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REPORT

S. O. Rohmann · J. J. Hayes · R. C. Newhall
M. E. Monaco · R. W. Grigg

The area of potential shallow-water tropical and subtropical coral ecosystems in the United States

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Abstract Geographic information system-based analysis was used to derive comprehensive, consistent estimates of the potential area of broadly defined, shallow-water, tropical and subtropical coral ecosystems within the territorial sea and exclusive economic zone of the United States. A coral ecosystem is composed of habitats including unconsolidated sediment, mangrove, hermatypic coral, colonized hardbottom, and submerged vegetation, and major structural zones like reef crest, lagoon, and fore reef. This broad definition reflects the importance of both reef and non-reef habitats and structural zones in the function of these ecosystems. Nautical charts, published by the National Oceanic and Atmospheric Administration's Office of the Coast Survey, provide a consistent source of 10-fathom (~18 m) and 100-fathom (~183 m) depth curve information. The 10-fathom or 100-fathom depth curves are used as surrogates for the potential distribution and extent of shallow-water coral ecosystems in tropical and subtropical U.S. waters. An estimated 36,813 sq·km area has been identified where coral ecosystems can potentially be found in waters less than 10 fathoms (18 m) deep. In addition, an estimated 143,059 sq·km area has been identified where coral ecosystems potentially can be found in U.S. waters at depths down to 100 fathoms (183 m). Results also indicate that previous studies underestimated the extent of potential coral ecosystems for some locations in U.S. tropical and subtropical waters by as much as 100% and that the regional distribution of coral ecosystems has been incorrectly reported.

Keywords Depth curves · Nautical chart · Coral reef distribution · Coral reef management · Coral ecosystem management

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S. O. Rohmann (✉) · J. J. Hayes · R. C. Newhall
Special Projects, National Ocean Service,
National Oceanic and Atmospheric Administration,
1305 East West Highway, Silver Spring, MD 20910, USA
E-mail: steve.rohmann@noaa.gov
Tel.: +1-301-713-3000
Fax: +1-301-713-4384

M. E. Monaco
Biogeography Team, National Ocean Service,
National Oceanic and Atmospheric Administration,
1305 East West Highway, Silver Spring, MD 20910 USA

R. W. Grigg
Department of Oceanography,
School of Ocean and Earth Science and Technology,
University of Hawai'i at Manoa, 1000 Pope Street,
Honolulu, HI 96822, USA

Introduction

Coral ecosystems around the world, including those in the United States, are reported to be in decline. Recent studies indicate that U.S. coral ecosystems, especially those both close to land and in water less than 10 fathoms (18 m) deep, are detrimentally affected by human-based and natural factors, including over-fishing, diseases, bleaching, climate change, urban and tourism-related coastal development, sedimentation, toxic chemical pollution, and ship-groundings (Davidson 2002; Wilkinson 2002; Gardner et al. 2003).

Comprehensive, consistently derived characterizations of the location and potential extent of tropical and subtropical coral ecosystems provide important information as scientists and managers set conservation priorities, establish and manage marine conservation areas, develop watershed-based coastal management plans, characterize the use of these habitats by humans and marine organisms, develop carbon budgets and calcification rates, develop fisheries management strategies, and assess changes in the ecosystems over time (Spalding and Grenfell 1997; Scavia et al. 2002; West and Salm 2003). Several recent articles discuss the state of coral ecosystem decline and the need to evaluate natural and human-induced perturbations at multiple scales (Pandolfi 2002; Bellwood et al. 2004; Lesser 2004).

We define a tropical coral ecosystem to be composed of both habitats and structural zones. Benthic habitats found in a coral ecosystem include unconsolidated sediments (e.g., sand and mud); mangrove; submerged vegetation (e.g., seagrass and algae); hermatypic coral reefs and associated colonized hardbottom habitats (e.g., spur and groove, individual and aggregated patch reefs, and gorgonian-colonized pavement and bedrock); and uncolonized hardbottom (e.g., reef rubble and uncolonized bedrock). Typical structural zones include the reef crest, fore reef, reef flat, and lagoon (FMRI 2000; Kendall et al. 2001; Coyne et al. 2003; NOAA 2003).

Coral ecosystems are found throughout tropical and subtropical oceans between 30°S and 30°N latitudes. The distribution of organisms—corals, seagrasses, algae, sponges, and associated animals—found in coral ecosystems is influenced by nutrient availability, salinity, light, substrate, wave forces, sediment, and temperature (Lalli and Parsons 1995; Hoegh-Guldberg 1999). Coral ecosystems occur where water temperatures are generally between 18°C and 29°C (Glynn 1996; Barnes and Hughes 1999). Many organisms living in a coral ecosystem are photosynthetic; thus, they decrease in abundance with increasing depth as visible light decreases. Generally, a coral ecosystem grows in water less than 30 m deep (Huston 1985; Grigg and Epp 1989), although some coral and algal species that do not rely on photosynthesis are able to grow in water more than 300 m deep (Maragos and Jokiel 1986; Veron 1986). Coral ecosystems generally establish themselves in water that is nutrient-poor, but they are known to occur in nutrient-rich water as well (Lalli and Parsons 1995; Barnes and Hughes 1999).

This article presents the results of the first geographic information system (GIS)-based analysis to derive comprehensive, consistent estimates of the potential area of broadly defined, shallow-water coral ecosystems within the territorial sea and exclusive economic zone of the United States. Other efforts to quantify the potential area of coral ecosystems in tropical and subtropical U.S. waters have either not used GIS analysis to derive the estimates or did not use consistent sources of information or methods of analysis for all areas. This has resulted in inappropriate and, in some cases, erroneous conclusions about the distribution and extent of U.S. coral ecosystems.

We do not compare our results to studies where detailed benthic habitat maps of coral ecosystems have been completed. Because of changes in mapping procedures, difficulties in generating complete maps of many locations, and a lack of availability of detailed maps for all locations in tropical and subtropical U.S. waters, comparisons were not conducted. As more complete detailed benthic habitat maps for more locations are completed, we will compare the results of our characterizations to these maps. Also, our study does not evaluate the extent of biologic endemism, quantify percentages of hermatypic coral or other cover types, compare predator to prey biomass or standing stock ratios, or analyze other characteristics that describe the uniqueness, intrinsic quality, or economic value of U.S. shallow-water coral ecosystems.

Methods

Nautical charts, published by the National Oceanic and Atmospheric Administration's (NOAA's) Office of the Coast Survey, provide a consistent, comprehensive source of depth curve information for all U.S. coastal waters. NOAA's nautical charts are used because they are readily available for all states, territories, commonwealths, and flag islands within the United States. They also employ a consistent methodology to define and ensure the quality of the depth curve information depicted on them.

The customary datum used for depth soundings and curves presented on nautical charts is fathoms rather than meters (1 fathom = 6 ft = 1.83 m). For this analysis, the 10-fathom ($\sim$18 m) and 100-fathom ($\sim$183 m) depth curves were generally used and are discussed in their native datum rather than converting values to meters. All area estimates are presented in square kilometers.

