



# Technical Notes on the Reefs at Risk Caribbean Threat Analysis

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This paper provides additional technical notes on the modeling methodology of the *Reefs at Risk in the Caribbean* analysis.

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## ***Reefs at Risk Project Purpose***

The *Reefs at Risk in the Caribbean* project brings together the best available knowledge on the Caribbean region's coral reefs, as a basis for a region-wide analysis using a consistent method. Wide-ranging information is consolidated within a geographic information system (GIS), including data on coral reef locations (maps); pressures on coral reefs (observed threats, pollution, physical impacts); changes in condition; observations of coral bleaching and disease; and information on the management of coral reefs. Once these data are collected and integrated, we review and improve the data sets, although many gaps in the information remain. The project then attempts to fill in some of those gaps through inferential modeling of threats to coral reefs from human activities, including overfishing pressure, coastal development, and pollution and sediment from land-based and marine-based sources. These threat estimates were calibrated using the data available from the compiled sources<sup>1</sup> and have been subjected to several reviews by experts. Changing climate, coral bleaching, and coral disease are also significant threats to Caribbean coral reefs, but we were not able to model such threats using currently available data. The *Reefs at Risk in the Caribbean* report, however, presents current knowledge of the extent of and projections for these threats, within the context of the other pressures facing Caribbean coral reefs.

## ***Threat Analysis Method***

The project's modeling approach involves identifying sources of stress that can be mapped for each threat category. These "stressors" include simple population and infrastructure features, such as population density and location and size of cities, ports, and tourism centers, as well as more complex modeled estimates of riverine inputs. Model rules were developed to build proxy indicators of threat level for these stressors. This process involved the development of distance-based rules by which the threat declines as distance from the stressor increases. For ease of interpretation, these threats are simply divided into "low," "medium," and "high" categories. Substantial input from scientists in the region contributed to the selection of the stressors and threat rules (thresholds) developed, while the threat indicators were further calibrated against available information on observed impacts on coral reefs.

Table 1 summarizes the threat analysis method and limitations for each threat category. The following sections provide details of the threat analysis methodology for coastal development,

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<sup>1</sup> Data from CARICOMP, AGRRA, Reef Check, and REEF were used. See a full description in a later section on model calibration and validation.

watershed-based sources of sediment and pollution, marine-based threats, and overfishing. Details of the model calibration and validation are at the end of this document.

