Atlas of the Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands

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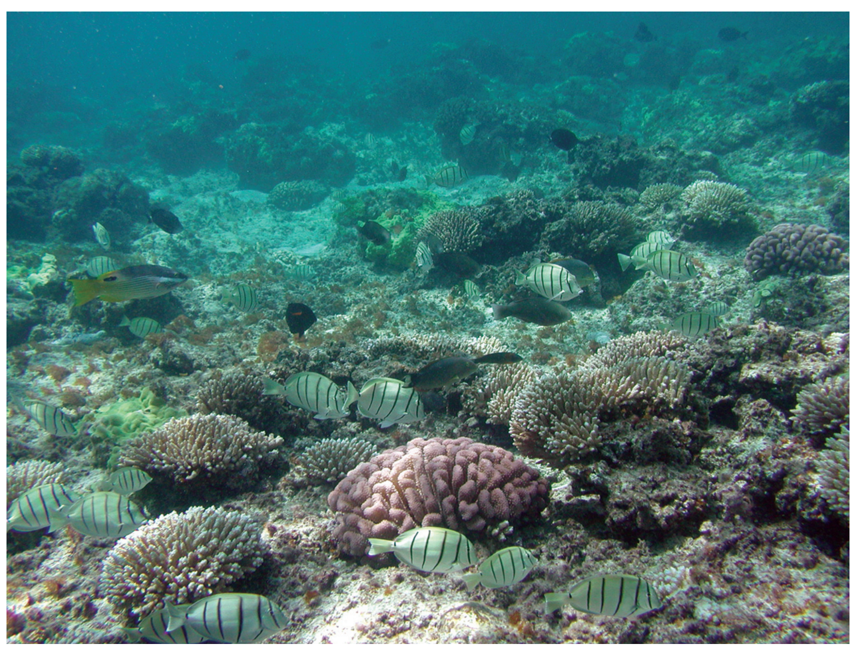

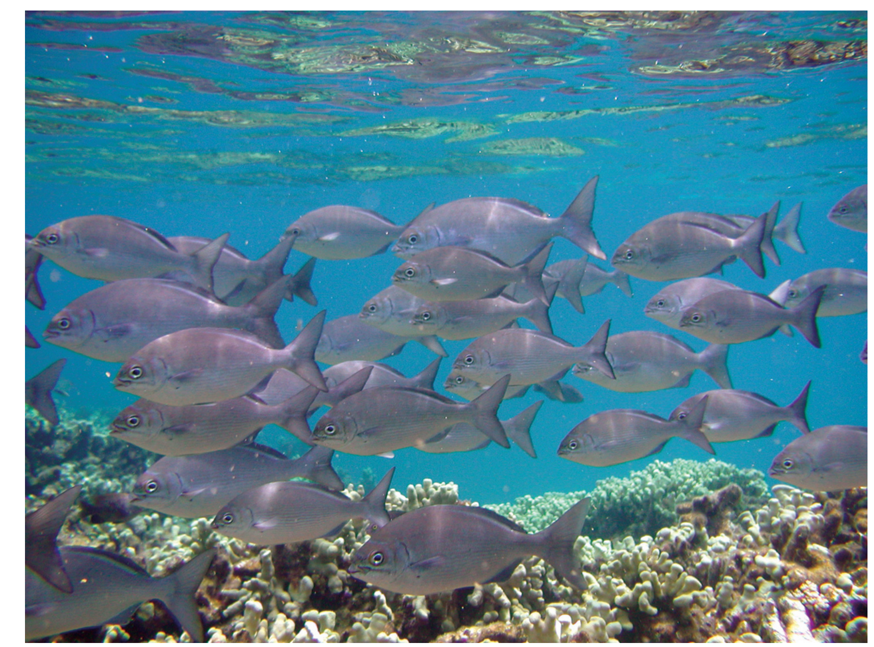

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Disclaimer

This draft Atlas of the Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands has been reviewed by numerous decisionmakers and scientists familiar with the Northwestern Hawaiian Islands region. Although they represent the best available characterizations of the shallow-water coral reef ecosystems of this region, the maps should be considered draft versions.

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Acknowledgements

This draft Atlas of the Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands (NWHI) has been developed by NOAA's National Ocean Service (NOS). Many organizations and individuals contributed to its development.

Richard Stumpf and Kristine Holderied, in NOS's National Centers for Coastal Ocean Science, processed the high-resolution IKONOS satellite imagery, and performed the image analysis to generate the benthic habitat maps and estimated depth maps. Aurelie Shapiro, in NOS's Special Projects Office, processed the moderate-resolution Landsat satellite imagery, generated the maps of the bank areas, and produced the map tiles depicted in the Atlas. Steve Rohmann and John Hayes, in NOS's Special Projects Office, designed and completed the layout of the Atlas. Colleen Labbe in NOS's Communications and Education Division, provided final editorial review of the Atlas.

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NOS held two workshops in Hawaiʻi where experts were provided access to draft maps of the shallow-water coral reef ecosystems of the NWHI. These workshops resulted in important information that was incorporated into the draft maps in this Atlas.

The U.S. Fish and Wildlife Service (FWS), NOAA's National Marine Fisheries Service (NMFS), and the Hawaiʻi Department of Land and Natural Resources (DLNR) provided permits for access to the marine and terrestrial environments of the NWHI. Alex Wegman participated in the mission to ensure no disturbance of any threatened or endangered animals.

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Dan Basta, Robert Smith and many others in NOS contributed to the development of this Atlas. Numerous people who have worked extensively in the NWHI reviewed and provided valuable comments to the draft benthic habitat maps depicted in this Atlas. They also provided valuable comments on this Atlas.

Earth Satellite Corporation of Rockville, Maryland, and GeoData Systems of Fairfax, Virginia, were involved in the processing of the IKONOS and Landsat satellite imagery used as the basis for the maps presented in this Atlas.

The maps presented in this Atlas were derived from IKONOS and Landsat satellite imagery. These derived maps can be provided without redistribution restrictions. For further information about the maps in the Atlas, please contact Richard Stumpf (Richard.Stumpf@noaa.gov; 301.713.3028). For general information about the Atlas, please contact Steve Rohmann (Steve.Rohmann@noaa.gov; 301.713.3000).

All photography in this Atlas was taken during the August-September 2001 GPS and benthic characterization mission to the NWHI. The photography is printed with the permission of the Hawaiian Islands National Wildlife Refuge and the Midway Atoll National Wildlife Refuge, U.S. Fish and Wildlife Service, Department of the Interior. The photograph of a Hawaiian monk seal is printed with the permission of the National Marine Fisheries Service-Honolulu Laboratory.

Uses of this Atlas

The maps in this Atlas provide baseline information about the locations and distributions of the shallow-water (0–30 m) benthic habitats in the NWHI. These maps can be used manually or digitally in comparative analyses with other data sets. Such comparative analyses can reveal patterns and indicate where changes have occurred in the mapped NWHI habitats resulting from natural or anthropogenic influences. In addition to serving as a valuable management tool, these maps are a useful source of information for managers, analysts, and scientists in both the public and private sectors.

All of the maps in this Atlas are oriented with North at the top. All of the maps, except the index maps, are presented with a one (1) kilometer grid overlay. All of the maps also have longitude and latitude tic marks along their peripheries.

Related Products

In addition to this Atlas, a set of two CD-ROMs are available. These CDs contain the digital, high resolution, detailed benthic habitat maps, the digital, aggregated habitat cover maps, and the digital, detailed estimated depth maps in GeoTIFF. These digital maps can be incorporated into a computerized GIS or other software for further use and analysis. The CDs also contain the metadata, associated field benthic characterization data, and other information related to mapping the benthic habitats of the Northwestern Hawaiian Islands.

The data on the CD-ROMs also are available on the Internet at http://biogeo.nos.noaa.gov/projects/pacific/nwhi/data.

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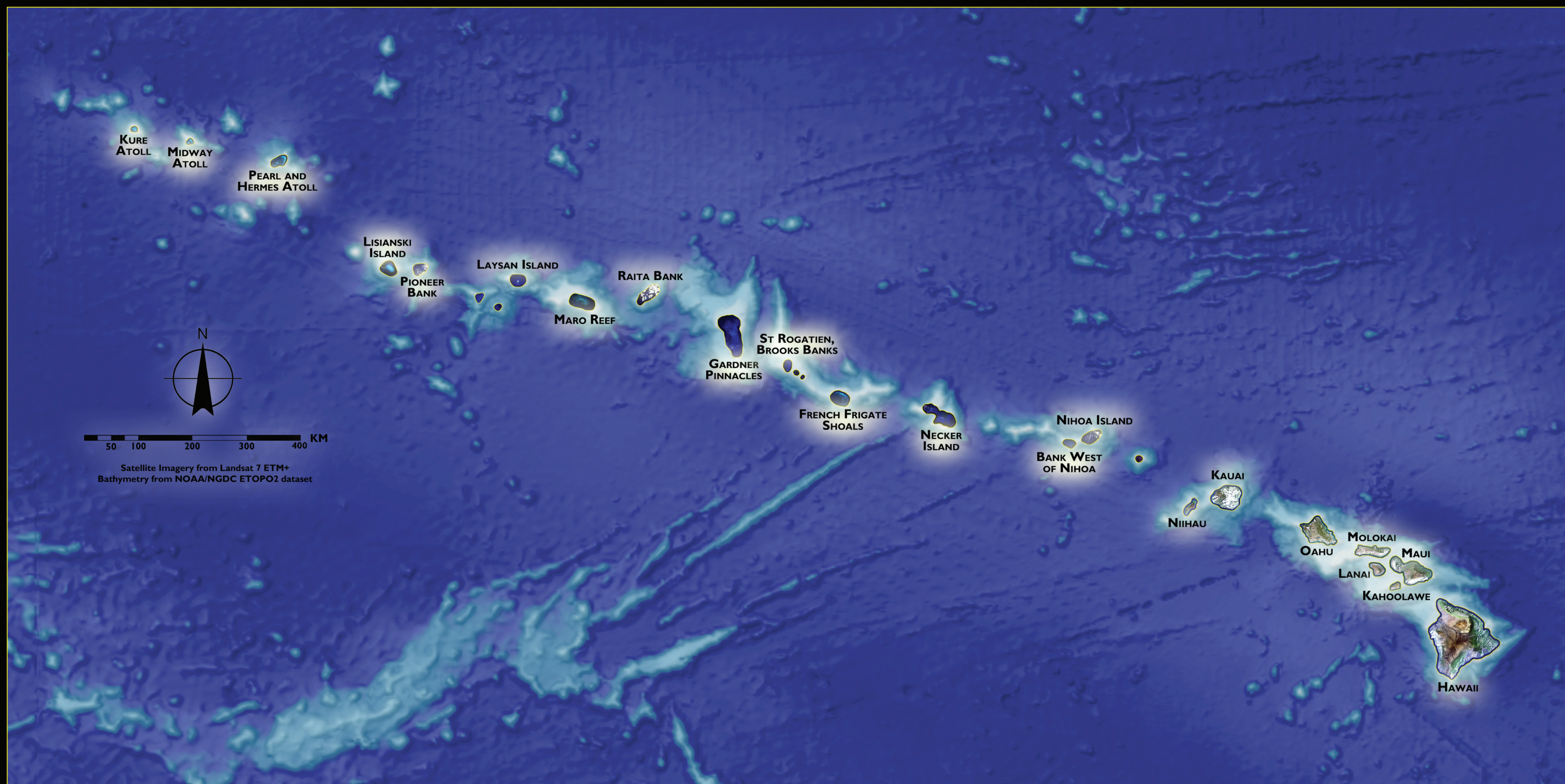

Northwestern Islands and Banks of the Hawaiian Archipelago

Introduction

This draft Atlas of the Shallow-Water Benthic Habitats of the Northwestern Hawaiian Islands (NWHI) has been developed to support research, management, and conservation of critical resources found in the region. In this Atlas, shallow-water refers to water generally less than 30 m deep. Other efforts and technologies will be used to characterize the deeper waters (generally greater than 30 m) of the NWHI. This Atlas also supports the U.S. Coral Reef Task Force's mandate to develop shallow-water coral reef ecosystem maps for all U.S. waters by 2009. For more information on the Task Force, please visit: http://coralreef.gov.
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The Region

The diverse, expansive and pristine shallow-water coral reef ecosystems of the NWHI are unmatched anywhere else on Earth. This ecosystem hosts a distinctive array of marine mammals, fish, sea turtles, birds, and invertebrates, including species that are endemic, rare, threatened, and endangered. Federally protected species include the endangered Hawaiian monk seal and the threatened green sea turtle. The shallow-water coral reefs and lands that support these species provide an amazing geological record of the volcanic and erosive powers that have

Dolphins at Midway Atoll.

shaped this area. These diverse natural resources are complemented by the area's rich historic significance. Numerous artifacts found on Nihoa and Necker Islands in the NWHI establish a close relationship with the Hawaiian culture in the main Hawaiian Islands, as well as to early Polynesian cultures. With its diverse history and significant natural resources, this shallow-water coral reef ecosystem also provides outstanding research opportunities for biologists, oceanographers, archaeologists and historians.

Table 1. Areas mapped in the Northwestern Hawaiian Islands are in square kilometers.

	Habitat area using IKONOS	Bank area mapped using Landsat
Bank E of Nihoa Island	–	91
Nihoa Island	74	487
Bank SW of Nihoa Island	–	247
Necker Island	228	1,314
French Frigate Shoals	418	712
Brooks Bank (most SE of St. Rogatien)	–	11
Brooks Bank (more SE of St. Rogatien)	–	65
Brooks Bank (just SE of St. Rogatien)	–	85
St. Rogatien Bank	–	315
Gardner Pinnacles	–	1,934
Raita Bank	–	503
Maro Reef	519	1,648
Laysan Island	127	453
Northhampton Seamounts (2)	–	269
Pioneer Bank	–	369
Lisianski Island	439	972
Pearl and Hermes Atoll	392	–
Gambia Shoal (nautical chart 10 fathom isobath)	–	15
Midway Atoll	96	–
Kure Atoll	70	–
Total	2,363	10,045*

* Total area includes 392 sq. km of mapped area at Pearl and Hermes Atoll, 96 sq. km of mapped area at Midway Atoll, and 70 sq. km of mapped area at Kure Atoll.

Table 1 provides the best available estimates of the extent of shallow-water coral reef ecosystems in the NWHI. With the exception of Gambia Shoals for which no satellite imagery is available, IKONOS high-resolution satellite imagery or Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite imagery was used to generate the maps depicted in this Atlas. In most cases, features in water up to 30 meters deep can be seen in the IKONOS or Landsat 7 ETM+ imagery. The IKONOS satellite imagery was used to generate the detailed benthic habitat maps, estimated depth, and aggregated habitat cover maps. The Landsat 7 ETM+ satellite imagery was used to characterize the extent of the shallow-water bank. No attempt was made to derive any habitat maps from the Landsat 7 ETM+ imagery. Shallow-water bank maps were not made using IKONOS imagery primarily because the cost of purchasing such large amounts of imagery was prohibitive.

The detailed benthic habitat maps in the Atlas are presented at 1:40,000 scale (1 cm = 0.4 km). The aggregated habitat cover maps and the estimated depth maps in the Atlas are presented at 1:80,000 scale (1 cm = 0.8 km). The bank areas are presented at scales ranging from 1:80,000 to 1:200,000 scale.