The most recent digital, georeferenced, raster version of each NOAA nautical chart was uploaded into the GIS software, and the 10-fathom, and 100-fathom depth curves were digitized from the screen (Fig. 1). Depth curve polygons for each location were delineated from nautical charts having a mapping scale that maximized the ability to identify the appropriate line work. This minimized, but did not eliminate, having to delineate depth curve lines from charts with different mapping scales. If more than one chart was used to delineate depth curve polygons for a location, adjoining charts with similar mapping scales were used whenever possible.

All the nautical charts were georeferenced to the North American Datum of 1983 (World Geodetic System 1984) and Albers equal area conic projection for Florida or Universal Transverse Mercator for the other locations. All calculations of area were performed using the GIS from the shoreline out to either the 10-fathom or 100-fathom depth curve.

Digital shoreline data were available for every location. Emergent vegetation (e.g., mangrove) is seaward of the land–water interface and is not delineated as part of the digital shoreline used in this analysis. The digital shoreline data for southern Florida came from NOAA's Medium Resolution Digital Vector Shoreline data product (NOAA, on-line) and was updated with finer resolution, digital shoreline data from the benthic habitats of the Florida Keys digital data product (NOAA 1998). The digital shoreline data for the main Hawaiian Islands were provided by the Hawai'i Department of Land and Natural Resources in Honolulu, Hawai'i. The shoreline data were digitized at the charted datum (generally, mean lower low water).

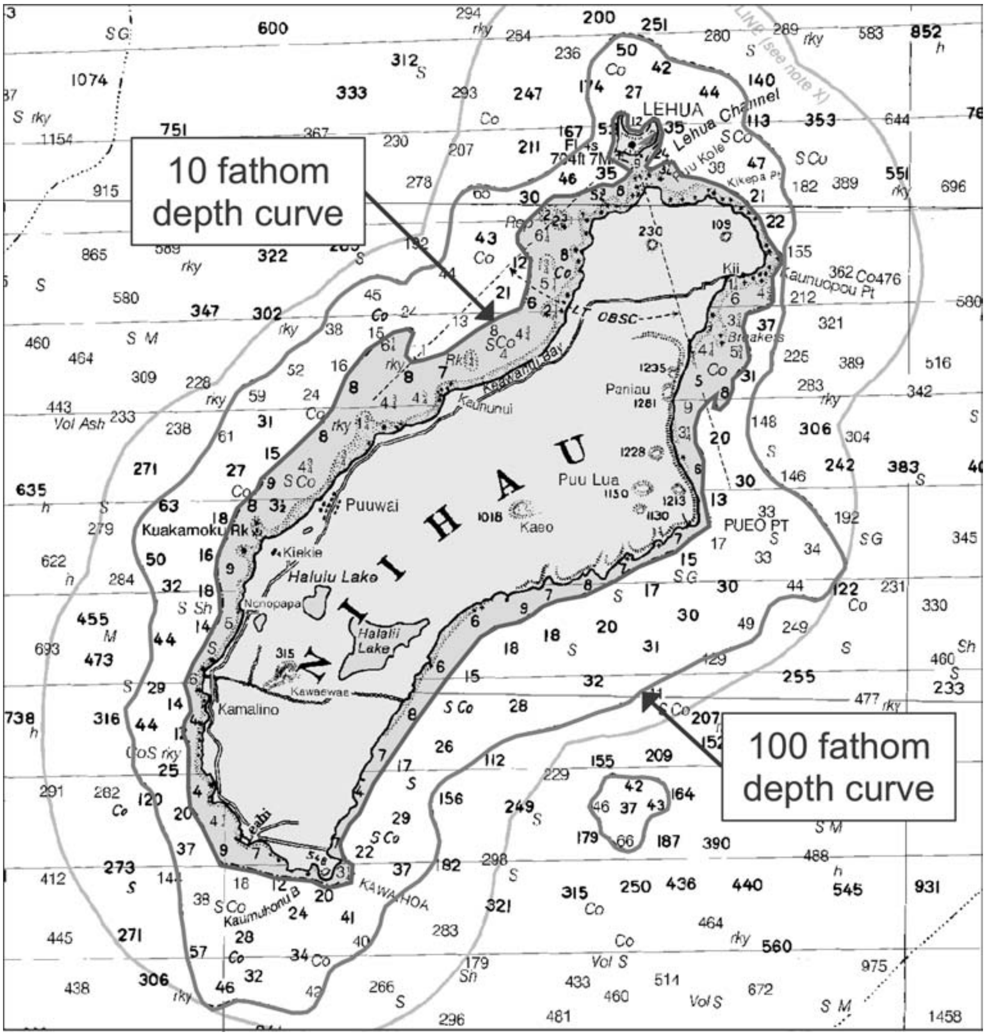

Fig. 1 A portion of NOAA's 1:247,282 scale nautical chart, number 19,380, of Ni'ihau, Hawaii displaying the 10-fathom and 100-fathom depth curves. These depth curves were digitized using a GIS to estimate the area between the shoreline and each depth curve

The digital shoreline data for the islands and atolls of the Northwestern Hawaiian Islands were provided by NOAA's Office of the Coast Survey in Silver Spring, Maryland or NOAA's Coastal Services Center in Charleston, South Carolina. NOAA (2004) provided the digital shoreline data for the islands and atolls of American Samoa, Guam, and the Northern Marianas. The digital shoreline data for the remaining islands and atolls in the U.S. exclusive economic zone were digitized from NOAA nautical charts (Appendix 1). These shoreline data were corrected to the NAD1983 datum, but with the exception of the islands and atolls of the northwestern Hawaiian Islands, were not tide corrected. These digital shoreline data were derived from recently collected source imagery and were more up-to-date and detailed than the shoreline depicted on nautical charts of these locations. As a result, the digital shoreline and the charted shoreline did not coincide exactly. A comparison was performed using both the charted shoreline and digital shoreline for Ofu, Olosega, and Tau, three small islands in American Samoa, to assess the overall discrepancy. The difference in calculated area inside the 10-fathom depth curve and 100-fathom depth curve using shoreline depicted on the nautical chart and the updated digital shoreline for these islands was less than 0.5%. Similar or smaller differences would be expected for larger islands with longer shorelines where both digital and charted shorelines are available for comparison.

Digital data depicting the 10-fathom and 100-fathom curves for the southern Florida region were obtained from the Florida Fish and Wildlife Research Institute (formerly the Florida Marine Research Institute; FMRI, on-line). Gaps found in the FMRI data were filled by digitizing depth curves from nautical charts. Scientists with the Florida Fish and Wildlife Conservation Commission, the Florida Department of Environmental Protection, and the Florida Keys National Marine Sanctuary provided recommendations on how far north along Florida's Gulf Coast (Tarpon Springs, Florida, USA) and Atlantic Coast (Jupiter Inlet, Florida, USA) shallow-water coral ecosystems extend. While exceptions exist (e.g., Grays Reef National Marine Sanctuary and surrounding areas or the banks associated with the Flower Garden Banks National Marine Sanctuary), shallow-water coral ecosystems tend to diminish further north along both the Atlantic and Gulf of Mexico coasts of Florida.