**Table 1. Reefs at Risk Analysis Method**

<b>Threat</b>	<b>Analysis Approach</b>	<b>Limitations</b>
<b>Coastal Development</b>	<p>-Threats to reefs evaluated based on distance from cities, ports, airports, and dive tourism centers. Cities and ports stratified by size.</p> <p>-Coastal population density (2000), coastal population growth (1990–2000), and annual tourism growth combined into indicator of “population pressure” treated as an additional stressor.</p> <p>-Thresholds selected for each stressor based on guidance from project collaborators and observations of local damage from coastal development (including sewage discharge). Stressors aggregated into single map layer.</p> <p>-Management effectiveness included as mitigating factor for threats to reefs inside marine protected areas (MPAs).</p>	<p>-Provides a good indicator of relative threat across the region, but is likely to miss some site-specific threats.</p> <p>-Data sets used are the best available, but limitations regarding accuracy and completeness are inevitable.</p> <p>-In particular, rapid growth of tourism sector makes it difficult to capture the most recent developments.</p>
<b>Watershed-Based Sources of Sediment and Pollution</b>	<p>-Watershed-based analysis links land-based sources of threat with point of discharge to the sea.</p> <p>-Analysis of sediment and pollution threat to coral reefs implemented for more than 3,000 watersheds discharging to the Caribbean.</p> <p>-Relative erosion rates estimated across the landscape, based on slope, land cover type, precipitation (during the month of maximum rainfall), and soil type.<sup>a</sup> Erosion rates summarized by watershed (adjusting for watershed size) to estimate resulting sediment delivery at river mouths.</p> <p>-Sediment plume dispersion estimated using a function in which sediment diminishes as distance from the river mouth increases. Estimated sediment plumes calibrated against observed sediment impacts on selected coral reefs.<sup>b</sup></p>	<p>-Nutrient delivery to coastal waters probably underestimated due to lack of spatial data on crop cultivation and fertilizer application and resulting use of a proxy (sediment delivery) for indirect estimation.<sup>c</sup></p> <p>-Sediment and nutrient delivery from flat agricultural lands probably underestimated, because slope is a very influential variable in estimating relative erosion rates.</p>
<b>Marine-Based Sources of Threat</b>	<p>-Threats to coral reefs from marine-based sources evaluated based on distance to ports, stratified by size; intensity of cruise ship visitation; and distance to oil and gas infrastructure, processing, and pipelines.</p>	<p>-Estimates focus on ships in or near port. Threat associated with marine travel lanes probably underestimated due to lack of sufficiently detailed database on Caribbean shipping lanes.</p>
<b>Overfishing</b>	<p>-Threats to coral reefs evaluated based on coastal population density and shelf area (up to 30 m depth) within 30 km of reef. Analysis calibrated using survey observations of coral reef fish abundance.</p> <p>-Management effectiveness included as mitigating factor for threats to reefs inside marine protected areas (MPAs).</p> <p>-Destructive fishing practices not evaluated, as these are rare in the Caribbean region.</p>	<p>-Local overfishing pressure captured in proxy indicator (based on human population per unit of coastal shelf area), due to lack of spatially-specific data on numbers of fishers, landing sites, fishing method/effort, or fish catch from reef fisheries.</p> <p>-Indicator reflects fishing within 30 km of shore. Impacts of larger-scale commercial fishing pressure, illegal fishing, or movement of fleets not included in analysis.</p>

**TABLE NOTES:**

a. "Relative Erosion Potential" was estimated at WRI using a simplified version of the *Revised Universal Soil Loss Equation*, United States Department of Agriculture (USDA) Agricultural Research Service (Washington, DC: USDA, 1989).

b. Data from Reef Check surveys and expert opinion from the Reefs at Risk workshop were used to calibrate the estimate of threat from inland sources. Data on percent live coral cover and algal cover from Atlantic and Gulf Rapid Reef Assessment (AGRRA) surveys were used to evaluate results.

c. Although phosphorus is often attached to soil particles, nitrogen is highly soluble and moves more independently of soil particles.

The *Reefs at Risk in the Caribbean* project implemented this analysis method at 1-kilometer resolution for the Wider Caribbean region. In order to better evaluate land-based sources of threat transported via small watersheds in the Eastern Caribbean, the watershed-based analysis was implemented at 270-meter resolution for the Eastern Caribbean sub-region. The methodology described in this document is scale-independent and can be implemented at finer scales, where more detailed data are available.

**THREAT: Coastal Development**

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

**Analysis Method**

Threats to reefs from coastal development were evaluated on the basis of distance to cities, ports, airports, and tourism centers (see Table 2).

**Table 2. Model Rules Implemented for Coastal Development Threat Analysis**

Subject / Stressor	Qualifier	High	Medium	Low
Cities	50,000 to 100,000		0 -10 km	
Cities	Over 100,000	0 -10 km	10 – 20 km	
Cities	Over 1 million	0 - 20 km	20 – 30 km	
Ports	Large	0 - 7 km	7 - 15 km	
Ports	Medium	0 - 5 km	5 - 10 km	
Ports	Small	0 - 2 km	2-5 km	
Ports	Very Small		0 - 3 km	
Airports	Military and Civilian		0 – 8 km	
Airports	Other / small		0 – 4 km	
Tourism Centers	Resorts and dive centers		0 – 4 km	
Coastal Pop Pressure	Coastal Population Density (people per sq km) was adjusted by population growth and tourism growth.	Up to 14 km	Up to 28 km	

In addition, “coastal population pressure” was included in the analysis; it is a function of coastal population density (2000), coastal population growth (1990 – 2000), and annual tourism growth. The management effectiveness of marine protected areas was included as a factor mitigating threat.

