparison to the indicator of overfishing pressure developed from Reef Check data. This indicator includes species reflecting commercial species overfishing and overfishing of herbivorous species. The minimum threshold for medium was 12 and the minimum threshold for high was 24.

7. Finally, an adjustment for regional-scale population-driven demand was added in recognition of the intense pressure in the world's most populated places. All reefs within 200km of half a million or more people currently rated as low threat were reclassified to medium threat, irrespective of distance from local population centers. These variables were additive.

Destructive Fishing

Modeled data for overfishing were combined with data on observed locations of destructive fishing, which includes dynamite (blast) fishing and poison fishing. These data were obtained from the Reef Check survey database (2009), the Tanzania Dynamite Fishing Monitoring Network (2009), and expert opinion from reef managers and local organizations. The destructive fishing layer designates threat of blast or poison fishing based on the frequency of the activity. Moderate (or medium) threat indicates areas where destructive fishing occurs on about a monthly basis, while Severe (or high) threat indicates areas where the destructive fishing occurs weekly or more frequently. Destructive fishing threat was defined to include a 10 km radius of the observed point location, unless otherwise specified by the expert. These data were combined with the results of the overfishing threat analysis such that the maximum threat score for any grid cell was used.

Management Effectiveness

Well-managed marine protected areas (MPAs) are less threatened by overfishing than unprotected or poorly managed marine areas. We combined several data sources to develop a comprehensive, global map of MPAs in coral reef areas. Our definition of a coral reef MPA includes all sites that overlap with coral reefs on the map (1,712 sites), but also those that are known (from a variety of sources) to contain reefs. To these we added a third category—sites considered likely to contain reefs or reef species. These are the sites with offshore or subtidal areas that occur within 20 km of a coral reef. We included these sites to avoid missing key MPAs due to mapping errors or inaccuracies. For example, we lack accurate boundary information for some MPAs, while reef maps themselves are also missing some areas of reef (notably small isolated patches or coral communities that are too small or deep to be properly mapped). The primary source for this information is the World Database of Protected Areas (WDPA), which provided the majority of sites. In addition, Reef Base provided information on over 600 LMMAs for Pacific Islands and the Phillipines. The Nature Conservancy provided data on over 100 additional sites in Indonesia, while reviewers provided about 50 additional sites. For the analysis, we differentiated the nine different management zones within the Great Barrier Reef Marine Park. The combined areas in each zone are substantial, and each zone offers strikingly different levels of protection. The final total of 2,679 sites is undoubtedly the most comprehensive listing ever produced. While our estimates of total reef area protected are derived from those sites which directly overlap our reef map, it is likely that we have an accurate picture of overall protection as these include all of the larger coral reef MPAs.

To evaluate the effectiveness of these MPAs, we built upon earlier work undertaken in the *Reefs at Risk in the Caribbean* and *Reefs at Risk in Southeast Asia* analyses, and used input from a number of other experts and a literature review. Sites were scored using a 3-point scale as follows: 1) Effective, where the site is managed sufficiently well that *in situ* threats are not undermining natural ecosystem function; 2) Partially effective, where the site is managed such that *in situ* threats are significantly lower than adjacent non-managed sites, but there may still be some detrimental effects on ecosystem function; and 3) Ineffective, where the site is unmanaged, or management is insufficient to reduce *in situ* threats in any meaningful way. Given that the sampling drew on field knowledge by regional experts rather than field practitioners, there is likely to be a sampling bias toward better-known sites, with perhaps a higher proportion of effective sites than would be found overall. In total, we obtained scores for 1,147 MPAs. Of these rated sites, 167 were rated as “effectively managed,” 436 were rated as “partially effective,” and 544 were rated as “not effective.”

The overfishing threat layer was then modified to downgrade threat for areas that lie within the boundaries of effective or partially effective MMAs. Overfishing threat within the boundaries of an effective MMA was downgraded to low threat, while overfishing threat within the boundaries of a partially effective MMA was downgraded one threat level (i.e., high to medium or medium to low).