The islands of Puerto Rico, Isla de Desecheo, Isla de Culebra, Isla de Vieques, St. Thomas, and St. John are all within the same continuous 100-fathom curve on nautical charts. To provide separate estimates for Puerto Rico and the U.S. Virgin Islands, the 100-fathom depth curve was split along the 65-degree 10-min meridian, which is the approximate territorial boundary. The 100-fathom depth curve that surrounds St. Thomas and St. John also extends across the international boundary between the U.S. Virgin Islands and the British Virgin Islands. The international boundary depicted on the nautical chart was used to split the 100-fathom depth curve for St. Thomas and St. John.

For the main Hawaiian Islands, the 100-fathom depth curve depicted on the nautical chart encompasses Maui, Moloka'i, Lana'i, and Kaho'olawe. The estimated area inside the 100-fathom depth curve for these four islands is presented as a single value. A 10-fathom depth curve was not available for Pearl and Hermes Atoll in the northwestern Hawaiian Islands. The location of the 10-fathom depth curve for Pearl and Hermes Atoll was approximated by digitizing the maximum extent of seafloor visible in an IKONOS high-resolution satellite image of the atoll. Stumpf et al. (2003) have demonstrated that IKONOS satellite imagery can be used to estimate depth to ~15 m in clear, coastal water.

At this time, no nautical charts are available depicting either depth or extent of shallow-water coral ecosystems for the Freely Associated States (the Republic of Palau, the Republic of the Marshall Islands, and the Federated States of Micronesia). Because the Freely Associated States are not within the U.S. exclusive economic zone and nautical charts are not available, estimates of potential coral ecosystem area have not been made for these areas.

Results

Table 1 presents a summary of the results of the GIS mapping and area analysis of shallow-water depth curves (generally 10-fathom and 100-fathom) for the subtropical and tropical United States. The area calculations for each location have been aggregated to provide values for regions. For example, the eight islands that compose the main Hawaiian Islands have been combined and presented as a single value for that region. Table 1 also presents the results of analyses to determine coral reef area, which were conducted by Hunter (1995), Miller and Crosby (1998), Spalding et al. (2001), and NOAA (2003).

Appendix 1 presents the results, by individual location, of the GIS mapping analysis to calculate the area between the shoreline and 10-fathom or 100-fathom depth curves on NOAA nautical charts. Appendix 1 also provides the chart number, inset chart identification information (if applicable), and scale of the nautical chart from which the 10-fathom or 100-fathom depth curves were digitized. For some locations, the 10-fathom or 100-fathom depth curve was not available, and another charted depth curve was used. The footnotes in Appendix 1 present specific information related to depth curve information encountered on nautical charts and used in this analysis.

An estimated 36,813 sq·km area has been identified where coral ecosystems can potentially be found in U.S. waters less than 10 fathoms deep in the southern Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and the Pacific Ocean. In addition, an estimated 143,059 sq·km area has been identified where coral ecosystems potentially can be found in U.S. waters at depths down to 100 fathoms.

An estimated 30,801 sq·km of potential coral ecosystem area inside the 10-fathom depth curve is found in the southern Florida region. The southern Florida region also has 113,092 sq·km of coral ecosystem area inside the 100-fathom depth curve. This differs from the 325 sq·km of coral reefs reported by Miller and Crosby (1998) and the 1,250 sq·km of hermatypic coral reefs reported by Spalding et al. (2001) for this region.

The U.S. Caribbean (Puerto Rico and the U.S. Virgin Islands) has an estimated 2,646 sq·km of potential coral ecosystems inside the 10-fathom depth curve and 7,632 sq·km of potential coral ecosystems inside the 100-fathom depth curve. In contrast, Miller and Crosby (1998) indicate that 700 sq·km of coral reefs and Spalding et al. (2001) indicate that 680 sq·km of hermatypic coral reefs occur in the U.S. Caribbean.

The main Hawaiian Islands and northwestern Hawaiian Islands have an estimated 1,231 and 1,595 sq·km, of potential coral ecosystem area inside the 10-fathom depth curve, respectively. In comparison, Hunter (1995) reports that 2,535 and 11,554 sq·km of coral reefs occur in these locations. Spalding et al. (2001) report that the combined area of hermatypic coral reefs in these two locations is 1,180 sq·km.

Discussion

The United States is responsible for managing and conserving extensive shallow-water coral ecosystems within its territorial sea and exclusive economic zone. The U.S. territorial sea originates at the baseline of each territory or coastal state and was expanded by U.S. Presidential Proclamation No. 5928 on December 27, 1988, from 3 to 12 nautical miles, the maximum breadth permitted under international law. The U.S. exclusive economic zone, which extends 200 nautical miles from a line coterminous with the seaward boundary (baseline) of each U.S. territory or coastal state, was established on March 10, 1983, by U.S. Presidential Proclamation No. 5030.

Table 1 The area of potential coral ecosystems within the U.S. territorial sea and exclusive economic zone[a]

Location[b]	Calculated area inside 10-fathom depth curve	Calculated area inside 100-fathom depth curve	Estimated coral reef area from Hunter (1995)	Estimated coral reef area from Miller and Crosby (1998)	Estimated coral reef area from Spalding et al. (2001)	Estimated area inside the 10-fathom depth curve NOAA (2003)	Estimated area inside the 100-fathom depth curve NOAA (2003)
Southern Florida[c,d]	30,801	113,092		325	1,250		
Navassa	3	14					
Flower Garden Banks National Marine Sanctuary[e]		164		2			
Grays Reef National Marine Sanctuary[e]		68					
Puerto Rico	2,302	5,506		500	480		
U.S. Virgin Islands	344	2,126		200	200		
Main Hawaiian Islands[f,g]	1,231	6,666	2,535		1,180		
Northwestern Hawaiian Islands[f,g,h]	1,595	13,771	11,554			1,416	13,367
American Samoa[f]	53	464	296		220		
Guam[f]	108	276	179		220		
Northern Marianas[f]	123	476	579		50		
U.S. Pacific Remote Islands and Atolls[f]	253	436	709				
Total	36,813	143,059					

The area inside the 10-fathom or 100-fathom depth curves was derived from nautical charts produced by the National Oceanic and Atmospheric Administration. The other estimates of coral reef or coral ecosystem area were taken from Hunter (1995), Miller and Crosby (1998), Spalding et al. (2001), and NOAA (2003). Area values are in square kilometer

[a] The U.S. territorial sea (and contiguous zone) extends 12 nautical miles from the baseline of each territory or coastal state. The U.S. exclusive economic zone extends 200 nautical miles from a line coterminous with the seaward boundary (baseline) of each territory or coastal state

[b] Appendix 1 provides a list of all locations included in the analysis, the calculated area inside the 10-fathom and 100-fathom depth curves for each location, information about the nautical chart used to derive estimates of coral ecosystem area, and specific footnotes regarding area analyses

[c] Southern Florida extends along the Atlantic Ocean coast of Florida to Jupiter Inlet, Florida and along the Gulf of Mexico coast of Florida to Tarpon Springs, Florida

[d] FMRI (2000) reports that the Florida Keys National Marine Sanctuary and the Dry Tortugas National Park have a combined area of 4,968 sq·km of potential coral ecosystem. This study calculated a combined 10,148 sq·km of potential coral ecosystem area for these two locations

[e] The NOAA nautical chart depicts only the 100-fathom depth curve for this location

[f] Miller and Crosby (1998) use the work of Hunter (1995) as the source of their coral reef area estimates for the U.S. Pacific remote islands and atolls

[g] Spalding et al. (2001) provide a single coral reef area value for both the main Hawaiian and the Northwestern Hawaiian Islands

[h] The area values in this table are improvements to those presented in NOAA (2003). NOAA (2003) used a combination of information digitized from nautical charts, estimates of submerged land area from the U.S. Fish and Wildlife Service, and other sources

Generally, both the 10-fathom and 100-fathom depth curves for locations included in this study lie entirely within the territorial sea. However, exceptions occur, such as Gardner Pinnacles, Maro Reef, Lisianski, and Necker Island, in the northwestern Hawaiian Islands. These areas exhibit vast, shallow-water banks that extend in part or wholly beyond the 12 nm territorial sea boundary.