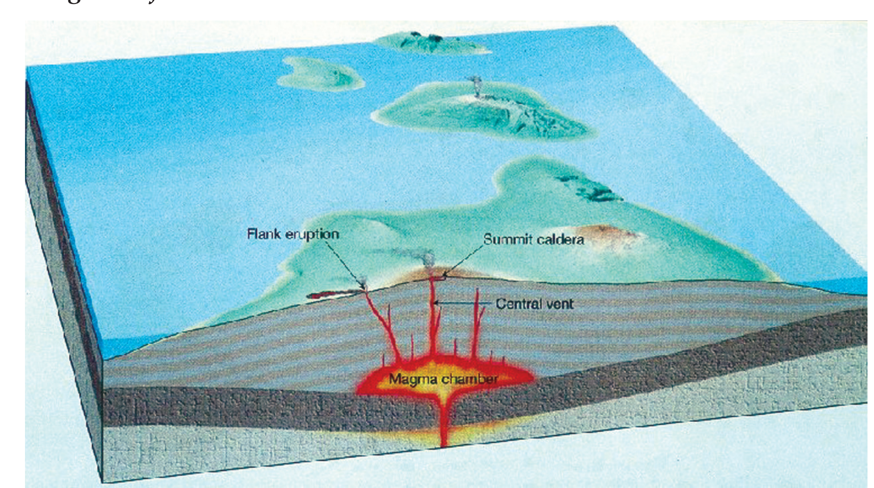
Formation and Geology

Beginning about 30 million years ago, a series of volcanic land masses emerged from a stationary geologic "hot spot" in the Pacific Ocean to form the Hawaiian Archipelago, which stretches for 2,579 kilometers from South Point on the island of Hawaiʻi to the west-northwest tip of Kure Atoll. Kure Atoll is the oldest island in the Hawaiian Archipelago (Grigg and Dollar, 1980). However, the Emperor Seamounts, located north and west of Kure Atoll, mark the western extent of the chain of islands. As the Pacific Plate crosses over the "hot spot" at a rate of approximately 10 cm. per year, a new shield volcano is created. The most recent shield volcano—submerged Loʻihi volcano—is still forming (Grigg, 1982; Rauzon, 2001).

The NWHI are very small islands, most less than 1.6 square kilometers in area. At the southeastern end is Nihoa Island, 210 km. from Niʻihau, the western most of the main Hawaiian Islands. Moving northwest, the 1,920-kilometer stretch of emergent lands are characterized as small rocky islands, atolls, coral islands and reefs, which become progressively older and generally smaller (Wells, 1988).

Kure Atoll lies at a latitude of approximately 29 degrees North. It is at this latitude that the so-called Darwin Point is reached. Named after Charles Darwin, this position on the earth marks where the slow growth rate of shallow-water coral reef ecosystems almost perfectly matches the slow erosion and subsidence of the shield volcano on which the reefs are growing (Grigg and Dollar, 1980). Because of their active volcanism, isolation, and linear progression, the NWHI, together with the main Hawaiian Islands, represent an excellent example of the evolution of island biogeography (MacArthur and Wilson, 2001; Gulko, 1998).

Diagram of a shield volcano.



Laysan Finch at Laysan Island.

The Shallow-water Coral Reef Ecosystem

Shallow-water coral reefs are centers of biological diversity and primary productivity. They convert sunlight into food and provide habitats for a wide range of marine organisms. All of this depends on the symbiotic relationship between two simple organisms—a tiny, soft-bodied animal (a coral polyp) and a smaller single-celled plant-like organism that lives within it (zooxanthellae algae).

The NWHI reefs were built by corals, which are composed of tiny, bottom-dwelling, sessile, marine invertebrate animals (polyps) that live in symbiosis with algae called zooxanthellae that exist within the polyp's tissues. These polyp-zooxanthellae corals are the primary reef builders. They build reefs in shallow, tropical ocean water because the zooxanthellae must have sunlight to create energy and the polyps must have warm water in which to flourish.

At night, the colonies of polyps emerge and extend their tentacles to extract calcium from seawater, which they use to build their communal shallow-water coral reef structure, and to capture tiny zooplankton delivered by marine currents. The digestion of the zooplankton provides energy for the polyp and releases carbon dioxide (CO2). During the day, the CO2 is used by the symbiotic zooxanthellae to convert sunlight into energy (carbohydrates) through photosynthesis and release oxygen as a by-product. The oxygen and carbohydrates help the coral animals to grow, reproduce, and build the limestone reef structure, which provides habitat for zooxanthellae algae, among other animals.

This codependent relationship between coral polyps and symbiotic zooxanthellae algae is critical for the survival and maintenance of shallow-water coral reef ecosystems. Major changes in water temperature, the presence of sediment, and the introduction of pollutants in the water can threaten this delicate symbiotic relationship, thereby weakening or killing the polyps and algae, and eventually destroying the living shallow-water coral reef ecosystem itself (National Geographic Society, 2000).

The healthy and extensive shallow-water coral reefs of the NWHI encompass over 11,550 square kilometers of shallow-water coral reef habitat, or about 65 percent of all shallow-water coral reefs in U.S. waters (Miller and Crosby, 1998). Pearl and Hermes Atoll, French Frigate Shoals, Maro Reef, and Lisianski Island have the most extensive near-shore reefs. Gardner Pinnacles, Lisianski Island, Maro Reef, and Necker Island have the most extensive shallow-water bank areas (see Table 1).

Debris at Pearl and Hermes Atoll.

Wreck at Kure Atoll.

The reefs support 47 species of hard coral and eight species of soft coral (Maragos and Gulko, 2002), a diversity and species richness that rivals that of the main Hawaiian Islands. But compared to other regions, the diversity of coral species is low and is often attributed to the biogeographic isolation of this island chain (Grigg, 1983; Maragos, 1977). This low diversity is thought to account for the exceptionally high numbers of endemic Hawaiian marine species.

Within the NWHI, the reefs differ in coral cover and species organization. Differences in the amount of coral cover within the NWHI are the result of natural variations between fringing reefs and atolls, and variations in latitude (Grigg, 1983; Maragos and Gulko, 2002). In the past, mean coral cover was thought to range from 8 percent to 69 percent among the islands (Green, 1997). This vast, shallow-water coral reef ecosystem supports a dynamic system of marine species. Maragos and Gulko (2002) report that up to 25 percent of the shallow-water organisms found in the Hawaiian Islands are endemic, or found nowhere else on earth. The NWHI act as stepping stones and reservoirs for organisms found in the main Hawaiʻi Islands. The shallow-water coral reefs are the foundation of an expansive ecosystem that hosts an interdependent association of vertebrates (monk seals, reef and bottom fish, turtles, birds, sharks), invertebrates (corals, anemones, jellyfishes, mollusks, shrimps, crabs, lobsters, sea urchins, sea stars, sea cucumbers) and extensive areas of algae.

Coral species in the NWHI generally are slower-growing than in areas closer to the equator. Climatic events, on an inter-annual scale, may play an important role in the ecosystem productivity of the northwestern chain. Declines in the productivity of sea-

Endangered Hawaiian monk seal at Necker Island.

birds, monk seals, reef fishes, and chlorophyll have been documented from the early 1980s to the present, and have been attributed, in part, to these climatic events (Friedlander, 1996). While severe tropical storms, or typhoons, are rare, winter storms are common and result in a noticeable increase in winds and high seas, which impact the reef system.

Marine Mammals and Sea Turtles

The NWHI ecosystem also plays an important role in supporting marine mammals. For example, the entire world population of endangered Hawaiian monk seals is found in the Hawaiian Archipelago, with areas in the NWHI designated as critical habitat under the Endangered Species Act. The current population of monk seals is estimated at about 1,300–1,400 animals, and mean beach counts of about 375 adult seals, including pups more than one year old, from the main reproductive sites remain essentially unchanged since 1993 (Johanos and Baker, 2000). Critical monk seal habitat includes all beach areas and land, lagoon waters, inner reef waters, and ocean waters out to a depth of about 40 m around all emergent land. Recent research demonstrates that Hawaiian monk seals typically range well outside of the currently designated critical habitat, foraging to depths of 500 m on deep-water fishes often associated with coral beds (Western Pacific Regional Fisheries Management Council, 2000; Parrish et al., 2002).

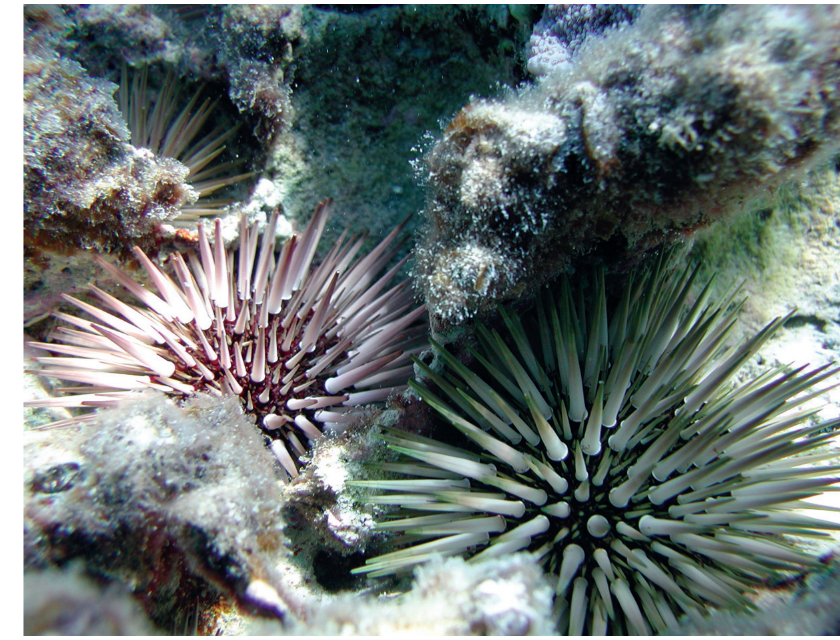
The National Marine Fisheries Service–Honolulu Laboratory has been conducting surveys and research related to the Hawaiian monk seal (*Monachus schauinslandi*) in the Northwestern Hawaiian Islands. These studies provide information needed to evaluate the status and trends in monk seal populations; survival, reproduction, growth, behavior, and feeding habitats; and the success of various activities aimed at supporting population growth.

Since the mid-1980s, adults have comprised a growing percentage of the total monk seal population, estimated to be about 375 seals (excluding those at Midway Atoll). This trend has resulted in fewer young females reaching reproductive age and more older females aging past reproductive age. The overall impact of this trend cannot be predicted reliably at this time. High mortality of immature seals appears to be a leading factor in this trend, especially at two important pupping locations, French Frigate Shoals and Laysan Island.

Starting in 1997, NMFS's marine mammal research program initiated three management activities in an attempt to increase the survival rate of immature seals. First, a program to remove debris in which seals could become entangled was initiated in all NMFS study sites. While conducting this debris removal activity, 13 seals were disentangled. Second, debris was removed from several areas of fringing reef at French Frigate Shoals and Pearl and Hermes Atoll to assess the feasibility of conducting a more extensive debris-removal activity. Third, weaned monk seal pups were redistributed at several suitable locations on French Frigate Shoals (Johanos and Ragen, 1999).

Hawaiian spinner and bottlenose dolphins also are year-round resident species. Numerous other dolphin and whale species (e.g., spotted and striped dolphins, humpback, beaked, killer and false killer whales) occur seasonally within the NWHI archipelago.

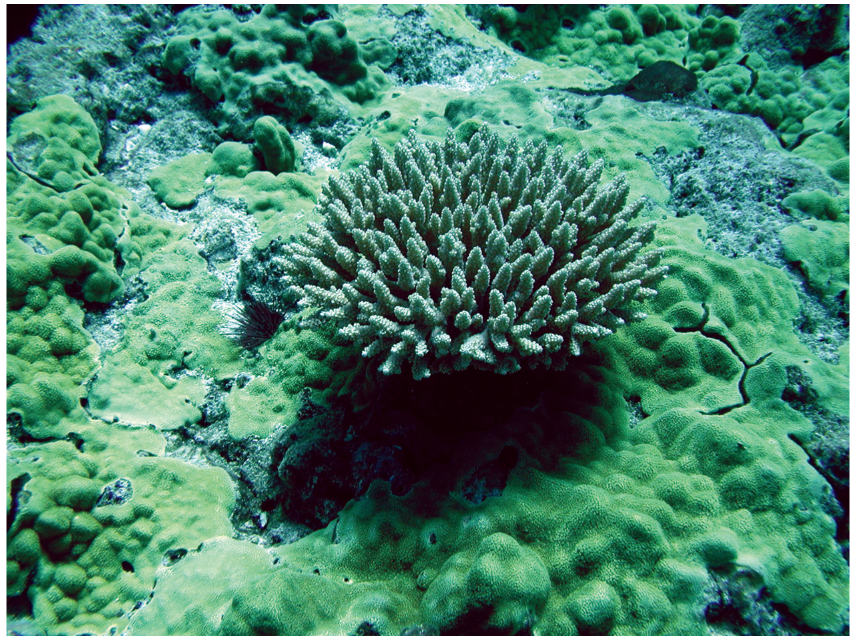
Red-footed boobies at Laysan Island.



Rock-boring urchins at Midway Atoll.

This ecosystem also is important nesting habitat for the threatened green sea turtle. Major nesting sites are found on French Frigate Shoals and, to a lesser extent, on Laysan Island, Lisianski Island, and Pearl and Hermes Atoll. The green sea turtle occupies three habitat types: open beaches, open sea, and feeding grounds in shallow, protected waters. Upon hatching, the young turtles gradually work their way from the beach, over shallow reef areas and extensive shoal areas to the open ocean. When their shells grow 8 to 10 inches long, they move to shallow feeding grounds over shallow-water coral reefs and rocky bottoms (U.S. Fish and Wildlife Service, 2000). Sexual maturity generally is reached between ages 20 and 50.

The green sea turtle was listed as threatened in 1978. Although the population has increased significantly since the 1970s, the total number of nesting females is still well below the historical levels of the late 1800s (NMFS, 2000). Scattered, low-level nesting occurs throughout the Hawaiian archipelago. However, more than 90 percent occurs at French Frigate Shoals. The shallow waters within French Frigate Shoals have been identified as inter-nesting habitat for adult females. Adult males also migrate to this area to breed (Dizon and Balazs, 1982). This amounts to approximately 200 to 700 females nesting annually (FWS, 2001). Research indicates that the range of adult green turtles using French Frigate Shoals is limited to the 2,457-kilometer stretch of the Hawaiian Archipelago (Balazs, 1976; 1983) and to Johnston Atoll, which lies south of the Hawaiian Archipelago (Balazs, 1985). While the green sea turtle is a resident species, the leatherback, olive ridley, and loggerhead sea turtles are considered transient species that occur seasonally in this expansive area.



Staghorn coral at French Frigate Shoals.

Fishes

The coral reef ecosystems in the NWHI are among the few remaining large-scale, intact, predator-dominated reef ecosystems left in the world. They offer scientists an opportunity to study how unaltered ecosystems are structured, how they function, and how they can most effectively be protected (Friedlander and DeMartini, 2002). Healthy reef ecosystems also enhance fishing opportunities and reduce the possibility of fishery collapse because they provide sources of recruits and propagules to the main Hawaiian Islands.

A total of 266 species of fishes are found around Midway Atoll, of which 258 are reef and shore fishes (Randall et al., 1993). This compares to 557 species known from the main Hawaiian Islands. Cooler water temperatures, lack of certain habitat types, and more difficulty in sampling may be causes for the lower number of species relative to the main Hawaiian Islands.