Global Threats

Unlike the modeling of local threats, the data and models used to evaluate climate and ocean-chemistry-related threats were obtained from external experts. For this work there were two aims: (1) to look at recent ocean warming events that may have already degraded reefs or left them more vulnerable to other threats; and (2) to project the future impacts from ocean warming and acidification over the medium (20 year) and longer (40 year) term. The stressors for these models include data from satellite observations of sea surface temperature, coral bleaching observations, and modeled estimates of future ocean warming and ocean acidification. Input from scientists from each of the major coral reef regions and from climate change experts contributed to the selection of threat thresholds for these threats. Table 5 summarizes the approach and limitations for the examination of global-level threats.

Table 5. *Reefs at Risk Revisited* Analysis Method—Global Threats

Threat	Analysis Approach	Limitations
Past thermal stress	Estimates of thermal stress over the past 10 years (1998 to 2007) combine the following two data layers: 1. Past intense heating events. These were areas known to have had high temperature anomalies (scores of degree heating weeks >8), based on satellite sea surface temperature data provided by NOAA Coral Reef Watch; and 2. Observations of severe bleaching from ReefBase. These point data were buffered to capture nearby bleaching, but modified and effectively reduced by the adjacent presence of low or zero bleaching records from the same year.	• Estimates of bleaching from remote sensing are a measure of the conditions that may cause bleaching based on the weekly temperatures and long-term averages at the location. • Bleaching susceptibility due to other factors (either local or climate-related, such as past climactic variability) was not captured in the model. • There is not always a strong correlation between the sea surface temperature and the observations of known bleaching. However, the latter have only a limited spatial and temporal coverage and so cannot be used alone.
Future thermal stress	• Projected thermal stress in the 2030s and 2050s is based on modeled accumulated degree heating months (DHM) and represents a “business-as-usual” future for greenhouse gas emissions. • The specific indicator used in the model was the frequency (number of years in the decade) that the bleaching threshold is reached at least once. • The frequencies were adjusted to account for historical sea surface temperature variability.	• Data represent a rough approximation of future threat due to thermal stress. • Models provide an approximation of a potential future, but variations in emissions and other factors will undoubtedly influence the outcome. • Besides historical temperature variability, the model does not incorporate other factors that may induce or prevent coral bleaching (for example, local upwelling, species type), or potential adaptation by corals to increased sea temperatures.
Ocean acidification	• The indicator of ocean acidification is the projected saturation level of aragonite, the form of calcium carbonate that corals use to build their skeletons. (As dissolved CO_2 levels increase, the aragonite saturation state decreases, which makes it more difficult for coral to build their skeletons.) Aragonite saturation levels were modeled for the future according to projected atmospheric CO_2 and sea surface temperatures levels for 2030 and 2050 based on a “business-as-usual” scenario.	• Data represent a rough approximation of present and future aragonite saturation levels. • Aragonite saturation is an important factor influencing growth rates, but it is likely not the only factor. Other factors (such as light and water quality) were not included in this model due to a lack of global spatial data.

THREAT: Past Thermal Stress

Thermal stress (i.e., abnormally high ocean temperatures) can cause corals to bleach. This threat has added to the local pressure on many reefs over the past 10 years.

Analysis Method

Past thermal stress on coral reefs between 1998 and 2007 was evaluated using a data set that combines two types of data: bleaching observations and satellite detection of sea surface temperature. While *in situ* bleaching observations are the best indicator of thermal stress on reefs, the observations are too few to reflect the global extent of coral bleaching; therefore, satellite detection of abnormally high ocean temperature was used to fill in the gaps in survey data.

Model Implementation

1) Point observations of "high" (i.e., severe) bleaching between 1998 and 2007 were extracted on a yearly basis from the ReefBase database of bleaching observations. These severe observations were buffered to 20 km to capture bleaching in the vicinity of the point observation *unless* a bleaching observation of "medium," "low," or "unknown" for the same year was recorded nearby. If a lower severity of bleaching was observed within 5 km, 10 km, or 20 km of a "high" bleaching observation, then the buffer was reduced based on proximity to that point. The buffers of "high" observations were ultimately either 6 km, 10 km, 15 km, or 20 km depending on proximity to lower severity bleaching observations in the same year.