Within U.S. waters, an estimated area of 36,813 sq·km of potential coral ecosystems for all locations lies inside the 10-fathom depth curve. This area is nearly two times the land area of the state of New Jersey. An estimated 143,059 sq·km of potential coral ecosystems for all locations lie inside the 100-fathom depth curve. This area almost equals the land area of the state of Iowa. The area values presented in Table 1 and Appendix 1 are the result of the first consistent, comparable, GIS-based analysis of the potential extent of U.S. coral ecosystems derived from readily available maps.

Depth curves on NOAA nautical charts are delineated using consistent, cartographic procedures. They are not considered to be exact representations of the location of water 10 or 100 fathoms deep. Rather, depth curves are conservatively estimated depictions of where these water depths are found based on bathymetric soundings shown on the nautical chart. Also, the depth curves on many nautical charts, especially those of the northwestern Hawaiian Islands and U.S. Territories in the Pacific have not been updated in as many as 50 years. NOAA works with other federal, state, and local organizations to gather data that will be used to update and improve the accuracy of the shoreline and bathymetric information, including depth curves, on nautical charts. Incorporating these data will continually improve the accuracy of estimates of coral ecosystem area between the shoreline and those depth curves.

For this analysis, the area inside a depth curve is used as a surrogate for the potential distribution and extent of shallow-water coral ecosystems in the tropical and subtropical United States. Whether or not coral ecosystems actually occur in water 10 or 100 fathoms deep is controlled by many natural and anthropogenic factors. Freshwater inflow, water clarity, light penetration, sedimentation, water temperature, nutrients, or other factors, individually or in combination, affect the spatial distribution of coral ecosystems on the seafloor (Szmant 2002; Leichter et al. 2003; Wolanski et al. 2003; Dulvy et al. 2004).

Although detailed, shallow-water (generally less than 30 m) benthic habitat maps of some U.S. locations are complete (FMRI 2000; Kendall et al. 2001; Coyne et al. 2003; NOAA 2003, 2004; NOAA/NOS 2003) and work is underway to produce similar maps of other U.S. locations, comprehensive, detailed maps of all shallow-water coral ecosystems in the U.S. territorial sea and exclusive economic zone waters are not expected to be completed until 2009. The detailed maps that have been produced include unknown areas because of differences in mapping techniques and remote sensing technologies used, turbidity, clouds, and cloud shadows in the source imagery, and water depth. In addition, there is a paucity of georeferenced seafloor characterization information for remote locations. Because of the limitations of available detailed habitat maps and a lack of detailed habitat maps for the entire tropical and subtropical United States, we did not compare our results to available detailed habitat maps. Our analysis provides consistently derived, comparative estimates of potential coral ecosystem area that can be used until detailed coral ecosystem maps are completed.

Nearly 84% of potential coral ecosystem area inside the 10-fathom depth curve and over 79% of potential coral ecosystem area inside the 100-fathom depth curve for the U.S. locations included in this analysis can be found in southern Florida (Table 2A). The West Florida shelf is a broad, relatively shallow area of unconsolidated sediments and rocky and sandy ledges and outcroppings with a low percentage of coral and is a critical

Table 2 A comparison of the distribution of potential coral ecosystems within the U.S. territorial sea and exclusive economic zone. (A) In this case, Southern Florida extends along the Atlantic Ocean coast of Florida to Jupiter Inlet, Florida and along the Gulf of Mexico coast of Florida to Tarpon Springs, Florida. (B) In this case, Southern Florida is defined as the Florida Keys National Marine Sanctuary, the Tortugas Ecological Reserve, and the Dry Tortugas National Park. These three locations have a combined area of ~10,447 sq·km

Location	Calculated area inside the10-fathom depth curve	Percent of total area associated with this location
A		
Southern Florida	30,801	83.7
Navassa	3	0.008
Puerto Rico	2,302	6.2
U.S. Virgin Islands	344	0.9
Main Hawaiian Islands	1,231	3.3
Northwestern Hawaiian Islands	1,595	4.3
American Samoa	53	0.1
Guam	108	0.3
Northern Marianas	123	0.3
U.S. Pacific Remote Islands and Atolls	253	0.7
B		
Southern Florida	6,626	52.4
Navassa	3	0.02
Puerto Rico	2,302	18.2
U.S. Virgin Islands	344	2.7
Main Hawaiian Islands	1,231	9.7
Northwestern Hawaiian Islands	1,595	12.6
American Samoa	53	0.4
Guam	108	0.9
Northern Marianas	123	1.0
U.S. Pacific Remote Islands and Atolls	253	2.0

The area inside the 10-fathom depth curve was derived from nautical charts produced by the National Oceanic and Atmospheric Administration. Area values are in square kilometer.

habitat for many eastern Gulf of Mexico organisms, while the Florida Keys and Atlantic coast of southern Florida is dominated by the Florida reef tract, which provides the critical habitat for Gulf of Mexico and Atlantic Ocean organisms (Jaap 1984; Causey et al. 2002).

The shallow-water shelf areas found in the U.S. Caribbean, especially around the islands that make up Puerto Rico, have the next largest area (2,646 sq·km) of potential coral ecosystem habitat. A broad, shallow shelf that supports large expanses of hermatypic coral and gorgonian-dominated habitat lies along the southern coast of the island of Puerto Rico and extends eastward to encompass Isla de Vieques and Isla de Culebra. The 100-fathom depth curve for this region encompasses Puerto Rico, Vieques, Culebra, and the islands of St. Thomas and St. John (Appendix 1). The island of St. Croix is physiographically isolated from the other U.S. Caribbean islands. A broad, shallow shelf similar to that found along the southern coast of Puerto Rico lies along the southern and eastern coasts of St. Croix.

The northwestern Hawaiian Islands have an estimated 1,595 sq·km inside the 10-fathom depth curve and 13,771 sq·km inside the 100-fathom depth curve of potential coral ecosystem habitat. The geologic history of these islands and atolls helps to explain the large differences between these two area estimates. The northwestern Hawaiian Islands are a series of small remnant islands or shallow atolls and banks that were formed by shield volcanoes. Over millions of years the volcanoes have subsided and their apexes have eroded to create shallow-water platforms with steep sides that drop off rapidly and eventually reach the abyssal plain (Grigg 1997). For some locations, such as Gardner Pinnacles, only three very small islands still are visible above the ocean surface. A vast platform (estimated to be nearly 2,447 sq·km in area) associated with these three islands lies in water less than 100 fathoms deep (Appendix 1). The geologic history of Necker Island and Nihoa Island resembles Gardner Pinnacles. Other locations have evolved into atolls (e.g., Midway Islands or Kure Atoll) and shallow banks (e.g., Pioneer Bank or St. Rogatien Bank). Eventually, all of the banks, atolls, and islands of the Hawaiian archipelago will disappear as the Pacific Plate—and the Hawaiian Island shield volcanos—is subducted at the Aleutian–Kuril Trench (Grigg 1997).