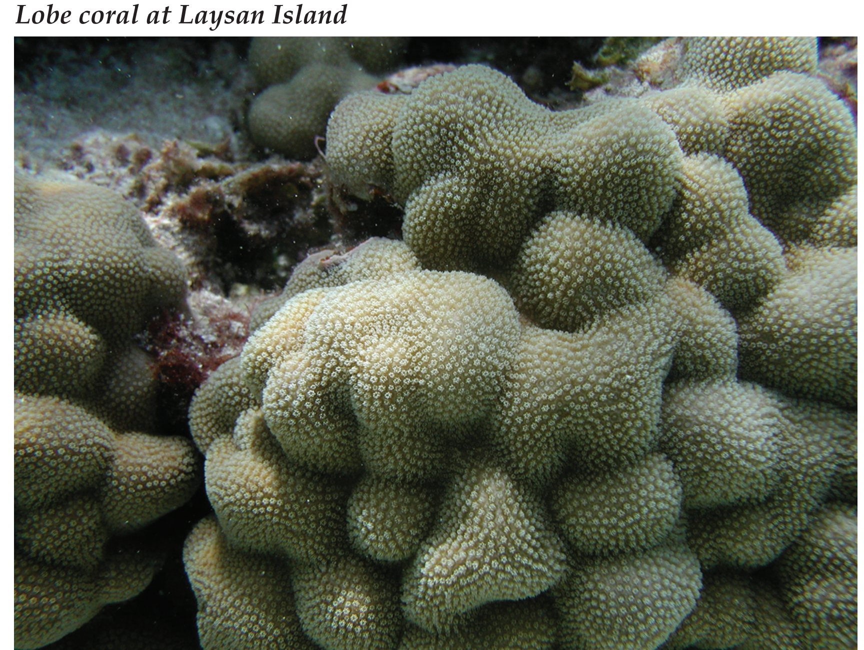
Reef fish trophic structure in the NWHI is strongly influenced by carnivores in numerical abundance and biomass (Parrish et al., 1985). In 2000, fish standing stock in the NWHI was more than 260 percent greater than in the main Hawaiian Islands (Friedlander and DeMartini, 2002). The most striking difference was the abundance and size of large apex predators (primarily sharks and jacks). More than 54 percent of the total fish biomass in the NWHI consisted of apex predators. This trophic level accounted for less than three (3) percent of the fish biomass in the main Hawaiian Islands.

One of the few large benthic predators found on Hawaiian coral reefs is the Hawaiian Grouper. This species is rarely found at SCUBA depths in the main Hawaiian Islands, but it is frequently observed on the forereef at Kure and Midway Atolls. Many species, such as the endemic spectacled parrotfish, the endemic Hawaiian Hogfish, and the bigeye emperor, are quite abundant and can grow to a large size in the NWHI. These species are heavily exploited for commercial, subsistence and recreational use in the main Hawaiian Islands. Their reduced numbers and size in the main Hawaiian Islands likely is the result of overfishing (Friedlander and DeMartini, 2002).

Several species that are rare in the main Hawaiian Islands are commonly found in the NWHI (Friedlander, 1996). The butterfly fish lives closely with the coral *Acropora*, which is common at French Frigate Shoals and Maro Reef, but rare or absent in the remainder of the Hawaiian Archipelago. Temperate and subtropical species exist on the shallow reefs of the northern portion of the archipelago, but they occur at much greater depths southward. These include two species of knifejaws, the spinyface soldierfish, the thicklipped jack, the Hawaiian Morwong and the boarfish. All of these species are found in both hemispheres but not in equatorial regions. They are thought to have established themselves here when surface waters were cooler in the NWHI (Randall, 1981).

The masked angelfish is a highly prized species in the ornamental fish trade. It is extremely rare in the main Hawaiian Islands, and is usually encountered at depths greater than 70 m (Hoover, 1993). This species is relatively common on reefs at Midway, Kure, and Pearl and Hermes in the 20- to 30-m depth range (Hobson, 1984; Friedlander and DeMartini, 2002).

Lobe coral at Laysan Island



Algae at Laysan Island.

Birds

The NWHI provide vital habitat for 14 million nesting seabirds and breeding species, many of which rely on the shallow-water coral reefs for food. Ninety-nine percent of the world's Laysan albatross and 98 percent of the world's black-footed albatross nest in these islands (Midway Atoll National Wildlife Refuge, 2000).

The Laysan finch is listed by the FWS as an endangered species. The Laysan finch, common only on Laysan Island, is a highly inquisitive bird that constantly inspects and probes all types of items. It does not appear to be innately wary of human-made items. As a result, the FWS has established special visitor restrictions on Laysan Island and Pearl and Hermes Atoll to eliminate the chance of accidental drowning, entanglement, and entrapment of the birds.

Similarly, most NWHI seabirds exhibit a lack of wariness toward human visitors. Most NWHI seabirds nest either under the ground, on the surface, or in the low trees and shrubs. Petrels and shearwaters nest in burrows that can be collapsed easily, trapping the adults, chicks or crushing the eggs. Grey-backed terns and brown noddies nest on the ground and can be easily forced off their nests. Thermal stress may also affect the chick and eggs. Any disturbance of the nest may cause the adults to leave the nest unattended, exposing the eggs or chicks to extreme temperatures, or overly wet conditions.

Frigate birds will take chicks and nest material from booby nests and other frigatebird nests when the nests are unattended. Also, if a nest is left unattended and finches are present, the finches have been known to peck a hole in the unattended eggs and consume the contents. Ruddy turnstones also display this behavior.

Invertebrates

The shallow-water coral reefs of the NWHI support diverse communities of benthic macroinvertebrates. Sixty-three species of macroinvertebrates, largely mollusks, echinoderms, and crustaceans, have been documented. Spiny and slipper lobsters were an important commercial fishery, and a vital link in the trophic food web of many other organisms in the near-shore, shallow-water coral reef ecosystem (Friedlander, 1996). The lobster fishery has been closed since 2000.

Algae

Algae are important to Hawai'i's shallow-water coral reef ecosystems as well. They serve as a food source for a number of reef organisms, and also serve as settling and attachment sites for small and cryptic reef species. Algae also are important as reef cement. About 205 species of marine algae, including a number of new deep-water species that were previously unknown in the area, have been identified in the NWHI (Abbott, 1989).

Culture and History

The NWHI are closely tied to the cultural heritage of Hawai'i and more broadly to U.S. history. Numerous artifacts found on Nihoa Island establish a close relationship with the Hawaiian culture in the main Hawaiian Islands. As many as 175 peoples

Jacks (Ulua) at French Frigate Shoals.

Galapagos shark at Kure Atoll.

are estimated to have lived there during prehistoric times. Evidence of habitation, religious ceremonies, agriculture, and burials at 88 archaeological sites on Nihoa Island has been found. Artifacts on Necker Island suggest that the island was used in prehistoric times, primarily for religious ceremonies. Of the 52 known archaeological sites, 33 are religious shrines. Many of the temple sites closely resemble those of the Marquesas Islands and Tahiti, establishing a possible link to early Polynesian cultures. Oral history and identified artifacts demonstrate that these islands have also served as fishing grounds for the people of Hawai'i for centuries. Both Nihoa and Necker Islands are on the National Registry of Historic Places (Rauzon, 2001).

The NWHI played a significant role in U.S. history during World War II. In June 1942, the famous Battle of Midway took place in the seas to the north of Midway Atoll. Midway Atoll, now part of the FWS National Wildlife Refuge System, is the only remote island National Wildlife Refuge open to the public (Hawai'i Department of Land and Natural Resources, 2000).

Preserving the Ecosystem

The NWHI ecosystem remains relatively pristine. Much of the NWHI has been protected from human visitation since 1909, when President Theodore Roosevelt signed an Executive Order establishing the Hawaiian Islands Bird Reservation. In 1940, President Franklin D. Roosevelt established the Hawaiian Islands National Wildlife Refuge in the area. Nine of the islands and bank areas in the NWHI are managed by the FWS as part of the Refuge System: Nihoa Island, Necker Island, French Frigate Shoals, Gardner Pinnacles, Maro Reef, Laysan Island, Lisianski Island, Pearl and Hermes Atoll, and Midway Atoll. Kure Atoll is managed by the Hawai'i Department of Land and Natural Resources.

Several islands within the Refuge Complex are especially pristine and, as a result, are rich in rare and special plants and animals. Nihoa Island has 13 potential candidate endangered insect species, numerous endangered plants and two endangered birds. Necker Island has endangered plants and seven endemic insects that are candidates for inclusion on the Endangered Species list. Endangered plants, five potential candidate endangered insect species, and the endangered Laysan finch and Laysan Duck live on Laysan Island.

Other islands in the Refuge Complex, such as Lisianski Island, Pearl and Hermes Atoll, and French Frigate Shoals provide habitat for a variety of endemic or endangered species and require special protection from alien species of plants, insects and animals. In 1902, rabbits were introduced on Laysan Island and caused the extinction of numerous plants and insect species and three endemic land bird species. The introduction of rats to Laysan Island has caused the extirpation of many burrowing seabird colonies. The introduction of exotic grasses to Laysan Island has crowded out the native grasses and eliminated nesting habitat for the endangered Laysan finch.

Marine Debris

Surveys of the NWHI from 1979 to 1983 reported relatively pristine reefs, but by 1996 the reefs were suffering from substantial anthropogenic damage, primarily due to the effects

Leopard blenny at Laysan Island.

Sea cucumber at French Frigate Shoals.

of derelict fishing gear. Derelict gear caught in the North Pacific Ocean gyre are deposited in the archipelago reefs, which act like a comb or straining filter. The North Pacific Subtropical Convergence Zone provides a mechanism for debris accumulation in this region. Much of this accumulated debris ultimately is deposited on the shallow-water coral reefs and beaches of the NWHI. The movement of derelict fishing gear across shallow atolls threatens the ecological balance of the reef community. Once derelict fishing gear snags on the NWHI shallow-water coral reefs, it begins a cycle of destructive activity. Derelict fishing gear modifies the reef structure by damaging the coral substrate that makes up the physical habitat for reef biota. After debris snags on shallow-water coral reefs, wave action causes the debris to break the coral heads on which debris is fixed. This action continues until the nets are removed or become adequately weighted with abraded coral to sink. Derelict fishing gear also poses a serious and lethal threat to macrofauna in marine and coastal environments. Endangered Hawaiian monk seals, sea turtles, and birds become entangled in marine debris, resulting in high mortality rates.

Coral Reef Ecosystem Investigation leads a multi-agency marine debris mitigation effort, funded by NOS and NMFS, to assess, monitor and mitigate the effect of marine debris on shallow-water coral reef ecosystems of the NWHI and U.S. Pacific Islands. This work is conducted in partnership with the USFWS, State of Hawai'i, and other nongovernmental organizations. Since 1996, 239.4 tons of debris have been removed from the reefs and beaches of the NWHI. In a 1997 cleanup effort, nearly 20 percent of the mass of marine debris removed at a Pearl and Hermes Atoll site consisted of dead coral (NMFS, 2000). In FY 2001, activities included marine debris survey and removal work at Pearl and Hermes Atoll and Kure Atoll. In FY 2002, detailed reef surveys for derelict fishing gear have been conducted at five NWHI sites: French Frigate Shoals, Pearl and Hermes Atoll, Lisianski Island, Kure Atoll, and Midway Atoll. Satellite and aircraft remote sensing technologies are being used to evaluate the feasibility of locating and efficiently removing concentrations of marine debris before shallow-water coral reefs and protected species are adversely impacted.

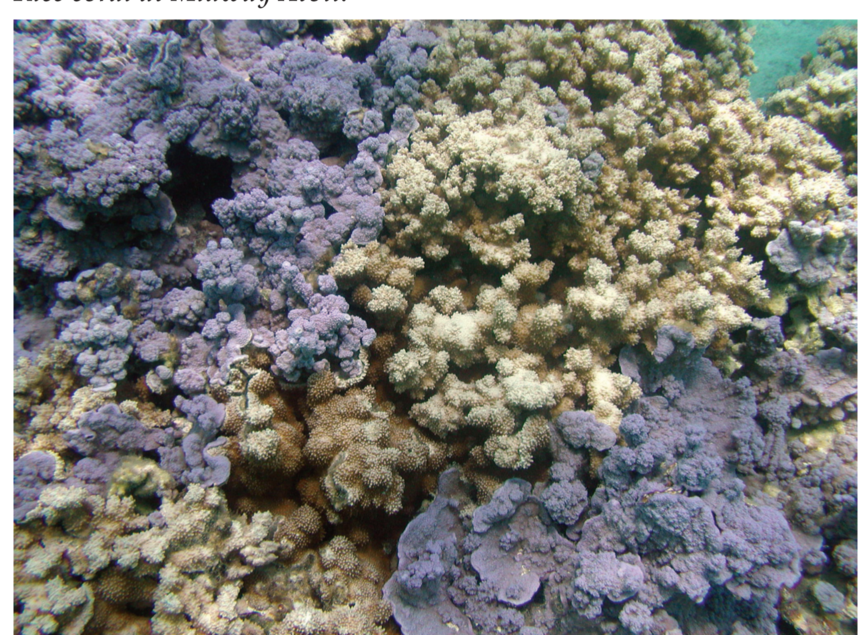
Management

The NWHI are managed by several federal and state agencies. These are described briefly below.

The Shallow-water Coral Reef Ecosystem Reserve

On December 4, 2000, the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve was created by Executive Order 13178. The Reserve encompasses an area of the marine waters and submerged lands of the NWHI extending approximately 2,222 kilometers long and 185 kilometers wide. The Executive Order contains conservation measures that restrict some activities throughout the Reserve, and establishes Reserve Preservation Areas around certain islands, atolls and banks where all consumptive or extractive uses are prohibited. A 30-day public comment period was initiated to receive comments regarding whether to make permanent the Reserve Preservation Areas. Comments also were requested on the conservation measures for the Reserve.

Rice coral at Midway Atoll.



Spectacled parrotfish at Kure Atoll.

On January 18, 2001, after the close of the 30-day comment period, the process and establishment of the Reserve was finalized by issuance of Executive Order 13196. This Executive Order modified Executive Order 13178 by revising certain conservation measures and making permanent the Reserve Preservation Areas with modifications. With this action, the establishment of the Reserve, including the conservation measures and permanent Reserve Preservation Areas, was completed.

The Executive Orders can be downloaded at:
http://hawaiireef.noaa.gov/PDFs/EO13178.pdf
http://hawaiireef.noaa.gov/PDFs/EO13196.pdf
http://hawaiireef.noaa.gov/PDFs/AmendmentSummary.pdf

The Reserve Council

In managing the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve, the Secretary of Commerce was directed to establish a Coral Reef Ecosystem Reserve Council, in accordance with the National Marine Sanctuaries Act. The role of the Council is to provide advice and recommendations to NOAA on the Reserve Operations Plan and the designation and management of the sanctuary.

The Council, which was officially established on December 5, 2000 plays an important role in helping shape the initiatives that will provide lasting protection to the marine resources of the Reserve and sanctuary. The Council operates under a charter developed by NOAA, which prescribes the frequency of meetings, objectives and roles, and operation of the Council. Council meetings are open to the public.

The voting members of the Council (except for the State of Hawai'i representative) are chosen through an open, competitive process held during December 2000 and January 2001. A call for applications is published in the Federal Register and posted on the Internet at http://hawaiireef.noaa.gov. Forty-seven applications were received, and 14 of these applicants were chosen by NOAA, in consultation with the State of Hawai'i and the Department of the Interior, to become members of the Council. Non-voting members were chosen by the organization they represent in a separate process. Members were announced on January 29, 2001.