2) The Coral Reef Watch program at NOAA provided remote sensing thermal stress data for 1998 to 2007. Their methodology for predicting bleaching from thermal stress is based on abnormally high and sustained sea surface temperatures (SST), measured in "degree heating weeks" (DHW), where one DHW is equal to one week of SST 1° C warmer than the historical average for the warmest month of the year. A DHW of 4 (e.g., 4 weeks of 1° C warmer or 2 weeks of 2° C warmer) may cause widespread coral bleaching and is referred to as a "Bleaching Alert Level 1." A DHW of 8 or more may cause severe bleaching and coral mortality, and is referred to as a "Bleaching Alert Level 2." For this report, Coral Reef Watch used their standard methodology to produce high-resolution DHWs based on the NOAA Pathfinder SST data set. The Pathfinder project provides a long record of quality-controlled SST data at 4km resolution from 1981 to 2009. Coral Reef Watch provided annual maximum DHW values for the *Reefs at Risk Revisited* analysis of past thermal stress.

   The thermal stress data used in this analysis were the locations where a Bleaching Alert Level 2 (DHW ≥ 8) occurred at least once during the period 1998 to 2007. An adjustment was made for the seas of the Middle East to compensate for values thought to be erroneously high (based on expert opinion) due to the heating effect from the land around these enclosed seas. For the Middle East, the threshold used was DHW ≥ 12.

3) The two data layers described above were combined to create a global layer of past thermal stress on coral reefs between 1998 and 2007. The final layer is binary, representing either where severe bleaching likely occurred or likely did not occur during the period of 1998 to 2007.

Data Sets Used in Past Thermal Stress Threat Analysis:

- **Bleaching observations between 1998 and 2007**—ReefBase with UNEP-WCMC Bleaching Data, WorldFish Center, 2009.

- **Thermal stress between 1998 and 2007**—National Oceanic and Atmospheric Administration, Coral Reef Watch, degree heating weeks data (calculated from NOAA's National Oceanographic Data Center Pathfinder Version 5.0 SST dataset), http://coralreefwatch.noaa.gov, 2010.

THREAT: Future Thermal Stress

The rapid increase of greenhouse gases in the atmosphere present a growing threat to coral reefs in the future. Increasing greenhouse gas emissions cause ocean temperatures to rise, which can induce coral bleaching.

Analysis Method

Future thermal stress was evaluated for the decades 2030 and 2050 based on data from models developed and provided by Simon Donner at the University of British Columbia. The indicator of future thermal stress is accumulated degree heating months (DHM) from the Geophysical Fluid Dynamics Laboratory (GFDL) general circulation models CM2.0 and CM2.1 forced with IPCC Scenario A1B. The A1B scenario represents a "business-as-usual" future, where the rate of emissions does not decrease in the future. The two GFDL models have climate sensitivities in the middle of the 2.1°–4.4°C range of the models used in the recent IPCC assessment. The model output varies from 1/3° at the tropics to 1° at higher latitude and longitudes.

The future thermal stress variable represents the frequency (percent of years) that the DHM exceeds the bleaching threshold in each decade. The bleaching threshold is a NOAA Bleaching Alert Level 2 (i.e., a DHM ≥ 2, which is the same as a DHW ≥ 8), which represents conditions that can cause severe coral bleaching and/or mortality. These thresholds were adjusted on a cell-by-cell basis for historical sea surface temperature (SST) variability. The adjusted threshold is the standard deviation of SSTs from the climatological warmest month in each grid cell. For example, if September is on average the warmest month, the threshold is determined from the standard deviation of September temperatures in the satellite record.

The final data layer representing the frequency of severe thermal stress for decades 2030 and 2050 were reclassified into three threat categories. "Low" threat areas will experience Bleaching Alert Level 2 conditions fewer than 25% of years in the decade; "medium" threat areas will experience Bleaching Alert Level 2 conditions 25% to 50% of years in the decade; and "high" threat areas will experience Bleaching Alert Level 2 conditions more than 50% of years in the decade.

Data Sets Used in the Future Thermal Stress Threat Analysis:

- **Future thermal stress for decades 2030 and 2050**—Adapted from Donner, S. 2009. "Coping with Commitment: Projected Thermal Stress on Coral Reefs under Different Future Scenarios." *PLoS ONE* 4: e5712.

THREAT: Ocean Acidification

As increasing atmospheric carbon dioxide (CO_2) is absorbed into the ocean, it causes ocean water to increase in acidity and decreases the availability of concentrations of minerals like calcite and aragonite that corals need to build their skeletons. Ocean acidification causes slower growth of corals and coralline algae and faster dissolution of skeletons, and may lead to a shift toward communities that include fewer reef-building corals.