“Coastal Population Pressure” was estimated as follows:

- a) Coastal population density within 10 km of the coast was extracted from the 1km resolution Landsat 2001 gridded data set. Because Landsat is a new, modeled data set, we “smoothed” the data using a 3km-on-a-side window to increase the reliability of the estimates. 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 fewer than 100 people per sq km. Class 10 (highest impact) have over 20,000 people per sq km.)
- b) Population growth by administrative district during 1990 – 2000 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. This factor was applied as a further adjustment to the above.
- 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. Tourism adjustment factors are listed in Table 3.

**Table 3. Tourism Adjustment by Country**

Anguilla	1.0	El Salvador	1.0	Netherlands	1.0
Antigua and Barbuda	1.0	Florida Keys	1.3	Netherlands Antilles	1.0
Aruba	1.0	France	1.0	Nicaragua	1.3
Bahamas	1.2	French Guiana	1.0	Panama	1.2
Barbados	1.0	Grenada	1.2	Puerto Rico	1.0
Belize	1.2	Guadeloupe	1.0	Saint Kitts and Nevis	1.0
Bermuda	1.0	Guatemala	1.0	St. Lucia	1.0
Brazil	1.0	Guyana	1.0	Suriname	1.5
British Virgin Island	1.0	Haiti	1.0	Trinidad and Tobago	1.0
Cayman Islands	1.2	Honduras	1.2	Turks and Caicos Isls.	1.0
Colombia	1.0	Jamaica	1.0	US Virgin Islands	1.0
Costa Rica	1.2	Martinique	1.0	United Kingdom	1.0
Cuba	1.2	Mexico	1.5	United States	1.0
Dominica	1.0	Montserrat	1.0	Venezuela	1.0
Dominican Rep	1.2	Navassa Island	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 17.5<sup>1</sup>

These are combined (multiplied) to get a population density pressure indicator (POP\_PRESS).

$$\text{POP\_PRESS} = \text{PD} * \text{PG} * \text{TG} * 17.5$$

The POP\_PRESS factor is used as the distance (in meters) for the medium threat buffer. For medium threat distances of 4000 m or greater, half the distance was used to identify areas of high threat.

The components described in Table 2 were combined into an aggregate coastal development threat estimate (THR\_CD\_RAW). This threat estimate was adjusted for areas that have active coastal management. Specifically, in Marine Protected Areas (MPAs) rated as having full or partial management effectiveness, the coastal development threat level was reduced by one grade (i.e., from high to medium or from medium to low). This reduction results in an estimate of coastal development threat adjusted for management (THR\_CD\_ADJ). Coral reef locations are overlaid and classified by this adjusted threat estimate.

#### **Data Sets Used in Coastal Development Threat Analysis:**

- Cities and towns—Environmental Systems Research Institute (ESRI), “World Cities” and “U.S. Cities,” 2002 and <http://www.world-gazetteer.com>.
- Ports—National Imagery and Mapping Agency (NIMA), “World Port Index,” 2002.
- Airports—NIMA, “VMAP,” 1997.
- Dive tourism centers—United Nations Environment Programme - World Conservation Monitoring Centre (UNEP-WCMC), “Caribbean Dive Centers,” 2002 and M.D. Spalding, *Guide to the Coral Reefs of the Caribbean* (Berkeley, USA: University of California Press, 2004).
- Population density—U.S. Dept. of Energy (DOE), “LandScan,” 2001.
- Population growth (by administrative district)—ESRI, “Administrative Districts,” 2002 and <http://www.ciat.cgiar.org>.
- Annual tourism growth (by country)—Caribbean Tourism Organization (CTO), *Caribbean Tourism Statistical Report 2001–2002*, 2002.

### **THREAT: Sedimentation and Pollution from Inland Sources**

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

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<sup>1</sup> A scaling factor of 17.5 was used to adjust for a variable which was dropped from the final version of the model. Earlier versions included Per Capita GDP to reflect the differential impact from people in poor versus wealthy coastal areas. Several reviewers disputed this assumption (or disagreed on the direction of the relationship) so the factor was deleted from the model. A constant of 17.5 is used in its place. This allows us to treat POP\_PRESS as a distance in meters.