The main Hawaiian Islands have an estimated 1,231 sq·km inside the 10-fathom depth curve and 6,666 sq·km inside the 100-fathom depth curve of potential coral ecosystem habitat. As with the northwestern Hawaiian Islands, the main Hawaiian Islands were, and in the case of Hawai'i still are being, formed by shield volcanic activity. Narrow fringing or barrier reefs surround most of the coast of the main Hawaiian Islands. As a result, while the islands have ~1,825 km of coastline where coral ecosystems could develop, the area of potential reef area is relatively small. This is in part due to the age of the islands, the structure of the coastline, and the oceanographic processes that influence coral reef formation. Many of the other islands and atolls in the U.S. Pacific display similar coral ecosystem formations to those associated with the main Hawaiian Islands (i.e., islands surrounded by relatively narrow fringing reefs) (Spalding et al. 2001). Johnston Atoll, however, has evolved into a semi-circular emergent reef only on the northern and western margin of the atoll platform (Lobel 2003). Together, these islands (American Samoa, Guam, the Northern Marianas, and the U.S. Pacific Remote Islands and Atolls) have an estimated 537 sq·km inside the 10-fathom depth curve and 1,652 sq·km inside the 100-fathom depth curve of potential coral ecosystem habitat (Table 1).

Several studies have used various techniques to estimate the extent of coral reefs or coral ecosystems in U.S. waters (Hunter 1995; Miller and Crosby 1998; Spalding et al. 2001). Table 1 compares their results to those of our study. Hunter (1995) estimated the potential coral reef area (0–100 m depth) for areas in the U.S. Pacific. For the main Hawaiian Islands, American Samoa, Guam, and the Northern Marianas, Hunter estimated the coral ecosystem area by multiplying an estimate of the percent of the shoreline of each island that was predominantly reef habitat by an estimated reef width. For some islands, a multiplier that approximates the area of coral reef outside the 3 nm state or territory boundary also was included in the calculation. In addition, Hunter estimated the area both inside and outside the 3 nm state boundary based on NOAA nautical charts.

The analysis conducted by Hunter (1995) generally overestimates coral ecosystem area inside the 10-fathom depth curve and underestimates coral ecosystem area inside the 100-fathom depth curve. For example, Hunter reports that, for O'ahu, Hawai'i, the approximate perimeter of the island is 336 km. The reef width multiplier is 2.0 km and ~75% of O'ahu's coast is coral reefs. Thus, Hunter reports that ~504 sq·km of coral reefs surround O'ahu in water to 100 m depth. Our GIS-based analysis indicates that an estimated 375 sq·km of potential coral ecosystem area is inside the 10-fathom depth curve and 944 sq·km of potential coral ecosystem area is inside the 100-fathom depth curve. The method used by Hunter (1995) to estimate coral reef area for the northwestern Hawaiian Islands and the U.S. Pacific remote islands and atolls does not clearly describe how the area estimates inside and outside the 3 nm boundary were calculated from NOAA navigation charts.

The method used in this study results in a reproducible, quantifiable estimate that assumes that the two-dimensional representation of the area of a circle—with the center, or land, cut out—is an acceptable approximation of the three-dimensional area of a coral ecosystem. In this case, the outer boundary of the circle is the 100-fathom depth curve and the inner boundary (cut out portion) of the circle is the 10-fathom depth curve. An analysis was conducted to determine, for several islands, the slope aspect ratio between the 10-fathom and 100-fathom depth curves. The slope aspect ratio was used to quantify the increase in coral ecosystem area when the third dimension—depth—was considered. The area of the 10-fathom and 100-fathom depth curves of Wake Island is 22.9 and 30.5 sq·km, respectively. The area of the 10-fathom and 100-fathom depth curves of O'ahu is 374.8 and 943.9 sq·km, respectively (Appendix 1). Assuming the seafloor between the 10-fathom and 100-fathom depth curves of these islands is essentially smooth, the slope aspect ratios of Wake Island and O'ahu are 1.09/1 and 1.0003/1, respectively. The estimated area of potential coral ecosystems surrounding Wake Island would increase from 7.6 to 8.3 sq·km because of the slope of that island's seafloor. Wake Island has the largest slope aspect ratio (1.09/1) of all islands and atolls included in this study. The estimated area of potential coral ecosystem area surrounding O'ahu would increase from 569.1 to 569.3 sq·km because of the slope of that island's seafloor. This analysis demonstrates that, given the broad, relatively flat seafloor of these islands and the relatively small change in depth (90 fathoms), slope will not greatly increase the area of potential coral ecosystems surrounding islands. Detailed bathymetric data and further analysis will be required to assess the importance of rugosity on estimating coral ecosystem area.

The results of an analysis by Miller and Crosby (1998) to estimate the area of U.S. coral reefs are presented in Table 1. All of the area estimates for the U.S. Pacific presented by Miller and Crosby were excerpted from Hunter (1995) without modification and are not discussed further. Miller and Crosby derived the area estimates for Puerto Rico, the U.S. Virgin Islands, and Texas/Louisiana (i.e., the Flower Garden Banks National Marine Sanctuary). While Miller and Crosby did not provide any explanation for how the values were computed, their analysis for these locations underestimated and, in the case of Puerto Rico, greatly underestimated the area of coral ecosystems. Miller and Crosby (1998) reported that ~500 sq·km of coral reefs occur in Puerto Rico, which is less than 22% of the area we estimated inside the 10-fathom depth curve where coral ecosystems potentially could be found. Some discrepancies will exist between the estimates of coral reef area reported by Miller and Crosby (1998) and the estimates of potential coral ecosystem area presented in this analysis. In addition, Kendall et al. (2003) have mapped in detail ~756 sq·km of coral reefs (defined as colonized hardbottom) around Puerto Rico. Without a better description of their methods, the discrepancies between Miller and Crosby (1998) and these other analyses cannot be explained.

The area estimate reported by Miller and Crosby (1998) for the Florida Keys was excerpted with modification from FMRI (2000). Miller and Crosby computed an area estimate of 325 sq·km for the Florida Keys by adding together the estimated area of two specific types of benthic habitats—Coral-Patch Reef and Coral-Platform Margin Reef—presented in the FMRI report. However, in combination, these two habitat types represent a very small portion (~8%) of the estimated 4,226 sq·km of coral ecosystems that were successfully mapped by FMRI. The remaining 92% of coral ecosystems mapped by FMRI includes seagrass, other hardbottom habitats, bare substrate, and unknown. FMRI (2000) reports that unknown areas occur because the water was either too deep (> 10 m) or too turbid to see seafloor features in the source imagery.