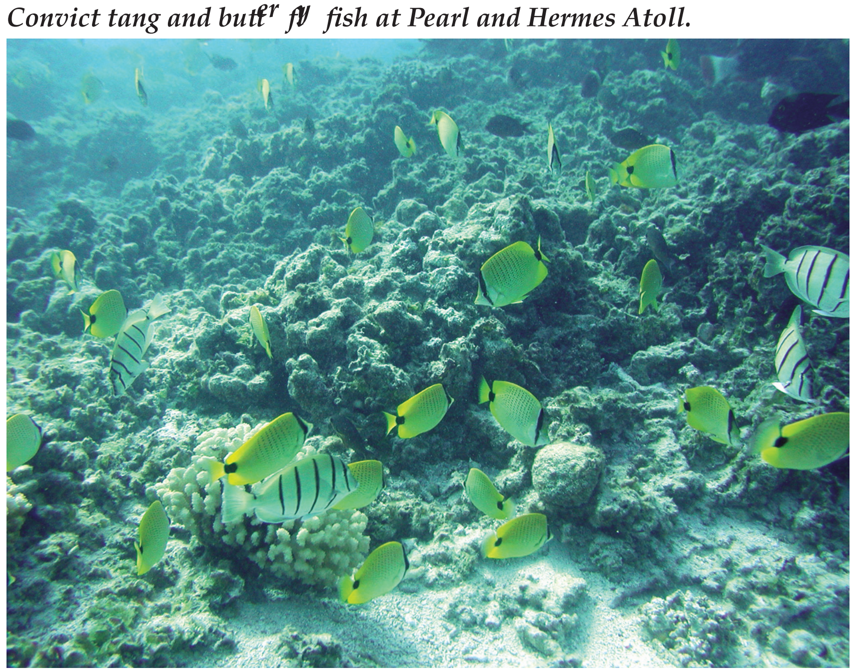
Alternates will be chosen for each seat to ensure adequate representation should a Council member be unable to attend a meeting. A call for applications for alternates was published in the Federal Register in February 2001. Applications were received through March 2, 2001. To increase the pool of applicants, another call for applications for alternates was published in the Federal Register on May 4, 2001. Applications were required by June 4, 2001. The alternates were selected in the same manner as voting representatives.

To learn more about NOAA's Sanctuary Designation Process, please read the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve Draft Reserve Operations Plan. To obtain a copy of this document, please visit: http://www.hawaiireef.noaa.gov/documents/documents.html.

Department of Land and Natural Resources

The Hawai'i Department of Land and Natural Resources (DLNR) is responsible for preserving Hawai'i's resources for the benefit of future generations. The DLNR is the state's lead agency in protecting the natural and cultural resources of the islands. The DLNR strives to balance use of resources with the long-term social, environmental and economic well-being of Hawai'i's people.

Convict tang and butterfly fish at Pearl and Hermes Atoll.



DLNR has aquatic resource trustee responsibility out to three nautical miles throughout the NWHI, with the exception of Midway Atoll. DLNR may share these responsibilities with other agencies. Also, DLNR supports pioneering research and programs that enhance ocean resources. Information collected by DLNR is used in planning for the future. The DLNR works with agencies, civic and non-profit organizations, community groups, residents and visitors to protect the resources of the NWHI.

The DLNR's Division of Aquatic Resources manages the State's marine and freshwater resources through programs in commercial fisheries and resource enhancement; aquatic resources protection, enhancement and education; and recreational fisheries. Major program areas include managing or enhancing fisheries for long-term sustainability of the resources, protecting and restoring the aquatic environment, protecting native and resident aquatic species and their habitat, and providing facilities and opportunities for recreational fishing consistent with the interests of the state.

Kure Atoll State Wildlife Refuge

Kure Atoll State Wildlife Refuge is managed by the DLNR Division of Forestry and Wildlife. Numerous research and invasive species removal activities are conducted at Kure Atoll by DLNR in partnership with NMFS, FWS and NOS. The removal of invasive plants from Kure Atoll is a high priority for DLNR. Also, DLNR has ongoing surveys to assess the extent of seabed habitats along the back reef portion of the atoll (Walsh et al., 2002).

Hawaiian Islands National Wildlife Refuge

The Hawaiian Islands National Wildlife Refuge (HINWR) was designated in 1909 by President Theodore Roosevelt. This refuge consists of the following remote Pacific islands: Nihoa Island, Necker Island, French Frigate Shoals, Gardner Pinnacles, Maro Reef, Laysan Island, Lisianski Island, and Pearl and Hermes Atoll.

The HINWR consists of a chain of islands, reefs and atolls extending about 1,287 kilometers in a northwesterly direction from the main Hawaiian Islands. This refuge has a total of 13.4 sq. km of emergent lands, and 2,469.2 sq. km of submergent lands. The HINWR is home to millions of seabirds, such as sooty terns and albatrosses, and provides a rich habitat for marine life.

Prehistoric remnants of early Polynesian cultures are found on Nihoa and Necker Islands.

Except for field stations on Tern and Laysan Islands, these remote islands are uninhabited by humans and are protected by the U.S. Fish and Wildlife Service. Even scientific research is limited and closely scrutinized to minimize unnecessary disturbance. Entry to the refuge is permitted by Special Use Permit only.

For more information:
U.S. Fish & Wildlife Service
Refuges Division
300 Ala Moana Boulevard
Room 5-231, Box 50167
Honolulu, Hawai'i 96850
(808) 541-1201

Hawaiian Islands National Wildlife Refuge Administrative Boundaries

The FWS has established certain administrative boundaries within the HINWR. Recreational and commercial activities are not allowed in the HINWR. The area has been set aside by the director of the FWS as a Research Natural Area. Authority for promulgation of Refuge Regulations is found in 16 U.S.C. 668dd, 50 CFR Parts 25–28. The boundaries are as follows:

Pearl and Hermes Atoll—the atoll and reef as defined by the 10 fathom isobath.

Lisianski Island—the island and shoal (Neva) as defined by the 10 fathom isobath.

Laysan Island—the island and atoll as defined by the 10 fathom isobath.

Soft coral at Laysan Island.

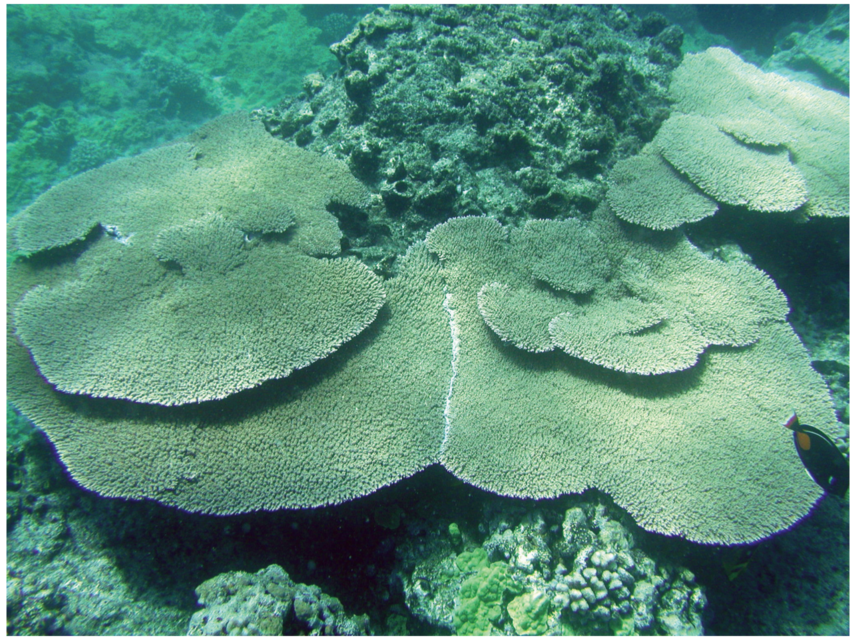


Table coral at French Frigate Shoals.

Maro Reef—the reef as defined by the 10 fathom isobath.

Gardner Pinnacles—the island and appurtenant (contingent) reefs as defined by the 10 fathom isobath.

French Frigate Shoals—the atoll and reef as defined by the 10 fathom isobath, except that a straight line shall be drawn from the western-most portions of the 10 fathom isobaths around Disappearing Island, Le Perouse Pinnacle, and Shark Island.

Necker Island—the island and shoal as defined by the 20 fathom isobath.

Nihoa Island—the island and reef as defined by the 10 fathom isobath.

Midway Atoll National Wildlife Refuge

Surrounded by thousands of miles of ocean, the islands of the northwest Hawaiian archipelago have become a peaceful oasis for seabirds, migrating shorebirds and marine life. Located 2,012 km west-northwest of Honolulu, the atoll measures approximately eight km in diameter. Sand Island is the largest island, measuring 2.9 km long by 2.4 km wide or about 5 sq. km; Eastern Island is approximately 1.4 sq. km; and Spit Island is only 0.02 sq. km.

Midway was discovered in 1859 by Captain N.C. Brooks. Brooks named the islands "Middlebrooks" because they are positioned almost halfway between North America and Asia. Brooks claimed these islands under the Guano Act of 1856, and the U.S. affirmed this claim by annexing and renaming the islands Midway in 1967.

Midway Atoll National Wildlife Refuge was established in 1988 as an "overlay" refuge, which allowed the FWS to help the U.S. Navy manage the atoll's unique wildlife and resources. After 93 years of U.S. Navy administration, Midway Atoll was transferred to the FWS on October 31, 1996. As part of the base closure and realignment process, the Navy completed its environmental cleanup and pulled out of Midway in June 1997. With the closure of Midway's Naval Air Facility, the FWS is charged with restoring its biological diversity, conserving its historic and natural resources, and providing opportunities for compatible public education and enjoyment on the refuge.

The FWS is committed to maintaining the historic spirit of Midway Atoll, and sharing its vital roles in the mid-Pacific with its visitors in a manner respectful of the past and as a reminder for the future. Remnants from Midway's military history tell of the atoll's strategic significance to the United States, including the supposedly "bombproof" Sand Island power plant, which was struck by a shell lobbed from a Japanese destroyer on December 7, 1941; ammunition storage huts; and gun emplacements. Several historic monuments commemorating the courageous soldiers who fought and died during World War II have been erected on Sand and Eastern Islands.

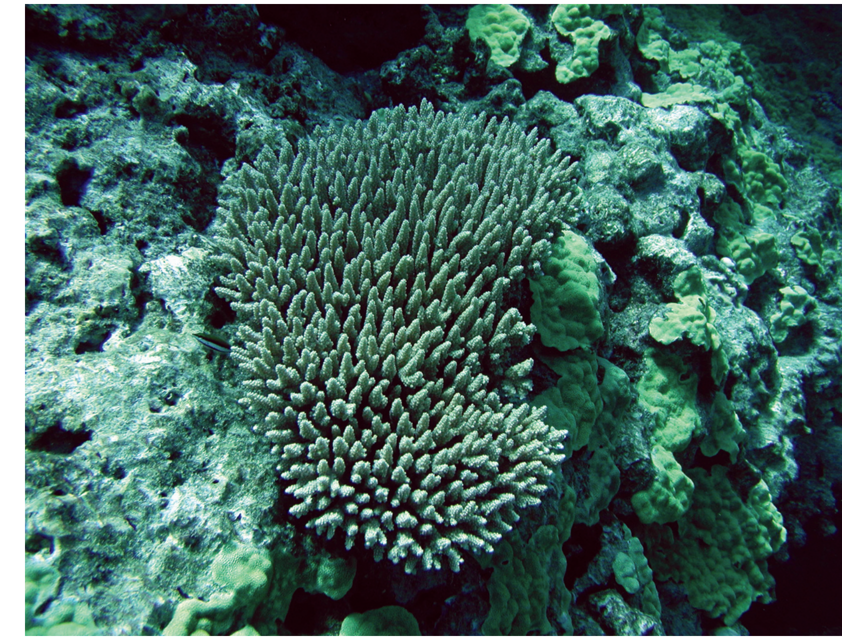
From November though July, Midway is alive with albatross, boasting the largest colony of Laysan albatross in the world and the second largest colony of black-footed albatross. At other times of the year, red-tailed tropicbirds may perform their aerial acrobatics overhead, curious white terns will flutter above, black and brown noddies may nod their greetings, and wedge-tailed shearwaters and Bonin petrels may serenade visitors to sleep.

Midway's only native mammal is the endangered Hawaiian monk seal. Adults and immature monk seals are frequently seen basking on the beaches of all three islands in the atoll. Midway Atoll's lagoon is an important feeding area for threatened green sea turtles, and they are frequently spotted within the harbor area of Sand Island or basking on Midway's beaches. Hawaiian spinner dolphins frequent Midway's shallow lagoon waters during the day and forage outside the atoll at night. Midway's lagoon and surrounding nearshore waters support more than 250 species of fishes, including many colorful reef fishes.

For more information contact:
Midway Atoll National Wildlife Refuge
P.O. Box 29460
Honolulu, Hawai'i 96820-1860

The Fishery Management Council

The Western Pacific Regional Fishery Management Council determines the management policies of fisheries in the exclusive economic zone (EEZ, generally 4.8 km to 320 km offshore)



Staghorn coral at French Frigate Shoals.

around the Territory of American Samoa, Territory of Guam, State of Hawai'i, the Commonwealth of the Northern Mariana Islands and US Pacific island possessions—an area of nearly 3,885,000 sq. km. The Council is one of eight regional councils in the United States that were established under the Magnuson Fishery Conservation and Management Act of 1976. This act as amended is known as the Magnuson-Stevens Act.

The Western Pacific Council consists of 13 voting and three non-voting members. Half of the members are appointed by the US Secretary of Commerce to represent fishing and related community interests in the region. The others are designated state, territorial and federal officials with fishery management responsibilities.

The main task of the Council is to protect fishery resources while maintaining opportunities for domestic fishing at sustainable levels of effort and yield. To accomplish this, the Council monitors fisheries within its region and prepares and modifies fishery management plans as needed. The regulations are enforced jointly by the NMFS, the US Coast Guard and deputized state and territorial agents. The Council encourages cooperative fishery management among the island and distant-water fishing nations throughout the the Pacific.

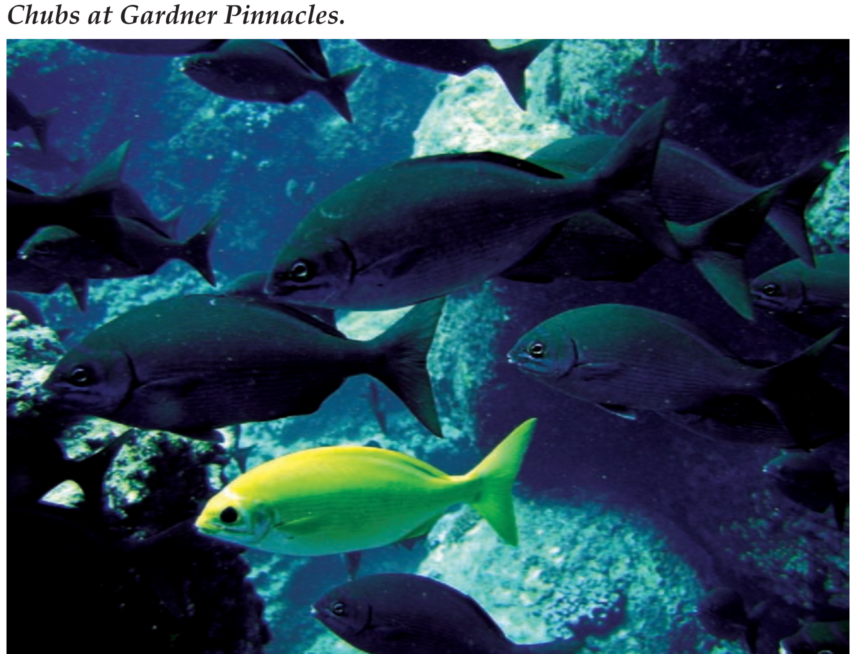
The Western Pacific Regional Fishery Management Council has developed several management plans relevant to the NWHI. To obtain these documents, please visit: http://www.wpcouncil.org/about.htm.

Coral Reef Ecosystem Investigation

The mission of the Coral Reef Ecosystem Investigation (CREI), established in 2001 at the National Marine Fisheries Service—Honolulu Lab (NMFS–HL), is to conduct research necessary to ensure long-term viability of shallow-water coral reef ecosystems in the Hawaiian Archipelago and other US-related islands in the Pacific Ocean. The objectives of the investigation are to conduct an ecosystem-based research program required for scientific support of the following groups and initiatives: the Coral Reef Ecosystem Fishery Management Plan of the Western Pacific Regional Fisheries Management Council; National Action Plan to Conserve Coral Reefs; Coral Reef Conservation Act; executive orders related to coral reef protection, Marine Protected Areas, and the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve; and recovery of critically endangered Hawaiian monk seals and threatened green sea turtles.