## Analysis Method

Watersheds are an essential unit for analysis, since they link land areas with their point of discharge to the sea. We have implemented a watershed-based analysis of sediment and pollution threat to coral reefs. This analysis 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 (or smaller) grid cell.<sup>1</sup> 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) were applied in order to estimate relative sediment delivery at the river mouth. Sediment plumes were estimated on the basis of relative sediment delivery and distance from each river mouth. Any given location can have contributions from multiple rivers. Model results were calibrated on the basis of available data on river discharge, sediment delivery, and observed impacts on coral reefs. It should be noted that relative erosion rates and sediment delivery are being used as a proxy for both sediment and pollution delivery.

## Model Implementation for the Wider Caribbean

**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).<sup>2</sup> 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 within the wider Caribbean.

### *Data Sets Use in the 1 km resolution analysis for the Wider Caribbean*

REP relies upon four input data sets:

- a) **Percent slope** (derived from USGS HYDRO1K digital elevation model, 2000), (1000-m resolution)
- b) **Relative erosion rate** by land cover type. The Global Land Cover Characteristics (GLCC) Database (USGS / Loveland, 2000) using International Geosphere-Biosphere Program land cover categories was reclassified to relative erosion rates, ranging from 15 (for forest) to 220 for barren land. (See Table 4 below) These relative erosion rates are based on published work involving conversion factors.<sup>3</sup> (1000-m resolution)
- c) **Precipitation** for the peak rainfall month (mm), based on monthly precipitation surfaces from Global Arc CD (U.S. Army CERL and Center for Remote Sensing and Spatial Analysis (CRSSA), Cook College, Rutgers University, "Global ARC" CD, 1996.) This variable was chosen instead of mean annual precipitation because it is

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<sup>1</sup> The analysis was implemented at 1 km resolution for the entire Caribbean drainage area, stretching from the headwaters of the Mississippi in the north to the headwaters of the Orinoco in the south. The analysis was also implemented at 270 m resolution for the Eastern Caribbean sub-region in order to better capture threat in these small watersheds.

<sup>2</sup> See <http://msa.ars.usda.gov/ms/oxford/nsi/rusle/>.

<sup>3</sup> Estimates of erosion from different land cover types (table 4) are based on Berner, E. and Berner R. 1987. The Global Water Cycle: Geochemistry and Environment, pp. 183-189. Yale University, Prentice-Hall International and Nyborg, Petter A. 1995. Assessment of Soil Erosion in Sierra Leone. The World Bank, Washington.

more indicative of the extreme rainfall events and because it captures more of the rainfall variability in the area. (0.08 DD or 9342-m resolution)

- d) **Soil porosity.** A polygon database on soil type (UN Food and Agriculture Organization (FAO), “World Soil Database,” 1995) provided soil texture and porosity attributes. Soil porosity is the soil characteristic used in calculations because of its relationship with infiltration capacity of the soil. (5000-m resolution)

**Table 4. Land Cover and Associated Relative Erosion Rates**

GLCC_ CODE	LAND COVER CATEGORY	RELATIVE EROSION RATE
19	Water bodies	5
1-5	Forest (All types of closed forest)	15
6	Closed shrub land	45
7	Open shrub land	50
8	Woody savanna	60
11	Permanent wetlands	80
9	Savannas	100
14	Cropland/natural	120
10	Grasslands	125
12	Croplands	200
13	Urban and built-up	210
16	Barren or sparse vegetation	220

*Equation 1:*

$$\text{REP (by 1-km grid cell)} = \text{pct\_slope} * \text{Land\_cov\_eros\_rate} * \text{Precip\_mm} * \text{porosity} / 1,000$$

Within this analysis, slope is the most influential input variable, followed by land cover, precipitation, and soil porosity. The most influential areas in the landscape in terms of high relative erosion rates are steep slopes with land converted to agriculture.