This analysis presents southern Florida as a single geographic region (Table 2A). Most of the hermatypic coral reefs in southern Florida are found in the Florida Keys portion of southern Florida. If the potential coral ecosystem area in the Florida Keys portion—defined by that portion of the 10-fathom depth curve within the boundaries of the Florida Keys National Marine Sanctuary, the Tortugas Ecological Reserve, and the Dry Tortugas National Park—of southern Florida is compared directly to the potential area of coral ecosystems for the other locations in this study, changes occur in both the total area of coral ecosystems in the U.S. territorial sea and exclusive economic zone, and the relative percentages of coral ecosystem area for each location (Table 2B). While the total area where coral ecosystems may be found in the tropical and subtropical U.S. decreases from 36,813 to 12,638 sq·km and the percentages found in each location change, the largest area of potential coral ecosystem area occurs in southern Florida.

Comparing area estimates for specific benthic habitat types for one location (e.g., the Florida Keys) with generalized estimates for another location (e.g., the main Hawaiian Islands) can result in significant misrepresentations of the extent of coral ecosystems in U.S. waters. Moreover, such comparisons may be used to inappropriately demonstrate the geographic importance of some coral ecosystems over others. For example, Miller and Crosby (1998) indicate that the main Hawaiian Islands have about 2,535 sq·km of coral reefs, while the Florida Keys have only 325 sq·km. When conducting an analysis to assess the geographic distribution and extent of coral ecosystems, particular care must be given to ensure that similar information is being compared. Our analysis indicates that about 30,801 sq·km of potential coral ecosystem area occur within the 10-fathom depth curve in southern Florida and about 1,231 sq·km of potential coral ecosystem area occur within the 10-fathom depth curve in the main Hawaiian Islands. The work of Miller and Crosby (1998) has been widely referenced in subsequent analyses and published reports. This has resulted in a critical misunderstanding about the distribution of coral reef area—and coral ecosystem area—in U.S. waters. Rather than having only about 2% of the estimated 16,879 sq·km (Miller and Crosby 1998), our analysis indicates that southern Florida has over 83% of the 36,813 sq·km of potential coral ecosystem area in U.S. territorial sea and exclusive economic zone waters (Table 1).

Another effort to estimate the extent of coral reefs in the U.S. has been completed by Spalding et al. (2001). The *World Atlas of Coral Reefs* is a compendium of the best available estimates of coral reef extent on a global scale. The atlas provides maps and area estimates of hermatypic corals but not coral ecosystems, as presented in this study. Maps in the atlas were derived from either digital or paper source maps that were generally 1:1 million scale, with many source maps at a 1:250,000 scale. Maps at these coarse scales generally would not depict features, such as coral reefs, with the same level of detail as fine scale (e.g., 1:80,000) maps regularly used in our analysis.

Using hermatypic (reef-building) corals as the definition of coral ecosystems, Spalding et al. derived area estimates very differently from those in this study (Table 1). Spalding et al. report that an estimated 220 sq·km of hermatypic coral reefs occur around both American Samoa and Guam. These values are much larger than our estimates for these locations (Table 1). Spalding et al. derived many of their estimates from small-scale (1:1 million scale) charts. These locations generally have very narrow fringing reefs that may be poorly characterized on maps of those scales. Our analysis used larger scale (e.g., 1:80,000 scale) nautical charts that provided finer detail about the location of the 10-fathom and 100-fathom depth curves for those locations (Appendix 1).

Spalding et al. (2001) report that ~1,180 sq·km of hermatypic coral reefs occur in both the main Hawaiian Islands and the northwestern Hawaiian Islands. They also report that 1,250 sq·km of hermatypic coral reefs occur in the Florida Keys region. These values are considerably below coral ecosystem area estimates derived from our analysis (Table 1). Spalding et al. (2001) characterize only one component—hermatypic coral reefs—of the coral ecosystem. In our analysis, we characterized the potential area of seagrass, sand, and the other components of a coral ecosystem as well. As a result, the estimates provided by Spalding et al. (2001) underestimate the extent of coral ecosystems in the main Hawaiian Islands, northwestern Hawaiian Islands, and southern Florida.

While hermatypic coral reefs are important marine habitats, other habitats, such as bare sand or seagrass, also are important to the overall ecology and function of coral ecosystems. Hardbottom coral habitats, mangrove forests, submerged vegetation habitats, and softbottom sand and mud habitats are important as spawning and growth areas within a coral ecosystem (Ogden and Ehrlich 1977; Lindeman 1986; Parrish 1989; Christensen et al. 2003; Kendall et al. 2003; Mumby et al. 2004). The estimates of area presented in Spalding et al. (2001) do not include softbottom area. Also, for our comparison, the area of mangrove from Spalding et al. (2001), if available, was not included in Table 1. Spalding et al. acknowledge that using a broader definition of coral reef would result in significantly higher reef areas than presented in their study. This study recognizes that estimating the extent of coral ecosystems was not the intent of Spalding et al. (2001).

NOAA (2003) nautical charts of the northwestern Hawaiian Islands indicate that ~1,416 sq·km of coral ecosystem area are inside the 10-fathom depth curves and 13,367 sq·km are inside the 100-fathom depth curves (Table 1). The draft NOAA (2003) report presents detailed area estimates for many of the locations in the northwestern Hawaiian Islands that are also listed in Appendix 1. The area estimates presented in the draft report were derived from depth curves on nautical charts, but these data were not digitized using a GIS. They were, in some cases, taken from a different depth curve (e.g., the 5-fathom rather than the 10-fathom depth curve), were not as accurately georeferenced, and were taken from older nautical charts. As a result, the area estimates reported in NOAA (2003) are less consistent, accurate, and reproducible compared to those presented in this analysis.

Conclusions

Knowing the geographic distribution and spatial extent of benthic habitats can lead to a better understanding of the habitats' ecological and economic importance. This information also helps scientists and managers set conservation priorities, establish and manage marine conservation areas, develop watershed-based coastal management plans, characterize the use of these habitats by humans and marine organisms, and monitor and assess changes in the ecosystems over time. The results and findings from these activities will be important as U.S. coral ecosystems come under continued or increased pressure from human and natural factors.

The analysis of potential coral ecosystem extent presented in this study provides the best available, comprehensive, consistently derived, quantitative estimates currently available for the waters of the U.S. territorial sea and exclusive economic zone. This study uses depth curves depicted on nautical charts as surrogates for quantitative analysis of the actual extent of shallow-water coral ecosystems in U.S. waters. This was done to ensure that consistent, comparable estimates are provided for all locations where coral ecosystems occur. Other studies have not been as geographically comprehensive, have not used consistently derived source information (i.e., nautical charts), have not used GIS to develop the estimates, or have not included consistent habitat types among regions in their analyses.