Analysis Method

The indicator of ocean acidification used in this analysis was aragonite saturation state. As dissolved CO_2 in the ocean increases, the aragonite saturation level decreases. The aragonite saturation state data used in this analysis were provided by Long Cao and Ken Caldeira at the Carnegie Institution Department of Global Ecology at Stanford University. The data are based on a global climate-carbon cycle model that projects aragonite saturation states at various atmospheric CO_2 stabilization levels. We chose stabilization levels for the present, 2030, and 2050 that are slightly more conservative (i.e., optimistic) than an IPCC A1B "business-as-usual" scenario. The CO_2 stabilization level representing the present (or roughly 2005) is 380 ppm; the stabilization level representing 2030 is 450 ppm; and the stabilization level representing 2050 is 500 ppm.

Thresholds for aragonite saturation that indicate suitability for coral growth were based on Guinotte, J. M., R. W. Buddemeier, and J. A. Kleypas. 2003. "Future Coral Reef Habitat Marginality: Temporal and Spatial Effects of Climate Change in the Pacific Basin." *Coral Reefs* 22: 551–558. Areas with an aragonite saturation state of 3.25 or greater were classified as under low threat (which is slightly more conservative than a threshold of 3.5, considered "adequate" saturation in Guinotte, et al.); areas between 3.0 and 3.25 were classified as medium threat (considered "low saturation" in Guinotte, et al.), and areas of less than 3.0 were classified as high threat (considered "extremely marginal" in Guinotte, et al.). Furthermore, the CO_2 stabilization levels of 450 ppm and 500 ppm chosen to represent 2030 and 2050, respectively, are slightly more conservative than an IPCC A1B "business-as-usual" emissions scenario in that these CO_2 stabilization levels assume some reduction in global emissions between 2030 and 2050.

Data Sets Used in the Ocean Acidification Threat Analysis:

- **Aragonite saturation state for the present, 2030, and 2050**—Adapted from Cao, L. and K. Caldeira. 2008. "Atmospheric CO_2 Stabilization and Ocean Acidification." *Geophysical Research Letters* 35: L19609.

Integrated Threat—The Reefs at Risk Threat Indices

To develop a single broad measure of threat, we combined the four individual threats to coral reefs into a single integrated local threat index that reflects their cumulative impact on reef ecosystems. We then adjusted this index by increasing threat levels to account for the impacts of past thermal stress. Finally, we combined the local threats with modeled future estimates of thermal stress and ocean acidification to predict threat to reefs in 2030 and 2050.

a) **Integrated Local Threat Index.** This index was developed by summing the four individual local threats, where reefs were categorized into low (0), medium (1), or high (2) in each case. The summed threats were then categorized into the index as follows:[a]

    - ***Low:***[b] 0 points (scored low for all local threats)
    - ***Medium:*** 1–2 points (scored medium on one or two local threats or high on a single threat)
    - ***High:*** 3–4 points (scored medium on at least three threats, or medium on one threat and high on another threat, or high on two threats)
    - ***Very high:*** 5 points or higher (scored medium or higher on at least three threats, and scored high on at least one).

    The resulting integrated local threat index is the most detailed output from the model and is presented on the map inside the front cover and on regional maps in Chapter 5 of the *Reefs at Risk Revisited* report. (*Maps of individual threats are also available online at www.wri.org/reefs.)*

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[a] Several integration methods were evaluated. This method was chosen because it had the highest correlation with available data on coral condition. The index is slightly more conservative than the previous *Reefs at Risk* reports where a "high" in a single threat would set the integrated local threat index to high overall.

[b] The default threshold is "low" when a coral reef is not threatened by a specific local threat. Thus, all reefs are assigned a threat level. This approach assumes that no reef is beyond the reach of human pressure.

b) **Integrated Local Threat and Past Thermal Stress Index.** Thermal stress can cause coral bleaching even on otherwise healthy reefs. When it coincides with local threats, it serves as a compounding threat. To reflect the pressure of thermal stress and local threats, we combined the integrated local threat index with data indicating locations of severe thermal stress events between 1998 and 2007. Reefs in areas of thermal stress increased in threat by one level.[24] These results are presented in the threat summary (Figures 4.6, Table 4.1, and Figures 5.1–5.6) in chapters 4 and 5 of the *Reefs at Risk Revisited* report.