**Step 2)** For the Caribbean-wide analysis, new watershed boundaries were developed for the region using a modified DEM (USGS HYDRO1K, 2000). At WRI the DEM was “filled” and rivers and lakes were “burned” as to improve the accuracy of the watersheds. Rivers are based on HYDRO1k rivers. This resulted in a data set of more than 2,100 watersheds with a minimum size of 35 sq km draining into the Caribbean.

**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)** An indicator of relative sediment delivery at the river mouth was estimated by multiplying total relative erosion in the basin (**REP\_SUM**) by the sediment delivery ratio

(SDR) for the basin, which is a function of watershed size.  $SDR = 0.41 * \text{basin area (in sq km)}^{-0.3}$ . This factor comes from published research on watersheds in the Western Caribbean.<sup>1</sup>

**Step 5)** Model results were calibrated against the limited number of observations of river discharge and sediment delivery for which estimates were available.<sup>2</sup>

**Step 6)** We estimated relative sediment plumes across the wider Caribbean by dispersing sediment from the river mouth using a distance-based degrading function. Relative sediment dispersion is based on the sediment delivery estimates at the river mouth and the distance from the river mouth. We used a 10 percent reduction in sediment per km from the river mouth.

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### **Model Implementation for the Eastern Caribbean sub-region**

A very similar model was implemented at 270-m resolution for the Eastern Caribbean subregion. Some adjustments had to be made to compensate for the change in spatial resolution. For example, percent slope will be higher in smaller grid cells (270 m) than when averaged over 1 km. In order to compensate for these differences and make results more comparable, the higher resolution results were divided by an adjustment factor. In addition, a different, higher resolution land cover data set was used in this analysis, which required a different table for conversion to relative erosion rate.

**Step 1)** The first step of the analysis involves estimating likely relative erosion rates for each 270 m resolution grid cell using a modified, simplified form of the USDA's RUSLE. Information on slope, land cover type, precipitation, and soil porosity was integrated to develop an indicator of relative erosion potential (REP) for all land areas in the Eastern Caribbean sub-region.

#### *Data Sets Use in the 270-m resolution analysis for the Eastern Caribbean*

REP relies upon four input data sets:

- a) **Percent slope** (derived at 270 m from a 3-cell-by-3-cell smoothed version of the 90-m resolution U.S. National Aeronautics and Space Administration (NASA), "Shuttle Radar Topography Mission" (SRTM) provisional data set, 2003.
- b) **Relative erosion rate** by land cover type. The University of Maryland, "Global Percent Tree Cover at a Spatial Resolution of 500 Meters: First Results of the MODIS Vegetation Continuous Fields Algorithm," 2003 was used as the land cover data set for the Eastern Caribbean, since it was the highest-resolution recent data set available

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<sup>1</sup> Thattai, D., B. Kjerfve, and W.D. Heyman, 2002. "Hydrometeorology and variability of water discharge and sediment load in the inner Gulf of Honduras, Western Caribbean," in *Journal of Hydrometeorology*.

<sup>2</sup> River discharge and sediment delivery estimates are required for validation of this model. At the time of publication, we had river discharge estimates for 13 rivers (correlation is .94 with our modeled results) and have sediment deliver estimates for only 5 rivers (correlation is .88 with our results). Further evaluation of the model results was done by expert reviewers.



for the entire subregion that corresponded well with higher resolution, validated data sets and with expert knowledge of land cover for the sub-region. Percent tree cover was re-mapped into relative erosion rates by land cover class using the factors listed in Table 5.<sup>1</sup>

- c) **Precipitation** for the peak rainfall month (mm), based on monthly precipitation surfaces from Global Arc CD.
- d) **Soil porosity**. A polygon database on soil type (FAO, 1995) provided soil texture and porosity attributes.