A coral ecosystem is a complex regime where submerged aquatic vegetation (e.g., seagrass or algal beds), bare substrate, hermatypic coral reefs, and other benthic habitats play critical roles in the ecosystem's abiotic and biotic functionality. Studies focused on assessing the distribution and extent of these ecosystems need to characterize all of these habitats. These studies also need to couple information on the distribution and extent of coral ecosystems with information on the spatial and temporal distribution of fishes and invertebrates by life stage and habitat affinities (Monaco et al. 2001; Christensen et al. 2003). By doing so, a better understanding of the ecosystem's interrelated function is achieved. In addition, one can better understand how perturbations in one or more of the specific habitats or organisms that use the habitats may affect the entire ecosystem. This understanding is especially important in locations like the Florida Keys, where extensive alterations to the community structure have been identified (Gardner et al. 2003), and in locations like the relatively pristine northwestern Hawaiian Islands (Friedlander and DeMartini 2002).

Since 1992, efforts have been underway to produce consistently derived, detailed, accurate maps of shallow-water (generally, less than 30 m) coral ecosystems in U.S. waters (FMRI 2000; Kendall et al. 2001; Coyne et al. 2003; NOAA 2003, 2004; NOAA/NOS 2003). As of February 2005, maps have been completed of ~4,968 sq·km of southern Florida, 2,297 sq·km of Puerto Rico, 488 sq·km of the U.S. Virgin Islands, 811 sq·km of the main Hawaiian Islands, 2,360 sq·km of the northwestern Hawaiian Islands, 71 sq·km of American Samoa, 105 sq·km of Guam, and 204 sq·km of the Northern Marianas. As noted earlier, there are many challenges associated with producing these maps, and considerable work, especially in remote U.S. locations, remains. As a result, a comprehensive, detailed comparison of the distribution and extent of shallow-water coral ecosystem habitats in the U.S. may not be available for several years. Until that time, the results of this analysis can provide consistently derived, comparable estimates of the area of potential coral ecosystems in the tropical and subtropical water of the United States.

This analysis estimates the potential extent of all the habitats that form a coral ecosystem. It is the entire ecosystem—not just components of it—that should be characterized, sustainably managed, and protected. This analysis also presents an analytical method for deriving consistent, comparable estimates of the extent of potential coral ecosystem area from available maps. While estimates of the extent of individual habitats, such as hermatypic corals, would be of particular value, many factors—including cost, availability of useful imagery, and challenges associated with producing and validating maps—limit being able to compile such estimates. This analysis provides a valuable and more easily producible surrogate for the detailed habitat estimates. Having better information describing the distribution and extent of shallow-water coral ecosystems provides scientists and managers with a better understanding of the interaction among humans and natural events on these ecosystems, the changes that result, and how both humans and these ecosystems will respond to these changes.

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Disclaimer: The use of trade names in this article does not constitute an endorsement of these products by the National Oceanic and Atmospheric Administration.

Appendix 1

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Table 3 The area from the shoreline to the 10-fathom or 100-fathom depth curve, the chart number, chart inset map identifier, and scale of each NOAA nautical chart used to digitize depth curves. For some locations, 10-fathom and 100-fathom depth curves were not available and other depth curves were digitized. Please refer to the footnotes for details. Area values are in square kilometer

Location	Calculated area inside the 10-fathom depth curve	Calculated area inside the 100-fathom depth curve	NOAA chart used to digitize the 10-fathom depth curve	Inset chart identifier	Chart scale	NOAA chart used to digitize the 100-fathom depth curve	Inset chart identifier	Chart scale
Southern Florida[a]	30,801.5	113,092.0	11400		1:456,394	11400		1:456,394
			11420		1:470,940	11420		1:470,940
			11434		1:180,000	11434		1:180,000
			11450		1:180,000	11450		1:180,000
			11460		1:466,940	11460		1:466,940
			11013		1:1,200,000	11013		1:1,200,000
Navassa[b]	3.0	14.0	26194		1:15,000	26194		1:15,000
Flower Gardens National Marine Sanctuary[c]		164.0				11340		1:458,596
Grays Reef National Marine Sanctuary[c]		68.0				11509		1:80,000
Puerto Rico								
Puerto Rico[d,e]	2,207.6	5,397.0	25640		1:326,856	25640		1:326,856
Isla de Vieques[d,e]			25650		1:100,000	25650		1:100,000
Isla de Culebra[e]	76.0		25650		1:100,000	25650		1:100,000
Isla de Mona and Isla Monito[f]	16.1	93.1	25671		1:100,000	25671		1:100,000
N. central Puerto Rico			25668		1:100,000	25668		1:100,000
Isla Desecheo	2.3	15.8	25671		1:100,000	25671		1:100,000
S. central Puerto Rico			25677		1:100,000	25677		1:100,000
U.S. Virgin Islands								
St. Thomas and St. John[g]	117.8	1,691.7	25641		1:100,000	25641		1:100,000
St. Croix	226.3	433.9	25641		1:100,000	25641		1:100,000
Main Hawaiian Islands								
Hawai'i	193.7	1,053.2	19320		1:250,000	19320		1:250,000
Maui[h]	164.6	3,764.4	19340		1:250,000	19340		1:250,000
Lana'i[h]	46.3		19340		1:250,000	19340		1:250,000
Kaho'olawe[h]	24.9		19340		1:250,000	19340		1:250,000
Moloka'i[h]	161.6		19340		1:250,000	19340		1:250,000
O'ahu	374.8	943.9	19340		1:250,000	19340		1:250,000
Kaua'i	178.8	559.3	19380		1:247,482	19380		1:247,482
Ni'ihau	86.7	274.8	19380		1:247,482	19380		1:247,482
Kaula Rock[c]		70.5	19380		1:247,482	19380		1:247,482
Northwestern Hawaiian Islands								
Bank E of Nihoa Island[c]		146.9				19016		1:663,392
Nihoa Island	5.6	570.8	19016	2,769	1:20,000	19016		1:663,392
Bank SW of Nihoa Island[c]		336.2				19016		1:663,392
Unnamed Bank 1 WNW of Nihoa Island[c]		63.8				19016		1:663,392
Unnamed Bank 2 WNW of Nihoa Island	2.3	5.3	19016		1:663,392	19016		1:663,392
Unnamed Bank 3 WNW of Nihoa Island[c]		66.7				19016		1:663,392
Necker Island	9.1	1,557.2	19016	2,768	1:20,000	19016		1:663,392
Unnamed Bank N of Necker Island	3.2	6.7	19016		1:663,392	19016		1:663,392
Unnamed bank NE of French Frigate Shoals[c]		9.2				19019		1:653,219

Table 3 (Contd.)