CREI uses comprehensive, multidisciplinary research approaches to address shallow-water coral reef ecological assessment and monitoring, habitat mapping and characterization, oceanographic processes affecting shallow-water coral reef ecosystems, and shallow-water coral reef restoration through marine debris mitigation. In addition, several applied research activities are conducted including examining ocean circulation patterns, evaluating the potential effectiveness of marine protected areas, ecosystem modeling of trophic linkages, spatially structured population modeling, evaluating the impacts of lobster trapping on habitat, and developing techniques to assess exploitable bottom fish populations.

Chubs at Gardner Pinnacles.



Sponge at French Frigate Shoals.

CREI conducts Rapid Ecological Assessments and towed diver surveys in water depths of 0-30 m in the NWHI and other Pacific islands. The results of these activities are used to groundtruth aerial and remote sensing data for benthic habitat mapping; create a species inventory: provide a baseline assessment of species abundance and distribution; and evaluate reef health, including coral bleaching, predation, algal overgrowth and breakage. Habitat mapping and characterization research in water depths of 20–400 m employs single- and multibeam acoustic technologies, bottom classification research, towed camera systems, and towed-diver surveys. CREI coordinates marine debris mitigation on shallow-water coral reefs and employs divers on multiple ships in multi-agency campaigns.

An array of tools and methods is used to determine the oceanographic processes that influence shallow-water coral reef ecosystems. These include the use of instrumented oceanographic moorings and buoys, oceanographic research vessels, and satellite remote sensing technologies. The oceanographic information collected in the NWHI provides time series of high resolution sea surface temperature, salinity, photosynthetically available radiance, ultraviolet-B, air temperature, barometric pressure, and wind direction and speed. These data help us better understand the influences of local environmental conditions on the health of the surrounding shallow-water coral reef. Data telemetry helps monitor the imminent or occurring shallow-water coral reef bleaching or other natural events (e.g., hurricanes, storm damage, heating/cooling) so that additional field observation and data collection efforts can be initiated. To learn more about CREI, please visit: http://crei.nmfs.hawaii.edu.

Map Development

The maps found in this Atlas were derived from satellite imagery. IKONOS high-resolution satellite imagery was used to derive the draft benthic (seabed) habitat maps, estimated depth, and the color images. Landsat moderate-resolution satellite imagery was used to derive the maps of banks.

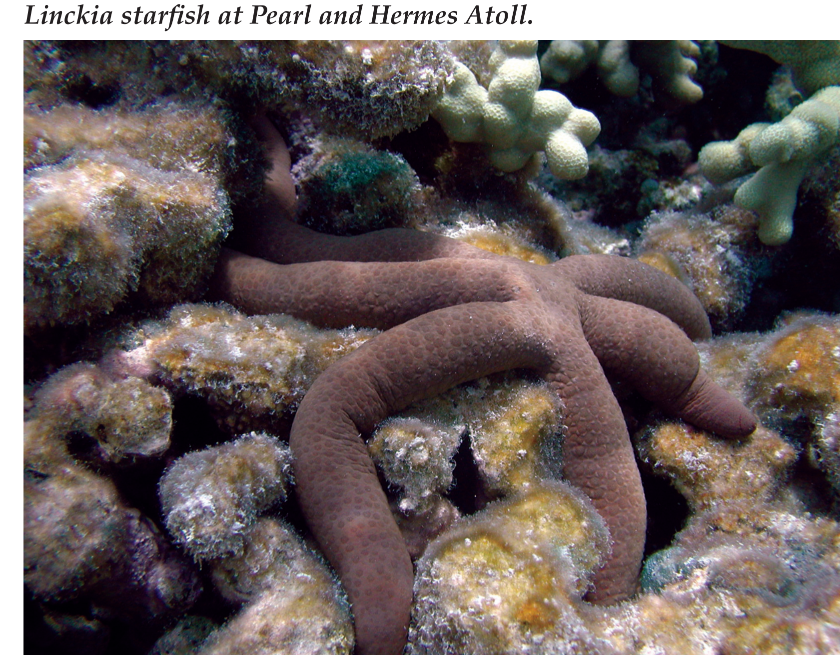
Generally, features (habitats) on the seabed to a depth of approximately 30 m can be seen in the satellite imagery. In some areas, such as portions of the southeastern part of Pearl and Hermes Atoll, turbidity in the water limited visibility to 12 m into the water column. In other areas, such as the southern part of Laysan, seabed features could be clearly identified in water 25–30 m deep.

Satellite Technologies

The IKONOS satellite provides commercially available panchromatic (black and white) and multispectral (blue/green/red/near-infrared) imagery. The panchromatic imagery has a 1-m pixel dimension (meaning features as small as 1 m square can be seen in the imagery). The multispectral imagery has a 4-m pixel dimension (meaning features as small as 16 sq. m can be seen in the imagery). IKONOS imagery is purchased under strict licensing agreement. Only licensed users can have access to the imagery. Derived products, such as the habitat maps presented in this Atlas, can be openly distributed.

The Landsat 7 Enhanced Thematic Mapper Plus (ETM+) satellite imagery has a 28.5 m multispectral pixel dimension (mean-

Linckia starfish at Pearl and Hermes Atoll.



IKONOS multispectral image of a portion of Midway Atoll.

ing features with an area of about 812 sq. m can be seen). The Landsat satellite has six color and near-infrared bands, including a red, a green, and a blue band. The spectral characteristics of the IKONOS and Landsat satellites are similar, which allows for easier analysis of the imagery to generate maps. There are no redistribution restrictions on Landsat 7 ETM+ imagery.

The IKONOS imagery is purchased in 11-km-wide swaths that are mosaicked together to produce complete images of locales. In total, the following areas of IKONOS imagery were purchased. For two areas, Kure Atoll and French Frigate Shoals, two image purchases were made. These two images were merged to reduce the amount of area obscured by cloud and cloud shadow.

Table 2. IKONOS imagery purchased to map the NWHI (sq. km).

Nihoa Island	120
Necker Island	317
French Frigate Shoals (1st purchase)	682
French Frigate Shoals (2nd purchase)	818
Gardner Pinnacles	87
Laysan Island	172
Lisianski Island	593
Maro Reef	680
Pearl and Hermes Atoll	563
Kure Atoll (1st purchase)	200
Kure Atoll (2nd purchase)	205
Midway Atoll	172
Total	4,609

Imagery Positioning

All of the IKONOS imagery was purchased in National Imagery Transmission Format with the associated Rational Polynomial Coefficients (RPCs or satellite ephemeris data). When using image analysis software capable of reading NITF files with associated RPCs, the horizontal positioning error never exceeded 15 m (for locations where there is little or no vertical relief to affect image pixel displacement).

NOS mosaicked the IKONOS imagery swaths, both panchromatic and multispectral, to within one pixel. In the case of the 1-m panchromatic imagery, the swaths overlap to within 1 m. For the 4-meter multispectral imagery, the swaths overlap to within 4 m.

NOAA's National Geodetic Survey (NGS) recently gathered very accurate ground control data (horizontally accurate to within 15 cm of its location on the earth) on nine locales in the NWHI. The only locale that was not successfully "occupied" was Maro Reef, where no permanent site could be found above sea level. Where available, NOS used these ground control data in its efforts to improve the geopositioning of IKONOS imagery.

Working with NGS, NOAA's Office of the Coast Survey will be publishing revised nautical charts for the NWHI. The revision of these charts included obtaining satellite imagery from sources not available to the public. NGS compiled vector shoreline for all but one NWHI locale (Maro Reef) using a combination of IKONOS and restricted-access imagery. Where available, NOS used this vector shoreline in its efforts to improve the geopositioning of IKONOS imagery. However, because the restricted-access imagery used to compile vector shoreline for some areas has a different resolution and was acquired at different times from the IKONOS imagery, complete superimposition is not possible.

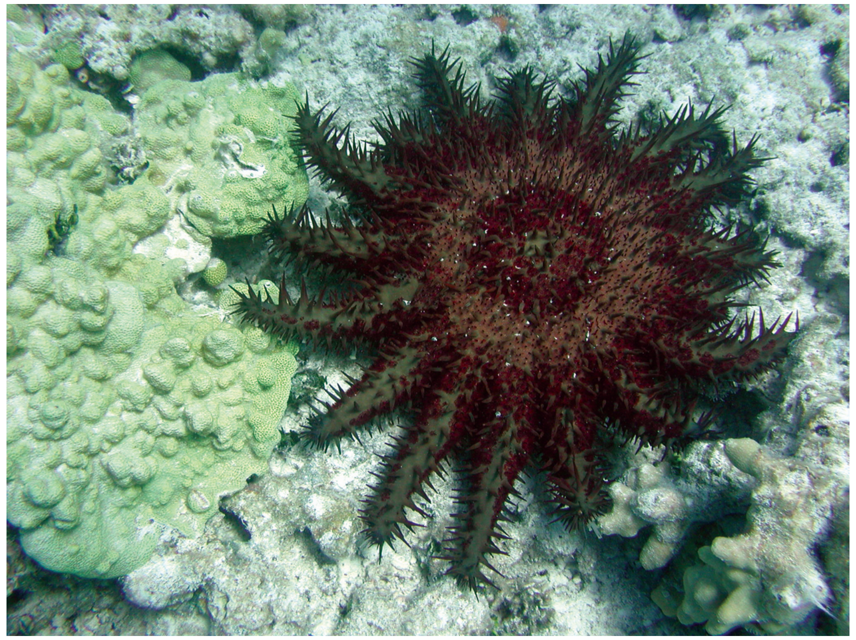
IKONOS panchromatic image of a portion of Midway Atoll.

Landsat ETM+ multispectral image of a portion of Midway Atoll.

For Kure Atoll, Midway Atoll, Pearl and Hermes Atoll, Laysan Island, Lisianski Island, and French Frigate Shoals, NOS used a combination of ground control data and vector shoreline data to further geoposition the IKONOS panchromatic and multispectral imagery. As a result, the mean horizontal positioning error at sea level of this imagery is less than 4 m (one pixel).

NGS successfully gathered ground control data and compiled vector shoreline for Necker Island, Nihoa Island and Gardner Pinnacles. However, the islands have considerable vertical relief. As a result, both the restricted access imagery and IKONOS imagery for these islands are affected by parallax (the displacement of an object as seen from two different points not on a straight line from the object). This parallax results in less accurate positioning of the imagery. NOS used a combination of ground control data and vector shoreline data to improve the geopositioning of IKONOS panchromatic and multispectral imagery. NOS believes the IKONOS imagery of Necker Island, Nihoa Island, and Gardner Pinnacles to be within 15 m of their actual locations at sea level.

For Maro Reef, neither supplemental ground control data nor vector shoreline data are available. However, trackline bathymetry with accurate GPS data was recently gathered at Maro Reef. These data were used to correct the position of the imagery. Using these data, the mean horizontal error at sea level for Maro Reef was 11 m.



Crown of Thorns starfish at Pearl and Hermes Atoll.

The IKONOS satellite is capable of collecting imagery of features on the earth's surface at angles as much as 45 degrees from nadir (when the feature is directly below the satellite). All of the IKONOS images of the NWHI were collected with collection angles of less than 20 degrees from nadir. Constraining the collection angle is important because positioning features on the seabed using satellite imagery is affected by refraction of light through the water column. When the collection angle is limited to less than 20 degrees, the maximum offset of seabed features would be less than 4 m (one IKONOS multispectral pixel) in water less than 15 m deep and less than 8 m in water less than 30 m deep. The combination of horizontal positioning error and light refraction error adds up to a maximum positioning error of approximately 12 m in water 30 m deep.

Two procedures were used to georeference the Landsat satellite imagery used to derive the maps in this Atlas. For Landsat imagery where contemporary IKONOS imagery was available, the Landsat imagery was positioned using the IKONOS imagery. As a result, these Landsat data are positioned to within 28.5 m (one Landsat pixel) of the IKONOS imagery. For Landsat imagery where contemporary IKONOS imagery was not available, several contemporary Landsat images were used to compute a least-squares fit of two or more images. As a result, these Landsat data are positioned to within 57 m (two Landsat pixels).

Image Analysis

Several intermediate, derived products were produced as the satellite imagery was processed to generate the benthic habitat maps. First, the raw satellite images were converted from Digital Numbers (DNs) to normalized reflectance. Normalized reflectance (or at-satellite reflectance) converts DNs into standardized, satellite-independent, comparable values. First developed for Landsat satellite imagery, the algorithm used to perform this conversion was modified for IKONOS image processing. As part of the conversion from DNs to at-satellite reflectance, the following equation is used (Green et al., 2000):

R = pi * L/ (Eo cos(theta0) 1/r^2)

L = radiance (from calibration provided by Space Imaging).
theta0 = the solar zenith angle.
r = earth-sun distance in Astronomical Units.
Eo = the mean solar exo-atmospheric irradiance in each band. (A convolution of the spectral response and solar radiation from Neckel and Labs (1984) was used to get Eo.)

The acquisition angles (ephemeris data) of the satellite relative to the ground at the time of image acquisition were also used. Calibration coefficients for the satellite, provided by Space Imaging, were used to calculate at-satellite radiance, which was then transformed to reflectance.

The normalized reflectance imagery was then transformed into water reflectance (or the signal < 10 cm above the water surface). Water reflectance uses the near-infrared band to remove radiance attributable to atmospheric and surface effects (Stumpf et al., in press). Water reflectance estimates how the signal (photons) received by the satellite is diminished as it passes through the atmosphere on the way down to the water-atmosphere boundary and on the way back up to the satellite after the signal leaves the water-atmosphere boundary. Water reflectance also estimates how the signal at the satellite is diminished by water vapor, clouds, specular effects at the water surface (wave surface glint), and other signal-absorbing and diffusing materials in the air and at the water surface (Green et al., 2000).

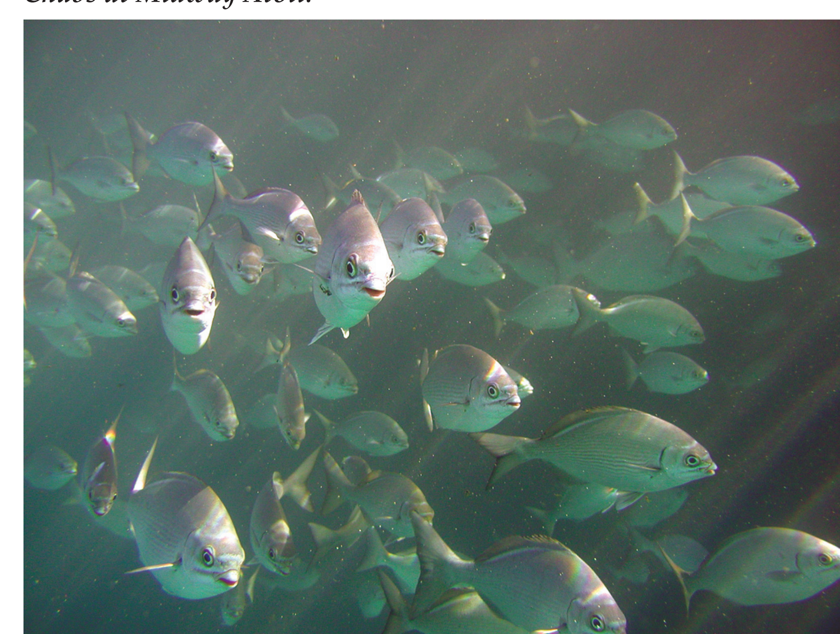
Estimating Depth

Water depth, in the form of estimated depth, is derived from the satellite imagery following the procedure of Stumpf et al. (in press). Knowing the depth of the water is important because water attenuates (absorbs) light. As the water depth increases, less and less light reaches the bottom and even less light is reflected off the bottom back up through the water column. Mapping relies on identifying and characterizing seabed features based on their spectral and morphologic characteristics. Due to water attenuation, the spectral characteristics of a seabed feature in 2 m of water is different than that same seabed feature in 10 m or 15 m of water. The estimated depth is used to compensate for the attenuation of light by the water column during analysis of satellite imagery. It also is used in the analysis to help determine seabed features such as patch reefs, linear reefs, and micro-atolls. Bathymetry provides valuable information for organism habitat use, where both structure and water depth affect distribution patterns. Estimated depth is being examined for use in vessel navigation, and this Atlas includes estimated depth for many areas in the NWHI. Estimated depth can be determined in clear water to between 20 m and 35 m, depending on the bottom type and absolute water clarity. The absolute accuracy of estimated depth varies with water depth. The error is generally 0.3 m for water less than 1 m deep. In water up to 15 m, deep the error is plus or minus 15 percent. In water 15 or more meters deep, the error is plus or minus 30 percent. The estimated depth maps in this Atlas depict structural features larger than 8 m in diameter.