**Table 5. Percent Tree Cover and Associated Relative Erosion Rates**

Percent Tree Cover in 500 m resolution grid cell	RELATIVE EROSION RATE
Under 10 percent	200
10 – 20	180
20 – 30	160
30 – 40	140
40 – 50	120
50 – 60	100
60 – 70	80
70 – 80	60
80 – 90	40
Over 90 percent	20

*Equation 2:*

$$\text{REP (by 270-m grid cell)} = \text{pct\_slope} * \text{Relative\_erosion\_rate} * \text{Precip\_mm} * \text{porosity} / 1,000 / 4$$

*Note: In this equation, there is a division by 4 in order to adjust for the higher average slopes of the 270-m as compared with - km resolution data.*

**Step 2)** For the Eastern Caribbean analysis, new watershed boundaries were developed from NASA's 90 meter resolution SRTM provisional data set. This process resulted in a data set of more than 1000 watersheds with a minimum size of 1.6 sq km (about 200 grid cells).

**Step 3)** Same as in 1-km analysis.

**Step 4)** Same as in 1-km analysis.

**Step 5)** Model results were calibrated against the limited number of observations of river discharge and sediment delivery for which estimates were available.

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<sup>1</sup> Landsat data classified in 2003 by Jennifer Gebelein, Florida International University (30-m resolution for select islands in the Eastern Caribbean) were used to establish "actual" land cover classes, and supported the conversion factors used in table 5.

**Step 6)** We estimated relative sediment plumes by dispersing sediment from the river mouth using a distance-based degrading function. Relative sediment dispersion is based on the sediment delivery estimates at the river mouth and the distance from the river mouth. We used a 15 percent reduction in sediment per km from the river mouth and a maximum distance of 50-km because of the area's high degree of fetch (openness to the Atlantic Ocean).

## **THREAT: *Marine-based Threats***

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 sources of pollution were evaluated on the basis of distance to ports stratified by size, volume of cruise ship visitation, and distance to oil and gas infrastructure, processing, and pipelines.

**Table 6. Model Rules Implemented**

Subject / Stressor	Qualifier	High	Medium	Low
Ports	Large	0 – 20 km	20 - 50 km	Areas not classified as high or medium default to low.
Ports	Medium	0 - 10 km	10 – 30 km	
Ports	Small	0 – 5 km	5 – 10 km	
Ports	Very Small	0	0 – 5 km	
Cruise Ship Ports of Call	Based on number of calls	Up to 4km	Up to 8km	
Oil Tanks and Wells and Processing centers	All types	0 – 5 km	4 – 5 km	
Pipelines			0-5 km	

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

### **DATA SET USED IN THE ANALYSIS OF MARINE-BASED THREATS**

- † Ports—NIMA, “World Port Index,” 2002.
- † Oil and gas extraction, processing, and pipeline locations—NIMA, “VMAP,” 1997.
- † Cruise ships (volume of visitation)—Information for this data set was derived from the “Choosing Cruising” website <http://www.choosingcruising.co.uk>, and georeferenced at WRI, 2003.

## **THREAT: *Overfishing***

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 within 30km of a reef location, adjusted by the area of shelf (up to 30m depth) within 30 km of the reef location. The analysis was calibrated using observation of coral reef fish abundance from surveys. The management effectiveness of marine protected areas was included as a factor mitigating threat.

### DATA SOURCES USED IN OUR ANALYSIS OF THE OVERFISHING THREAT:

1. Population density—U.S. DOE, “LandScan,” 2001.
2. Shelf area—Developed at WRI on the basis of data from the Danish Hydrological Institute (DHI), “MIKE C-MAP” depth points and data on coastline location—NASA, “SeaWiFS” and NIMA, “VMAP,” 1997.
3. Coral reef fish abundance—Reef Environmental Education Foundation (REEF) website <http://www.reef.org> (accessed 10 February 2003.)
4. Target fish geographic ranges - FAO. 2002. *Living Marine Resources of the Western Central Atlantic, (The)*. FAO Species Identification Guides for fishery purposes. Report GIS data (unpublished).
5. Ecological Units—K.J. Sullivan Sealey and G. Bustamante *Setting geographic priorities for marine conservation in Latin America and the Caribbean* (Arlington, Virginia: The Nature Conservancy, 1999) project GIS data (unpublished)
6. Target species - List of 16 species recommended by Phil Kramer (AGRAA and The Nature Conservancy) and discussed by Reefs at Risk workshop participants.