c) **Integrated Local Threat and Future Climate-Related Threat Index.** We combined the integrated local threat index with modeled projections of ocean acidification and thermal stress in 2030 and 2050 (described in Table 5) to estimate the future threats to coral reefs from climate change. In combining these threats, we weighted local threats more heavily, in light of the greater uncertainty associated with future threats, and the finer resolution of local threat estimates. Reefs are assigned to their threat category from the integrated local threat index as a starting point. Threat is raised one level if reefs are at high threat from either thermal stress or ocean acidification, or if they are at medium threat for both. If reefs are at high threat for both thermal stress and acidification, the threat classification is increased by two levels. In order to portray some nuance in the degree of threat, we have extended the rating scale to include one additional threat category above very high called "critical." The analysis assumes no change in current local threat levels, either due to increased human pressure on reefs or changes in reef-related policies and management. The results of this analysis are presented in Figure 4.9 and Maps 4.2a, b, and c in chapter 4 of the *Reefs at Risk Revisited* report.

Model Limitations

The analysis method is of necessity a simplification of human activities and complex natural processes. The model relies on available data and predicted relationships, but cannot capture all aspects of the dynamic interactions between people, climate, and coral reefs. Climate change science, in particular, is a relatively new field in which the complex interactions between reefs and their changing environment are not yet fully understood.

The threat indicators gauge current and potential risks associated with human activities, climate change, and ocean acidification. A strength of the analysis lies in its use of globally consistent data sets to develop globally consistent indicators of human pressure on coral reefs. We purposefully use a conservative approach to the modeling, where thresholds for threat grades are set at reasonably high levels to both counter any data limitations and avoid exaggerating the estimated threats.

The *Reefs at Risk Revisited* analysis is unique in its global scope and ability to provide a big-picture view of threats to reef condition. However, the model is not perfect, and omissions and other errors in the data are unavoidable. For example, the modeling did not include the potentially compounding threats of coral disease or increased storm intensity because of too many uncertainties in their causes, distribution, and relationships. However, a map of global observations of coral diseases can be found in chapter 3 (Map 3.5) of the *Reefs at Risk Revisited* report.

Monitoring data and expert observations were used, where available, to calibrate the individual threat layers and validate the overall model results. The thresholds chosen to distinguish low, medium, and high threat rely heavily on the knowledge of project collaborators with expertise across regions and aspects of reefs and reef management. Their review of model results also served as our most comprehensive validation of results. (Appendix 2 lists collaborators who contributed data or advised on modeling methods.)

Model Calibration and Validation

The modeling method for each threat component was developed in collaboration with project partners who provided input on threat indicators and preliminary thresholds. Each threat component was then calibrated individually, using available data from surveys and through review by project partners. The calibration guided the selection of thresholds between threat classes that are applied on a global basis. As such, Reefs at Risk indicators (for individual threats and the integrated local threat index) remain globally consistent indicators.

A range of monitoring and assessment data were used to explore patterns of coral reef degradation and calibrate the threat analysis:

- **Reef Check**—Volunteer survey program that has collected biophysical data at reef sites for more than 3,000 survey sites in about 80 countries globally since 1997.
- **Atlantic and Gulf Rapid Reef Assessment (AGRRA)**—Database of 819 survey sites compiled during 39 assessments of the Atlantic region between 1997 and 2004.
- **Global Coral Reef Monitoring Network (GCRMN)**—Regional data on the proportion of coral reef area that experienced bleaching or mortality between 1998 and 2008.
- **Global Environment Monitoring System (GEMS/WATER)**—Data tables of water quality, discharge, and sediment yield statistics for major rivers.
- **MODIS Aqua**—Annual and seasonal composite data of remotely sensed chlorophyll plumes at river mouths.

Expert opinions, combined with the monitoring and assessment data listed above, were used to calibrate the current threat model results. Reef Check and AGRRA data on anthropogenic impacts, coral condition (e.g., live coral cover, algae cover), and species counts were aligned with modeled impacts from overfishing, coastal development, watershed-based pollution, and marine-based pollution. The MODIS Aqua remote sensing data and GEMS/WATER river discharge and sediment yield data were used to calibrate the size of modeled watershed-based pollution plumes. The GCRMN regional bleaching damage and mortality statistics were used to check and calibrate the past thermal stress data layer.