Using the estimated depth and water reflectance, bottom albedo (bottom reflectance) is computed. The image analysis to identify and characterize seabed features (i.e., map) is performed on the bottom reflectance. Bottom reflectance is the approximate reflectance of bottom features when the water column is removed. Approximations of light attenuation are computed, based on real or estimated water depth, and "added" to the actual reflectance signal received from the bottom. The result is a "normalized" bottom feature reflectance.

The seabed habitat maps are generated using digital image analysis of the color and depth information. The analysis uses methods originally developed for land classification. The computer-based image identifies seabed features in the imagery based on spectral and spatial characteristics of seabed

Chubs at Midway Atoll.



Laysan ducks dabbling in hypersaline lake at Laysan Island.

features that are of similar type, but in different water depths. For example, sand has a much brighter appearance in water 5 m deep than in water 20 m deep. The analysis starts by incorporating numerous examples of the spectral and spatial characteristics of various habitats. In total, 1,130 of these site-specific examples were available for mapping the NWHI. These and other data (e.g., the estimated depth) are used to analyze the spectral and spatial characteristics of the image. The habitat maps have a minimum mapping unit of about 100 sq. m (six IKONOS pixels). Through a series of iterative steps, a final draft map is generated that depicts as many as 25 separate seabed habitats. The analysis also requires that a habitat classification scheme be developed.

Classification Scheme

The habitat classification scheme, developed with extensive input from locally-knowledgeable, shallow-water coral reef experts, describes the characteristics of each seabed habitat identified in the imagery. The scheme is designed to separate structure (e.g., unconsolidated or hard bottom) from cover (e.g., coral or macroalgae). The classification scheme for mapping the NWHI is presented on page 14. The classification scheme separates habitat on the basis of substrate, structure and cover. A total of 23 habitat types have been mapped in the NWHI. Indeterminate cover is identified on the maps, but is not considered a unique class. The draft NWHI classification scheme also can be downloaded at the following Web site: http://biogeo.nos.noaa.gov.

In addition to the 1,130 site-specific characterizations used, several other sources of information were used as part of the sonal communication also were used to support the mapping effort.

Map Validation

Once generated, the draft benthic habitat maps were evaluated for accuracy. Two types of validation were employed to validate the maps in this Atlas. First, two workshops were held in Hawai'i to enable locally-knowledgeable, shallow-water coral reef experts to review the draft maps and provide comments. The comments from these workshops were incorporated into the draft benthic habitat maps in this Atlas.

Participants in the draft habitat map review workshops include:

Alan Friedlander, Oceanic Institute
Ed Carlson, NOS, NGS
Rusty Brainard, NMFS, CREI
Jean Kenyon, NMFS, CREI
Joyce Miller, NMFS, CREI
Stephanie Holzwarth, NMFS, CREI
Frank Parrish, NMFS-Honolulu Laboratory
Ray Boland, NMFS-Honolulu Laboratory
Michael Parke, NMFS-Honolulu Laboratory
Dave Foley, NMFS-Honolulu Laboratory
Jim Maragos, FWS
Ron Salz, FWS
Miles Anderson, Analytical Laboratories of Hawai'i
Dave Gulko, DLNR
Dave Smith, DLNR
Will Smith, University of Hawai'i
Paul Jokiel, University of Hawai'i
Eric Brown, University of Hawai'i
Isabelle Abbott, University of Hawai'i
Fenny Cox, University of Hawai'i
Celia Smith, University of Hawai'i
Jennifer Smith, University of Hawai'i
Eric Hochberg, University of Hawai'i

Second, statistical analysis to compute a "user" and "producer" error was performed using a subset of the 1,100 site-specific habitat characterization data available for the NWHI. This analysis quantified the differences, i.e., the error, between what a habitat was in reality and what it was interpreted to be using rule-based image analysis. "User" accuracy is the probability that a habitat polygon interpreted from the image actually represents that habitat in the field. "Producer" accuracy is the probability that

Seajelly and jack at Maro Reef.

any polygon of a particular habitat is correctly classified (Green et al., 2000). The major habitat categories depicted on the draft maps will be evaluated for both "User" and "Producer" error. A Kappa Statistic is computed as part of the accuracy assessment. A Kappa Statistic of 0.59 (59 percent) implies that the classification process is avoiding 59 percent of the errors that a completely random classification would generate (Congalton, 1991; Green et al., 2000).

In addition, a Tau Coefficient is computed. The Tau Coefficient measures the accuracy of the entire map across all major categories. The Tau Coefficient is valuable because it indicates how many more habitat polygons (groups of pixels) were correctly classified than would be expected by chance alone (Ma and Redmond, 1995).

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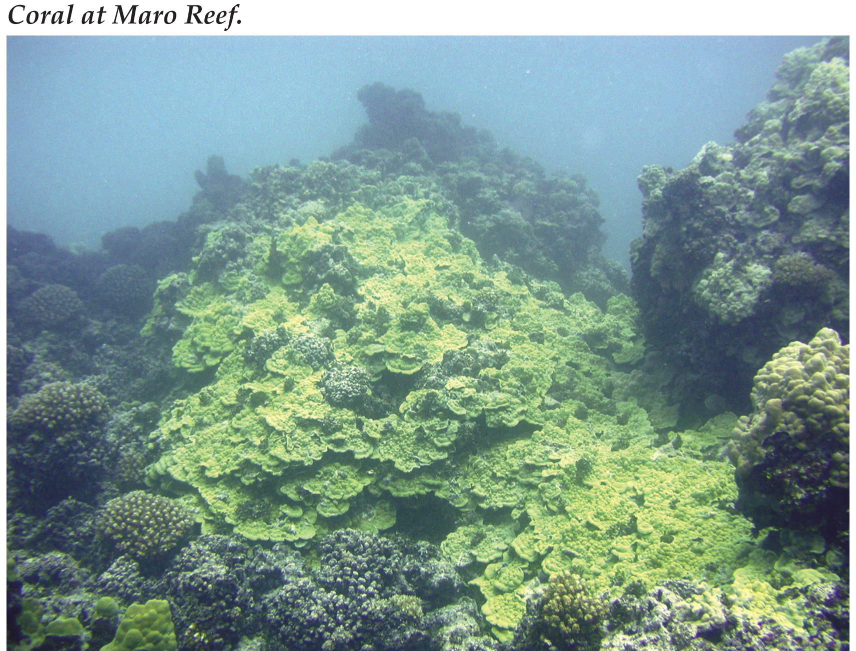
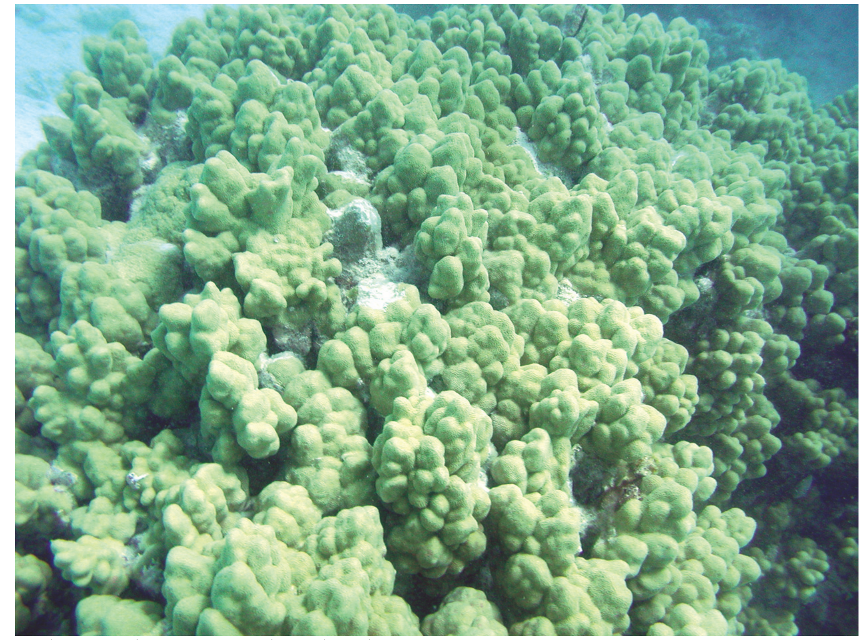
Coral at Maro Reef.





Lobe coral at Lisianski Island.

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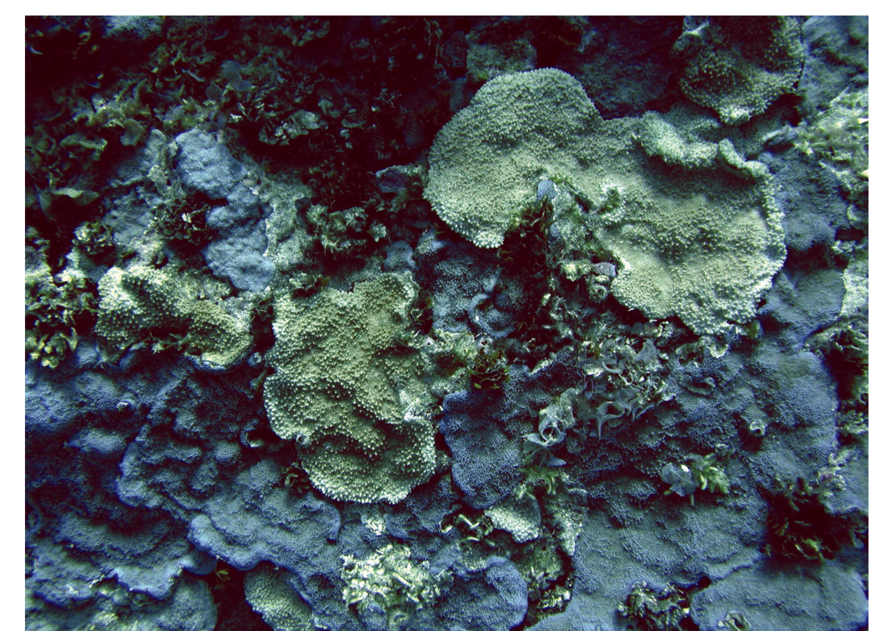
Rice coral at Lisianski Island.



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Unit Conversion Table

1 square kilometer	=	247.1 acres
	=	100 hectares
	=	0.29 square nautical miles
	=	0.39 square statute miles
1 kilometer	=	3,281 feet
	=	1,094 yards
	=	0.54 nautical miles
	=	0.62 statute miles

The Classification Scheme Used to Map the NWHI

A hierarchical benthic habitat classification scheme was used to define and delineate habitats in the NWHI. The scheme was developed with extensive input from shallow-water coral reef experts in Hawai'i. The structure of the classification scheme was initially based on schemes developed by NOS for shallow-water coral reef ecosystems in the Caribbean (Kendall et al, 2001) and main Hawaiian Islands (Coyne et al, 2001). Modifications were required to adapt these schemes to NWHI habitats and to characterization methods using satellite imagery.

The IKONOS satellite provided the imagery used for mapping the aggregated cover and detailed benthic habitats. The Landsat satellite provided the imagery for mapping the bank areas. Digital processing of the imagery to produce maps made it possible to establish a minimum mapping unit (MMU) of approximately 100 sq. m (1/40 acre). The spatial and spectral information from the satellite imagery was used to characterize detailed and aggregated benthic habitats and estimated depth. Combining digital image processing and establishing a small MMU enabled benthic features to be characterized that would not otherwise have been mapped.

Site-specific benthic feature characterization data and tow-board data collected in the NWHI by CREI and NOS were used extensively to develop and validate the digital image analysis procedures. These data also provided information used to better define several of the categories of habitat found in the classification scheme, particularly the macroalgae subcategory. The classification scheme was reviewed by shallow-water coral reef experts during a workshop held in Hawai'i and at several follow-up meetings and discussions.

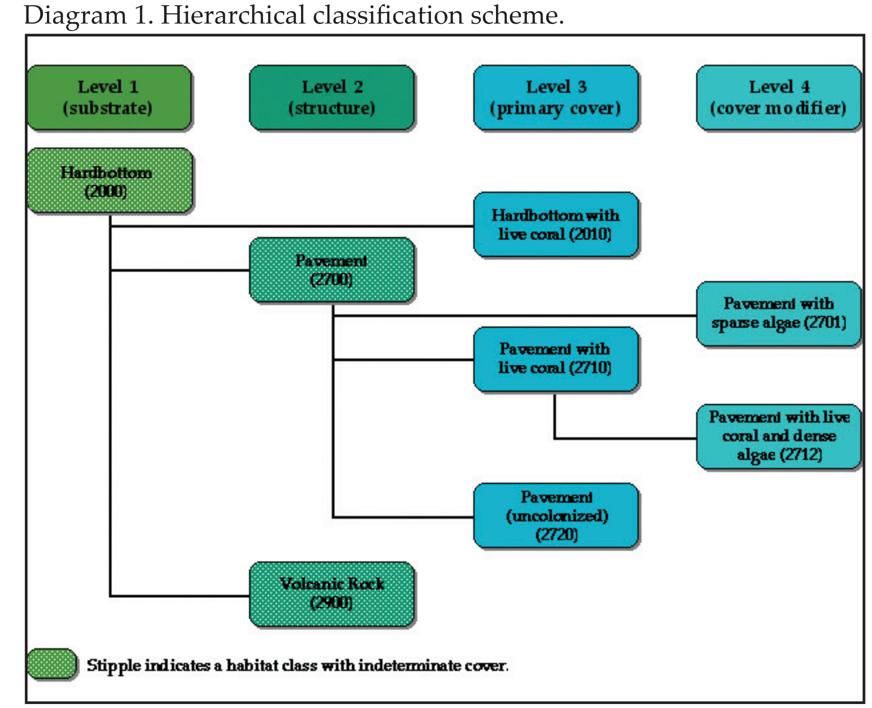
The classification scheme is designed to categorize benthic habitat by substrate category (unconsolidated and hardbottom), structure (e.g., linear reef or pavement) and cover (e.g., coral or macroalgae). Shallow-water coral reef ecosystems also can be grouped into larger geomorphological systems such as atoll and bank, and geographic zones such as lagoon and back reef. However, this Atlas focuses only on grouping by substrate, structure and cover.

The habitat scheme is hierarchical, descending from the broad substrate category (level 1), followed by structure (level 2), cover (level 3) and cover modifier (level 4). This format allows for flexible classifications; characterization of levels can be validated at a given time, and updated later as additional information becomes available (see Diagram 1). The structure of the classification scheme for NWHI is presented in the table below, with the class numbers designating the classification level (e.g., 1000 represents a first-level class, 1100 a second, 1110 a third, and 1111 a fourth).

A total of 30 unique classes of benthic habitat were included in the NWHI classification scheme. Of these independent classes, 23 have been identified and mapped at one or more atolls in the NWHI. Including both unique and upper level classes, a total of 45 separate habitat classes are identified on the maps included in the Atlas. For more information on the NWHI mapping effort, please visit: http://biogeo.nos.noaa.gov.

Descriptions of the detailed benthic habitats mapped in the NWHI can be found starting on page 16. Descriptions of the aggregated benthic cover habitats mapped in the NWHI can be found starting on page 21.