**Table 7. Target reef species**

Common name	Family	Common name	Family
Nassau Grouper	Serranidae	Yellowtail Snapper	Lutjanidae
Yellow mouth Grouper	Serranidae	Rainbow parrotfish	Scaridae
Yellowfin Grouper	Serranidae	Stoplight parrotfish	Scaridae
Black Grouper	Serranidae	Redfin parrotfish	Scaridae
Tiger Grouper	Serranidae	Redtail parrotfish	Scaridae
Cubera Snapper	Lutjanidae	Queen parrotfish	Scaridae
Mutton Snapper	Lutjanidae	Hogfish	Labridae
Lane Snapper	Lutjanidae	Barracuda	Sphyraenidae

### Developing a coastal population adjusted for shelf area:

Our indicator of overfishing pressure is based on a ratio of human coastal population within 30 km of a coral reef adjusted by the coastal shelf area within 30 km of the reef.

#### Steps:

1. We calculated the shelf area (number of 1 km resolution shelf cells) within 30 kms of each cell;
2. In order to weight resource availability (i.e. factor into the analysis the fact that the same population would exert greater pressure on a smaller-sized available fishing area) we adjusted the population density according to the shelf area (<30 m) within a distance of 30 km. A population cell where there was a high surrounding shelf would be reduced, but a cell where there was no or little shelf would remain the same, with

- values inbetween altered proportionally. Each cell was reclassified to the order of 100% (for lowest shelf area) down to 50% (for highest shelf area);
3. Human population was identified (clipped) within 10 km of the coastline.
  4. The coastal population value was then multiplied by the reclassified shelf layer (a percentage) to give new values for coastal population weighted by shelf area.

Population pressure per unit of shelf area was then calculated as the population (adjusted by shelf) within 30 km of a grid cell, which is our proxy indicator for overfishing threat to coral reefs. Coral reefs were then overlaid and classified using country-level expert opinion/literature as a guide. This threat estimate (THR\_OVF\_RAW) was adjusted for areas that have active coastal management. Specifically, in Marine Protected Areas (MPAs) rated as having full or partial management effectiveness, the overfishing threat level was reduced by one grade (i.e., from high to medium or from medium to low). This reduction results in an estimate of overfishing threat adjusted for management (THR\_OVF\_ADJ). Coral reef locations are then overlaid and classified by this adjusted threat estimate.

### **Calibration**

For each ecological unit, the average number of species observed from the REEF survey sites was calculated for that unit. This average was then divided by the number of species expected to be found, to give a value (when multiplied by 100) of the average percent of target species observed. This data set was then used to calibrate the population density modeling.

### **Validation**

We subsampled the REEF surveys done by experts and for each survey site calculated the average number of our target species observed. We then looked for a reverse correlation between the estimated threat level and the average number of target species observed (i.e. the higher the threat level, the lower the number of target species that would be observed). We found that there was a strong correlation, showing that the higher the threat level, the fewer (on average) target species would be seen.

## ***Integrated Threat – The Reefs at Risk Threat Index***

The four threats described above were integrated into a single index – the Reefs at Risk Threat Index. The Reefs at Risk Threat Index is based on the four individual threats at each location, each rated Low, Medium, or High. For each location, the index is set to the highest value achieved by any individual threat. In areas where three or four of the threats were rated as high, the index is set to very high. In areas where three or four of the threats were rated as medium, the index is set to high in order to reflect cumulative threat.