Location	Calculated area inside the 10-fathom depth curve	Calculated area inside the 100-fathom depth curve	NOAA chart used to digitize the 10-fathom depth curve	Inset chart identifier	Chart scale	NOAA chart used to digitize the 100-fathom depth curve	Inset chart identifier	Chart scale
French Frigate Shoals	469.4	943.4	19401		1:80,000	19401		1:80,000
Brooks Bank 4–most SE of St. Rogatien Bank[c]		29.4				19019		1:653,219
Brooks Bank 3–more SE of St. Rogatien[c]		142.3				19019		1:653,219
Brooks Bank 2–just SE of St. Rogatien[c]		158.5				19019		1:653,219
Brooks Bank 1–small bank E of St. Rogatien Bank[c]		3.4				19019		1:653,219
Brooks Bank–NW of St. Rogatien Bank[c]		67.8				19019		1:653,219
St. Rogatien Bank[c]		383.1				19019		1:653,219
Gardner Pinnacles	0.7	2,446.6	19421	Inset	1:20,000	19421		1:100,000
Raita Bank	16.0	571.1	19019		1:653,219	19019		1:653,219
Maro Reef	217.5	1,935.3	19441		1:80,000	19441		1:80,000
Laysan Island	26.4	584.5	19442	Inset	1:40,000	19019		1:653,219
Northhampton Seamounts-4 seamounts[c]		404.3				19019		1:653,219
Pioneer Bank[c]		434.6				19022		1:642,271
Lisianski Island and Neva Shoal	215.6	1,246.6	19442		1:40,000	19022		1:642,271
Unnamed Bank NW of Lisianski Island[c]		106.7				19022		1:642,271
Unnamed Bank SSE of Pearl and Hermes Atoll[c]		5.5				19022		1:642,271
Unnamed Bank ESE of Pearl and Hermes Atoll[c]		4.8				19022		1:642,271
Pearl and Hermes Atoll[i]	374.5	816.6				19022		1:642,271
Salmon Bank[c]		163.2				19022		1:642,271
Gambia Shoal[c]		0.5				19480		1:180,000
Ladd Seamount[j]	54.2	144.1	19480		1:180,000	19480		1:180,000
Nero Seamount[j]	25.0	71.8	19480		1:180,000	19480		1:180,000
Midway Islands	85.4	344.1	19480		1:180,000	19480		1:180,000
Kure Atoll[k]	90.2		19481		1:180,000			
American Samoa								
Tutuila Island, Aunu'u Island, and banks	35.8	353.2	83484		1:60,000	83484		1:60,000
Ofu and Olosega[l]	3.6		83484		1:80,000			
Tau[l]	3.8		83484		1:80,000			
Rose Atoll	7.9	91.0	83484		1:80,000	83484		1:80,000
Swains Island	2.4	18.4	83484		1:40,000	83484		1:40,000
Guam								
Guam	91.3	202.8	81048		1:100,000	81048		1:100,000
Galvez Bank[c]		39.4				81048		1:100,000
Santa Rosa Reef	16.4	33.2	81048		1:100,000	81048		1:100,000
Northern Marianas								
Rota	12.1	57.1	81063		1:25,000	81063		1:25,000
Tinian and Agrijan	17.3	102.3	81067		1:75,000	81067		1:75,000
Saipan	56.8	171.8	81067		1:75,000	81067		1:75,000
Farallon de Medinilla[m]	2.4		81086	C	1:45,602			
Anatahan[n]	5.2	19.2	81086	J	1:72,962	81086	J	1:72,962
Sarigan[n]	1.9	12.9	81086	B	1:45,602	81086	B	1:45,602
Guguan[n]	1.1	9.1	81086	H	1:45,602	81086	H	1:45,602
Alamagan[n]	3.2	12.2	81086	G	1:45,602	81086	G	1:45,602
Pagan	11.1	45.1	81092		1:25,475	81092		1:25,475
Agrihan[n]	8.6	24.6	81086	E	1:72,962	81086	E	1:72,962

Table 3 (Contd.)

Location	Calculated area inside the 10-fathom depth curve	Calculated area inside the 100-fathom depth curve	NOAA chart used to digitize the 10-fathom depth curve	Inset chart identifier	Chart scale	NOAA chart used to digitize the 100-fathom depth curve	Inset chart identifier	Chart scale
Asuncion Island	0.5	8.5	81086	D	1:41,275	81086	D	1:41,275
Maug Islands	2.1	8.1	81092		1:26,420	81092		1:26,420
Farallon de Pajaros[n]	0.8	3.8	81086	A	1:36,481	81086	A	1:36,481
Howland Island[k]	3.0		83116		1:15,000			
Baker Island[k]	5.2		83116		1:15,000			
Jarvis Island[k]	3.0		83116		1:15,000			
Johnston Atoll[o]	150.1	240.4	83637		1:50,000			
Kingman Reef[p]	20.9	102.4	83153		1:25,000			
Palmyra Atoll	47.2	63.0	83157		1:10,000	83157		1:10,000
Wake Island[q]	22.9	30.5	81664		1:15,000			

[a] Southern Florida extends along the Atlantic Ocean coast of Florida to Jupiter Inlet, Florida and along the Gulf of Mexico coast of Florida to Tarpon Springs, Florida
[b] The NOAA nautical chart depicts 30- and 200-m depth curves for this location[c] The NOAA nautical chart depicts only the 100-fathom depth curve for this location
[d] The estimated area inside the 10-fathom depth curve for Puerto Rico includes the 10-fathom area surrounding Isla de Vieques
[e] The estimated area inside the 100-fathom depth curve for Puerto Rico includes the 100-fathom area surrounding Isla de Vieques and Isla de Culebra. It also includes the area of the 100-fathom depth curve extending east (toward St. Thomas, U.S. Virgin Islands) to the 65-degree 10-min meridian
[f] The estimated area inside the 10-fathom or 100-fathom depth curves for Isla de Mona and Isla Monito was aggregated
[g] The estimated area inside the 10-fathom or 100-fathom depth curves for St. Thomas and St. John was aggregated. Area estimates for the 10-fathom and 100-fathom depth curves extended NE to the international boundary between the U.S. Virgin Islands and the British Virgin Islands. The 100-fathom depth curve extended west (toward Isla de Culebra and Isla de Vieques) to the 65-degree 10-min meridian
[h] The estimated area of the 100-fathom depth curve for Maui includes the 100-fathom area surrounding Moloka‘i, Kaho‘olawe, Molokini, and Lana‘i. The estimate also includes all of the Penguin Bank
[i] The location of the 10-fathom depth curve was estimated for this location by digitizing the maximum extent of visible seafloor in high-resolution IKONOS satellite imagery
[j] The NOAA nautical chart depicts 50-fathom and 100-fathom depth curves for this location
[k] The NOAA nautical chart depicts only the 20-fathom depth curve for this location
[l] Very little 10-fathom depth curve information and no 100-fathom depth curve information is provided on the NOAA nautical chart for this location. The 10-fathom depth curve was generated by digitizing the charted extent of "reef" depicted on the chart, the small 10-fathom depth curve area depicted on the chart, and using the GIS to generate a 100-m "buffer" around the remaining shoreline for this location
[m] The NOAA nautical chart depicts only the 20-m depth curve for this location
[n] The NOAA nautical chart depicts the 20- and 200-m depth curves for this location
[o] The NOAA nautical chart depicts the entire 10-fathom depth curve but only a portion of the 100-fathom depth curve for this location. The location of the remainder of the 100-fathom depth curve was estimated by digitizing the maximum extent of visible seafloor in high-resolution IKONOS satellite imagery
[p] The NOAA nautical chart depicts the entire 10-fathom depth curve but only a portion of the 100-fathom depth curve for the location. The depth curve was completed by connecting depth soundings on the chart approximately equal to 100-fathoms with the available 100-fathom depth curve lines
[q] The NOAA nautical chart depicts only a portion of the 10-fathom and 100-fathom depth curves for the location. The depth curve was completed by connecting depth soundings on the chart approximately equal to either 10-fathoms or 100-fathoms with the available 10-fathom or 100-fathom depth curve lines

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