Diagram 1. Hierarchical classification scheme.



The Detailed Benthic Habitat Classification Scheme of the Northwestern Hawaiian Islands. The numbers in parentheses are hierarchical, 4-digit codes assigned to each habitat type.

Unconsolidated sediment* (1000)

- Sand* (1100)
  - Sand with seagrass (1110)
  - Sand with macroalgae (1120)
    - Sand with patchy (10–50% cover) macroalgae* (1121)
    - Sand with dense (>50% cover) macroalgae* (1122)
- Calcareous Mud (1200)
- Unconsolidated Rubble* (1300)
  - Unconsolidated Rubble with sparse (10–50% cover) algae* (1301)
  - Unconsolidated Rubble with dense (>50% cover) algae* (1302)
- Sand and Rubble* (1400)
- Groove* (1500)
- Hardbottom* (2000)
  - Hardbottom with sparse (10–50% cover) algae* (2001)
  - Hardbottom with live coral (>10% cover)* (2010)
  - Hardbottom, uncolonized* (2020)
  - Hardbottom with crustose coralline algae (>10% cover)* (2030)
- Linear Reef* (2100)
  - Linear Reef with live coral (>10% cover)* (2110)
  - Linear Reef, uncolonized* (2120)
    - Linear Reef, uncolonized with sparse (10–50% cover) algae* (2121)
  - Linear Reef with crustose coralline algae (>10% cover)* (2130)
- Aggregated Coral Heads* (2200)
  - Aggregated Coral Heads with live coral (>10% cover)* (2210)
- Spur and Groove* (2300)
- Individual Patch Reef* (2400)
  - Patch Reef with live coral (>10% cover)* (2410)
  - Patch Reef, uncolonized* (2420)
    - Patch Reef, uncolonized with sparse (10–50% cover) algae* (2421)
  - Patch Reef with crustose coralline algae (>10% cover) (2430)
- Aggregated Patch Reef* (2500)
  - Aggregated Patch Reef with live coral (>10% cover)* (2510)
- Scattered Coral/Rock in sand with live coral (2600)
  - Scattered Coral/Rock in sand with live coral (>10% cover)* (2610)
- Pavement* (2700)
  - Pavement with sparse (10–50% cover) algae* (2701)
  - Pavement with dense (>50% cover) algae* (2702)
  - Pavement with live coral (>10% cover)* (2710)
    - Pavement with live coral (>10% cover) and dense (>50% cover) algae* (2712)
  - Pavement, uncolonized* (2720)
    - Pavement, uncolonized with dense (>50% cover) algae* (2722)
  - Pavement with crustose coralline algae (>10% cover)* (2730)
- Pavement with Sand Channels* (2800)
  - Pavement with sand channels and live coral (>10% cover)* (2810)
  - Pavement with sand channels, uncolonized* (2820)
- Volcanic Rock* (2900)
  - Volcanic Rock with dense (>50% cover) algae* (2902)
  - Volcanic Rock with live coral (>10% cover)* (2910)
  - Volcanic Rock, uncolonized* (2920)

Other Delineations* (3000)

- Deep water* (3010)
- Reef crest* (3020)
- Dredged channel* (3030)
- Land* (3100)
  - Artificial* (3110)
- Flags* (3200)
  - Cloud cover* (3210)
  - Shadow* (3220)
  - Surf* (3230)
  - Missing Data* (3240)
- Unclassified* (3300)

No Data* (4000)

The Aggregated Cover Benthic Habitat of the Northwestern Hawaiian Islands. This classification scheme combines numerous detailed habitat categories into more general cover habitat categories.

Hardbottom with >10% live coral
- Hardbottom with live coral (>10% cover)* (2010)
- Linear Reef with live coral (>10% cover)* (2110)
- Aggregated Coral Heads with live coral (>10% cover)* (2210)
- Patch Reef with live coral (>10% cover)* (2410)
- Aggregated Patch Reef with live coral (>10% cover)* (2510)
- Scattered Coral/Rock in sand with live coral (>10% cover)* (2610)
- Pavement with live coral (>10% cover)* (2710)
- Pavement with live coral (>10% cover) and dense (>50% cover) algae* (2712)
- Pavement with sand channels and live coral (>10% cover)* (2810)
- Volcanic Rock with live coral (>10% cover)* (2910)

Hardbottom with >10% crustose coralline algae
- Hardbottom with crustose coralline algae (>10% cover)* (2030)
- Linear Reef with crustose coralline algae (>10% cover)* (2130)
- Patch Reef with crustose coralline algae (>10% cover)* (2430)
- Pavement with crustose coralline algae (>10% cover)* (2730)

Hardbottom (uncolonized)
- Hardbottom, uncolonized* (2020)
- Linear Reef, uncolonized* (2120)
- Patch Reef, uncolonized* (2420)
- Pavement, uncolonized* (2720)
- Pavement with sand channels, uncolonized* (2820)
- Volcanic Rock, uncolonized* (2920)

Hardbottom with >10% macroalgae
- Hardbottom with sparse (10–50% cover) algae* (2001)
- Linear Reef, uncolonized with sparse (10–50% cover) algae* (2121)
- Patch Reef, uncolonized with sparse (10–50% cover) algae* (2421)
- Pavement with sparse (10–50% cover) algae* (2701)
- Pavement with dense (>50% cover) algae* (2702)
- Pavement with live coral (>10% cover) and dense (>50% cover) algae* (2712)
- Pavement, uncolonized with dense (>50% cover) algae* (2722)

Hardbottom with indeterminate cover
- Hardbottom* (2000)
- Linear Reef* (2100)
- Spur and Groove* (2300)
- Individual Patch Reef* (2400)
- Aggregated Patch Reef* (2500)
- Pavement* (2700)
- Pavement with Sand Channels* (2800)
- Volcanic Rock* (2900)

Unconsolidated with 10% or less macroalgae or seagrass
- Unconsolidated sediment* (1000)
- Sand* (1100)
- Unconsolidated rubble* (1300)
- Sand and rubble* (1400)
- Groove* (1500)

Unconsolidated with >10% macroalgae or seagrass
- Sand with macroalgae (1120)
- Sand with patchy (10–50% cover) macroalgae* (1121)
- Sand with dense (>50% cover) macroalgae* (1122)
- Unconsolidated Rubble with sparse (10–50% cover) algae* (1301)
- Unconsolidated Rubble with dense (>50% cover) algae* (1302)

(* - This habitat category or other delineation was identified on a map.)

Detailed habitat classification descriptions

The detailed benthic habitat classification scheme was designed to categorize benthic habitat by substrate category (unconsolidated and hardbottom), structure (e.g., linear reef or pavement) and cover (e.g., coral or macroalgae). The scheme is hierarchical, descending from the broad substrate category (level 1), followed by structure (level 2), cover (level 3) and cover modifier (level 4). This enables researchers, managers, and others to use the maps to answer questions at varying levels of detail. For more information on how benthic habitat maps are used for research and management activities, please visit: http://biogeo.nos.noaa.gov.

Unconsolidated sediments, **Hardbottom** and "**Other Delineations**" represent the first level of habitat categories. **Unconsolidated sediments** were further divided into sand, mud and rubble at the structure level, into presence of vegetation at the cover level, and into percent cover at the cover modifier level.

Hardbottom was divided into nine categories of coral or rock formations at the structure level, into three categories of coral/coralline algal cover at the cover level, and into percent macroalgal cover at the cover modifier level. Because low macroalgal and/or turf algal cover was frequently found on hardbottom substrate in NWHI, algal cover was considered on a separate level for hardbottom, in order to better distinguish, where possible, combinations of macroalgae with live coral or coralline algal cover. Note that distinction was made between the macroalgal beds (e.g., *Halimeda spp.*) on sand substrate (class 1120), and low macroalgae (e.g., *Microdictyon spp.*) found on **hardbottom** substrates (level 4 classes).

Turf algae is commonly found on both **unconsolidated rubble** and **hardbottom** substrates. Habitat features that cover areas smaller than the MMU were not mapped as separate features, but described as a class that aggregates them into larger areas (e.g., **Scattered Coral/Rock in Sand**). Similarly, some habitat classes were included that combine substrate types, where the combination has particular biological and/or structural significance (e.g., **Pavement with Sand Channels**).

Other Delineations includes features identified in the imagery, but are not benthic habitat, such as deep water, intertidal reef crest, dredged channels, and land, as well as areas that are obscured by cloud, shadow or surf. Areas of imagery that were not obscured, but which were not conclusively classified (typically deep areas where the bottom was marginally visible) are listed as "unclassified."

The Detailed Benthic Habitat Classification Scheme of the Northwestern Hawaiian Islands.

Unconsolidated sediment* (1000): Mobile substrate that varies in coarseness (from mud to sand to rubble), and which is characterized by some degree of instability in response to water motions.

Five habitat subcategories exist within the Unconsolidated sediment habitat category. These Level 2 subcategories include:

Sand* (1100): Coarse sediment typically found in areas exposed to currents or wave energy. See Figures 1, 15 and 16.

Calcareous Mud (1200): Fine sediment associated with buildup of organic material in areas sheltered from high-energy waves and currents. This habitat category is not found in the NWHI.

Unconsolidated Rubble* (1300): Dead, unstable coral rubble that appears predominantly pebble- and cobble-sized. This habitat often occurs landward of well-developed reef crest formations or in the back reef, as well as at the base of patch reef and linear reef formations. See Figures 2 and 15.

Sand and Rubble* (1400): Sediment composed of approximately even amounts of sand and rubble that cannot be separately distinguished in the imagery for the given area.
Groove* (1500): Narrow, linear sand feature that alternates with coral formations in spur and groove habitat (see Figure 6), and which is oriented perpendicular to the shore or bank/shelf escarpment. Groove is delineated as an individual category when the channel is clearly larger than the MMU.

A Level 3 subcategory describes the type of algae found on the **Unconsolidated** sediment substrate. Two Level 3 subcategories have been defined:

Sand with seagrass* (1110): Sand with 10 percent or greater cover of seagrass, where percent cover refers to coverage of the substrate by the bed, rather than shoot density. Note that this habitat is very uncommon in NWHI. Representative species: *Halophila sp.*

Figure 1. Sand at Midway Atoll.

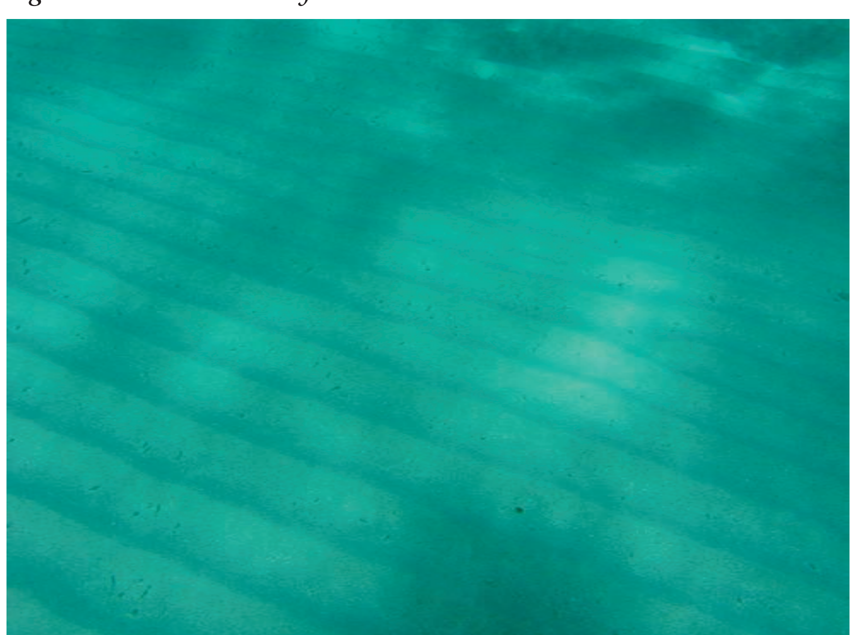


Figure 2. Unconsolidated rubble at Midway Atoll.

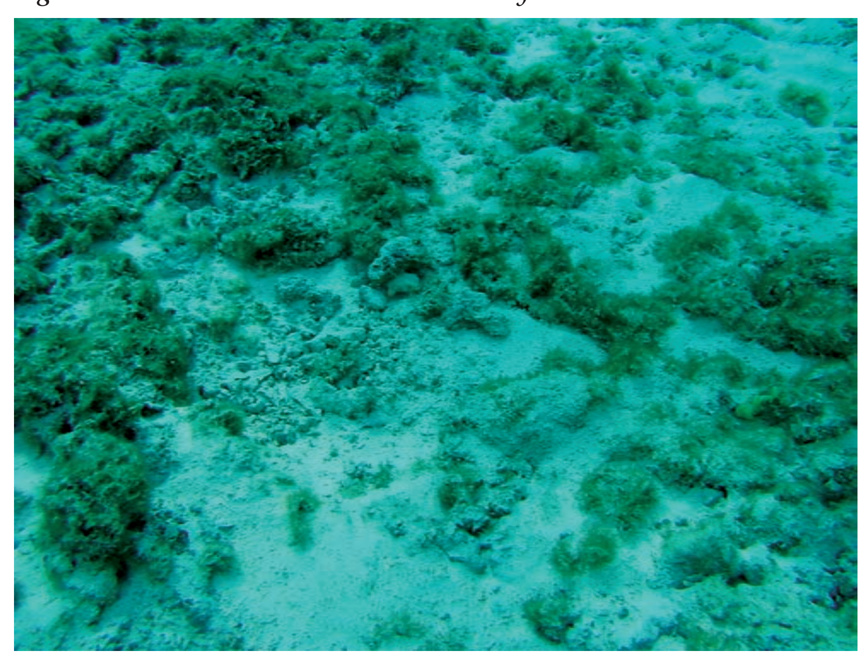
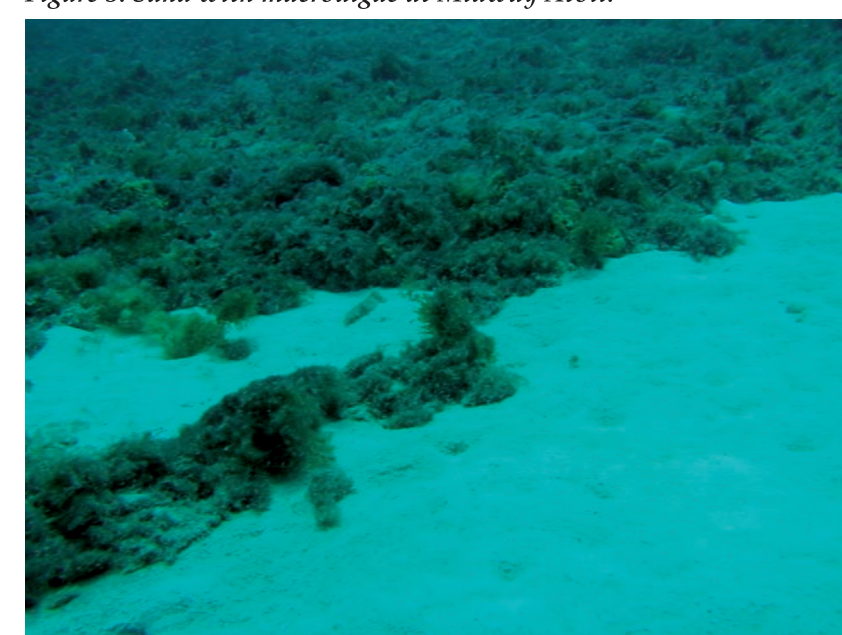


Figure 3. Sand with macroalgae at Midway Atoll.



Sand with macroalgae* (1120): An area with 10–100 percent coverage of any combination of numerous species of red, green or brown macroalgae. Typically occurs at the base of patch and linear reef structures and can be a transient feature. Note that this habitat is much less common in NWHI than is macroalgal cover on rubble or hardbottom substrate. Representative species: *Dictyosphaeria spp.*; *Halimeda spp*. See Figure 3.