### ***Model Limitations***

The *Reefs at Risk* analysis approach is 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 and coral reefs. The *Reefs at Risk* analysis provides a series of regionally consistent indicators of human pressure on coral reefs. A strength of the analysis lies in applying a modeling approach to regionally consistent

data sets. However neither the data sets nor the modeling approach are perfect. There are inevitably omissions and other errors in the “input data sets,” such as ports, oil wells, and tourism centers. In addition, the models are limited by the available data sources. For example,

- Because we lack data on number of fishers and coral reef consumption by country, we base our proxy indicator on human population per unit of shelf area.
- In the analysis of land-based sources of sediment and pollution, since we lack spatial data on agricultural crops and fertilizer application, we use sediment as a proxy for both sediment and pollution delivery.
- In the analysis of marine-based threats, because we lack a sufficiently detailed data set on shipping lanes, we could not include this information in the analysis probably resulting in underestimation of the threat from invasive species.
- We were not able to model the threat related to coral bleaching, coral disease, or changes in storm frequency because of the lack of spatial detail in region-wide physical and oceanographic data sets, and some uncertainties, such as the cause of many of the diseases.

Table 1 Summarizes model limitations by threat category.

The *Reefs at Risk in the Caribbean* model results should be regarded as our best attempt to evaluate relative human pressure on Caribbean coral reefs, using currently available sources. It should be noted that these are indicators of pressure, rather than condition. In areas identified as threatened, however, degradation of coral, including reduced live coral cover, increased algal cover, or reduced species diversity, is likely within the next five to ten years.

## ***Model Calibration and Validation***

Data from a range of monitoring and assessment programs were used to explore patterns of degradation, calibrate the threat analysis, and validate the results:

- Caribbean Coastal Productivity Program (CARICOMP)—Coral reef habitat parameters for 27 reef locations across 20 countries (1993 – 2001).
- Atlantic and Gulf Rapid Reef Assessment (AGRRA)—This assessment protocol has been applied at over 730 reef locations in 17 countries across the region between 1997 and 2001, providing a (one-time) snapshot of many indicators of reef condition.
- Reef Check—Volunteer survey program. The protocol has collected social, physical, and biological parameters at 186 sites in 16 countries within the region since 1997.
- The Reef Environmental Education Foundation (REEF) Fish Survey—Data on coral reef fish populations from more than 2,500 locations across the region.

## **Model Calibration**

Reefs at Risk project partners have provided valuable guidance on threat model development and review of model results. This expert opinion, coupled with observations of threats to reefs from Reef Check, was used to calibrate the estimates of threat from coastal development and

watershed-based sediment and pollution. Data on coral reef fish populations from REEF were used to calibrate the estimate of threat from fishing pressure. Because data of sufficient detail were limited, expert opinion during the Reefs at Risk in the Caribbean workshop was the main source for calibration of the estimate of marine-based threat.

### **Threat Analysis Validation and Exploration of Relationships with Indicators from Assessment and Monitoring Programs**

Using results from the 22 CARICOMP sites that have trend information (multiple years of data between 1993 and 2001), the study finds:

- Sites identified as threatened by sediment and pollution from inland sources had substantially higher average levels of decline in hard coral cover (loss of 9 percent in high-threat areas versus loss of 1 percent in low-threat areas).
- Sites identified as threatened (medium or high threat) from coastal development or marine-based pollution had much larger average increases in extent of algal cover than sites rated as low threat. (Increase was about twice as large on threatened sites.)
- Few CARICOMP sites were identified as under low threat from overfishing. Sites identified as under high threat from overfishing pressure had larger average loss of hard coral cover and larger gains in algae cover as compared with medium-threat sites.

We developed several coral condition indicators for the 432 AGRRA assessment sites. These include coral density, ratios of different coral species, extent of hard coral cover, recent and old mortality, and a macroalgal index. Of these indicators, the macroalgal index, old mortality, and hard coral cover had the only statistically significant (95%) relationships with the threat indicators. The three pollution-related threats (coastal development, marine-based threats, and pollution and sediment from inland sources) were combined for this analysis. The findings:

- The average extent of old mortality was higher on sites identified as threatened by pollution (29 percent on high- versus 26 percent on low-threat sites.)
- The average hard coral cover was slightly higher on sites identified as being under low threat from pollution (8.2 percent) than on high-threat sites (7.3 percent).
- The average macroalgal index was higher on sites identified as threatened by pollution (150 on high- versus 123 on low-threat sites).
- In addition, the average macroalgal index was higher on sites identified as threatened by overfishing (170 on high- versus 100 on low-threat sites).