Finally, Level 4 subcategory describes the percentage of algae found on the **Unconsolidated** sediment substrate. Six Level 4 subcategories have been defined.

Patchy seagrass (1111): Discontinuous seagrass (10–50 percent cover), with breaks in coverage that are too diffuse or irregular, or result in isolated patches of seagrass that are too small (less than the MMU) to be mapped as dense beds. This category of habitat is found at Midway Atoll, and, possibly, at Pearl and Hermes Atoll.

Dense seagrass (1112): Seagrass beds covering greater than 50 percent of the substrate. This habitat may include blowouts (no coverage) of less than 10% of the total area that are too small (less than the MMU) to be mapped independently. This category of habitat is not found in the NWHI.

Sand with patchy (10–50 percent cover) macroalgae* (1121): Discontinuous macroalgae (10-50 percent cover), with breaks in coverage that are too diffuse or irregular, or result in isolated patches of macroalgae that are too small (smaller than the MMU) to be mapped individually as dense beds.

Sand with dense (>50 percent cover) macroalgae* (1122): Macroalgae covering 50–100 percent of the sand substrate. May include blowouts (no coverage) of less than 10 percent of the total area that are too small (less than the MMU) to be mapped independently.

Unconsolidated Rubble with sparse (10–50 percent cover) algae* (1301): Rubble with 10–50 percent cover of macroalgae or turf algae. Turf algae is the most frequent cover type.

Unconsolidated Rubble with dense (>50 percent cover) algae* (1302): Rubble with greater than 50% cover of macroalgae or turf algae. See Figure 15.

Hardbottom * (2000): Hardened substrate of unspecified relief formed by the deposition of calcium carbonate by reef building corals and other organisms (relict or ongoing) or existing as exposed bedrock or volcanic rock. Habitats within this category typically have some colonization by live coral. If no coral colonization is present, habitats would be categorized as **Uncolonized**.

Nine habitat subcategories exist within the **Hardbottom** habitat category. The Level 2 subcategories generally describe structural features found within shallow-water coral reef ecosystems. These nine Level 2 subcategories include:

Linear Reef* (2100): Linear coral formations that often are oriented parallel to shore or the shelf edge, but which are also found within NWHI atolls, without a particular axis relative to the shore/shelf edge. This category includes habitat structures that are commonly referred to as fore reef, fringing reef, and shelf edge reef. See Figures 4 and 15.

Aggregated Coral Heads* (2200): Coral formations that are composed of relatively monotypic coral colonies, typically isolated from other shallow-water coral reef formations by unconsolidated sediment, where the hardened substrate is larger than the MMU. This habitat can include large individual coral heads and clusters of coral heads that are too small (less than the MMU) or too close together to be mapped separately. Small, individual coral heads that are isolated from each other by larger areas of sediment normally will be classed as scattered coral/rock (see below), rather than as aggregated coral heads. Representative species: *Porites spp.; Montipora spp.; Acropora spp.* See Figures 5 and 15.

Spur and Groove* (2300): Habitat having alternating sand and coral formations that are oriented perpendicular to the shore or bank/shelf escarpment. The coral formations (spurs) of this feature typically have a high vertical relief relative to pavement with sand channels (see below) and are separated from each other by 1–5 m of sand or bare hard bottom (grooves). The height and width of the spurs and grooves may vary considerably. This habitat type typically occurs in the fore reef or bank/shelf escarpment region and is frequently found seaward of breaks in the barrier reef. The spur and groove habitat is important for dissipating wave energy. See Figures 6, 15 and 16.

Figure 4. Linear reef at Midway Atoll.

Figure 5. Aggregated coral heads at Kure Atoll.

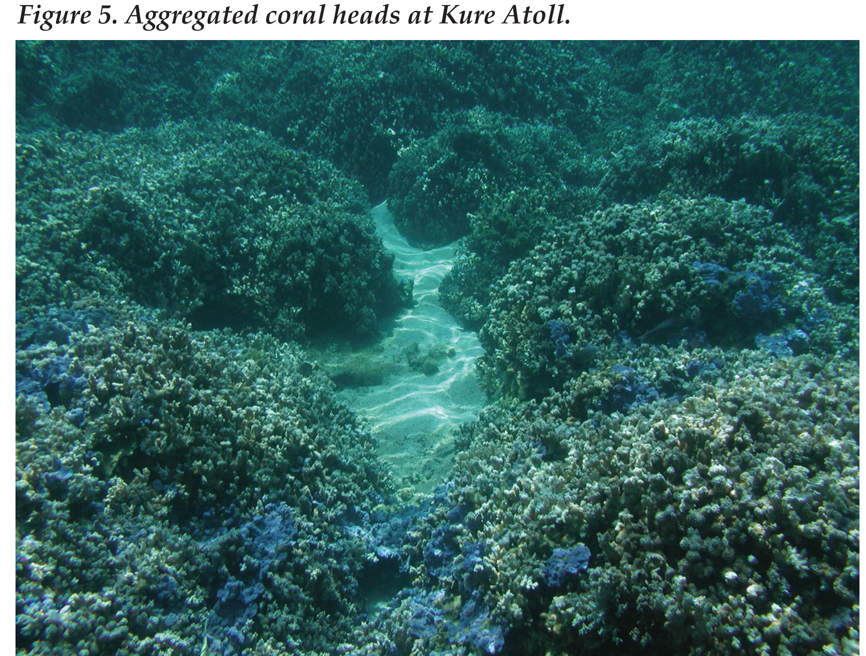


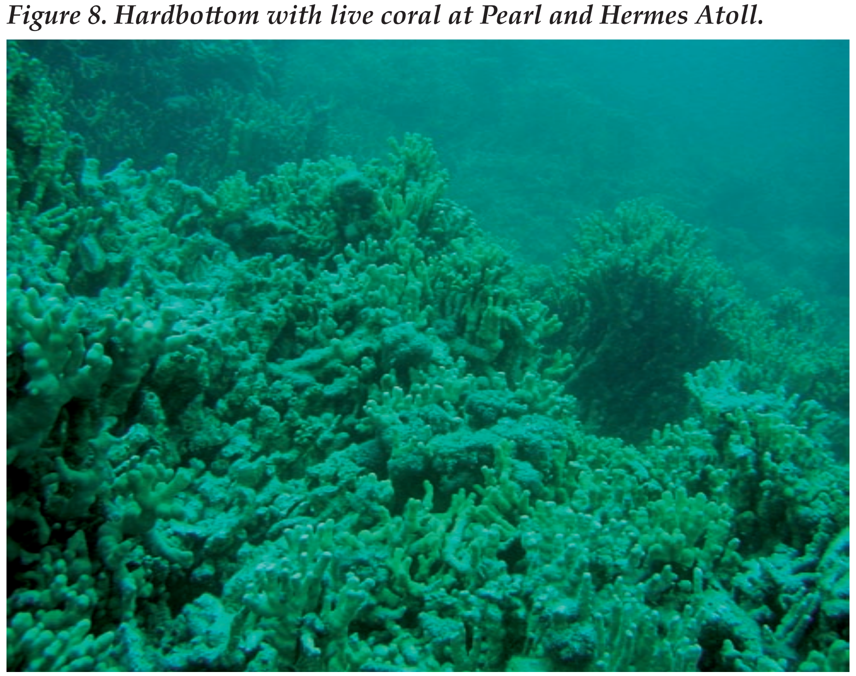
Figure 6. Spur and groove at Midway Atoll.

Figure 7. Individual patch reef at Midway Atoll.

Individual Patch Reef* (2400): Shallow-water coral reef formations that are isolated from other shallow-water coral reef formations by unconsolidated sediments and that have no organized structural axis relative to the contours of the shore or shelf edge. Unlike aggregated coral heads, patch reefs typically consist of a diverse assemblage of coral and algal species. Distinctive single patch reefs are larger than or equal to 100 sq. m. See Figures 7, 15 and 16.

Aggregated Patch Reef* (2500): Clustered patch reefs that are individually too small (less than the MMU) or are too close together to map as individual patch reefs.

Figure 8. Hardbottom with live coral at Pearl and Hermes Atoll.



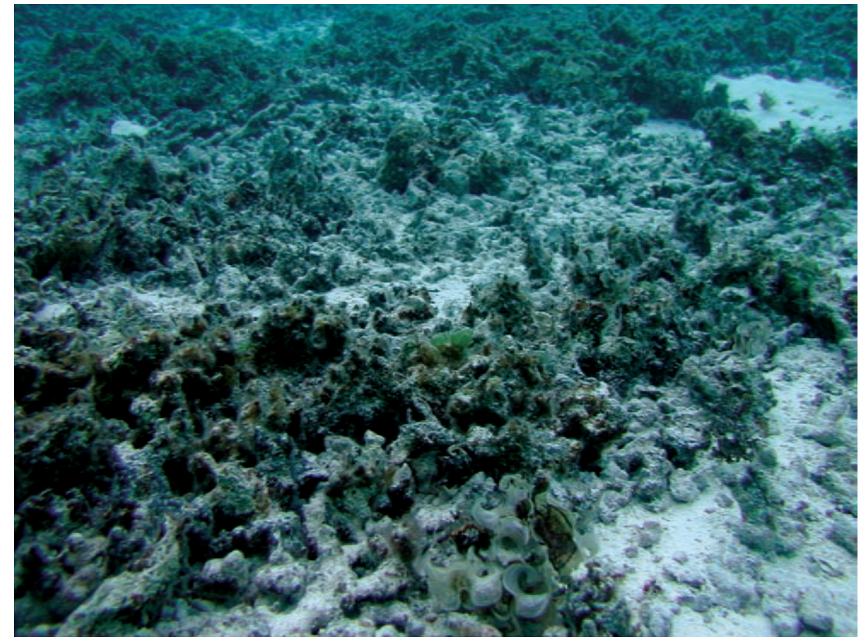


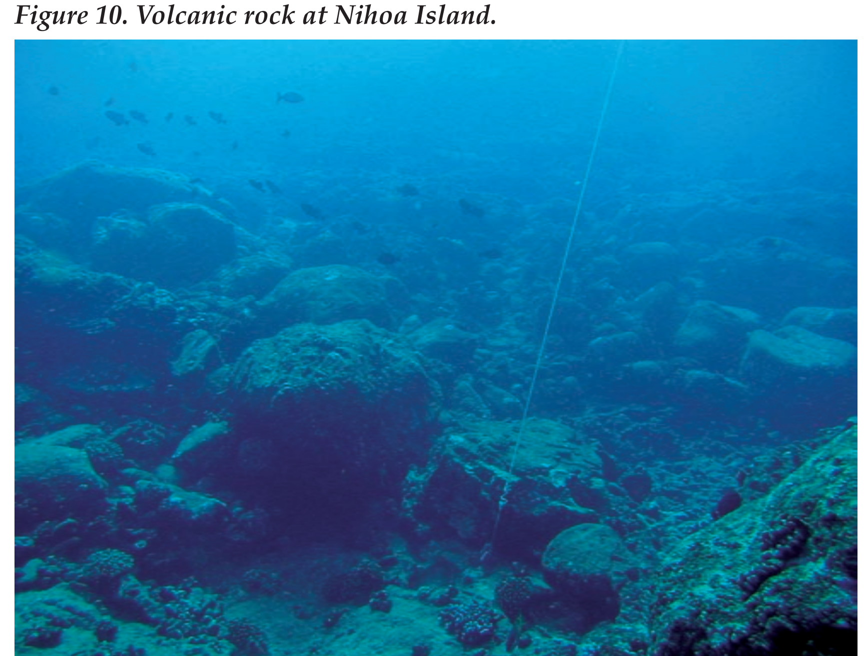
Figure 9. Pavement with macroalgae at Kure Atoll.

Scattered Coral/Rock in sand with live coral* (2600): Sand or rubble substrate with scattered rocks, or small, isolated coralheads that are too small to be delineated individually (i.e., too small to be identified as individual patch reef or aggregated coral heads).

Pavement* (2700): Flat, low-relief, solid carbonate rock. See Figures 9, 15 and 16.

Pavement with Sand Channels* (2800): Habitat with alternating sand and pavement substrates that are oriented perpendicular to the shore, fringing reef or bank/shelf escarpment. The sand channels of this feature have low vertical relief relative to spur and groove formations. This habitat type occurs in areas exposed to moderate wave surge such as the bank/shelf zone or areas just landward of breaks in the barrier reef. See Figure 16.

Figure 10. Volcanic rock at Nihoa Island.



Volcanic Rock* (2900): Substrate of exposed basalt rock, which frequently includes large boulders and blocks. This habitat is typically found in nearshore environments around small basalt islands. See Figure 10.

A Level 3 subcategory describes the type and percentage of coral and/or crustose coralline algae found on the **Hardbottom** substrate. Three Level 3 subcategories have been defined. These second-level subcategories may apply to more than one Level 2 subcategory.

Hardbottom with live coral (>10 percent cover)* (2x10): Substrates formed by the deposition of calcium carbonate by reef-building corals and other organisms. Habitats within this category have greater than 10 percent colonization by live coral. Representative species: *Porites compressa*, *Porites lobata*, *Montipora spp.*, *Pocillopora meandrina*. See Figure 8.

Hardbottom, uncolonized* (2x20): Hard substrate composed of relict deposits of calcium carbonate or exposed volcanic rock. Habitats within this category have 10 percent or less coverage of hard coral or crustose coralline algae, but total coverage from both cover types may exceed 10 percent. See Figure 11.

Figure 11. Uncolonized hardbottom at Midway Atoll.

Hardbottom with crustose coralline algae (>10 percent cover)* (2x30): An area with 10 percent or greater coverage of any combination of numerous species of encrusting or coralline algae. This habitat is typically found on reef crest and in shallow back reef and fore reef areas. Representative species: *Porolithon gardineri*. See Figure 12.

Finally, a Level 4 subcategory describes the percentage of algae found on the **Hardbottom** substrate. Two Level 4 subcategories are defined. These Level 4 subcategories may apply to more than one Level 3 subcategory.

Sparse (10–50 percent cover) algae* (2xx1): Discontinuous macroalgae and/or turf algae, covering 10–50 percent of the hardbottom substrate.

Dense (>50 percent cover) algae* (2xx2): Discontinuous to continuous macroalgae and/or turf algae, covering greater than 50 percent of the hardbottom substrate. See Figure 13.

Other Delineations* (3000): Describes several types of features found in the imagery that are not representative of shallow-water coral reef ecosystem. This specific category also is used to identify the saline lake found on Laysan Island.

Deep water* (3010): Areas where the bottom cannot be detected (identified) in the imagery. In most cases, this occurs in water more than 30 m deep. However, turbidity in the water column can obscure the bottom in water as little as five m deep. Areas affected by turbidity and where field-based supplemental information was lacking were labeled "unclassified."

Reef crest* (3020): The flattened, emergent or nearly emergent segment of a reef. This feature typically is found along barrier reef lines in NWHI and is frequently covered with dense macroalgae. Breaking waves are typically found at or just seaward of the reef crest and are delineated as surf (see below) if present in the imagery. See Figures 14, 15 and 16.

Dredged channel* (3030): Area where excavation or dredging has occurred.

Land* (3100): Areas determined to be above the water line in the imagery at the time the imagery was acquired. See Figure 16.

Artificial * (3110): Human-made habitats such as dredged channels, large piers, submerged wrecks, submerged portions of rip-rap jetties, and the shoreline of islands created from dredge spoil.

Flags* (3200): Areas where the water or land surface in the imagery is obscured. The types of flags include:
Cloud cover (3210)
Shadow (3220)
Reef crest or Surf (3020; 3230) See Figures 15 and 16.
Missing data (3240; data dropouts in the imagery)

Unclassified * (3300): Areas where the bottom type is unclassified because of turbidity in the water, surface glint, or other types of interference. This category also includes areas where the seabed cannot be classified due to a lack of supplemental field-based information, or for other reasons.

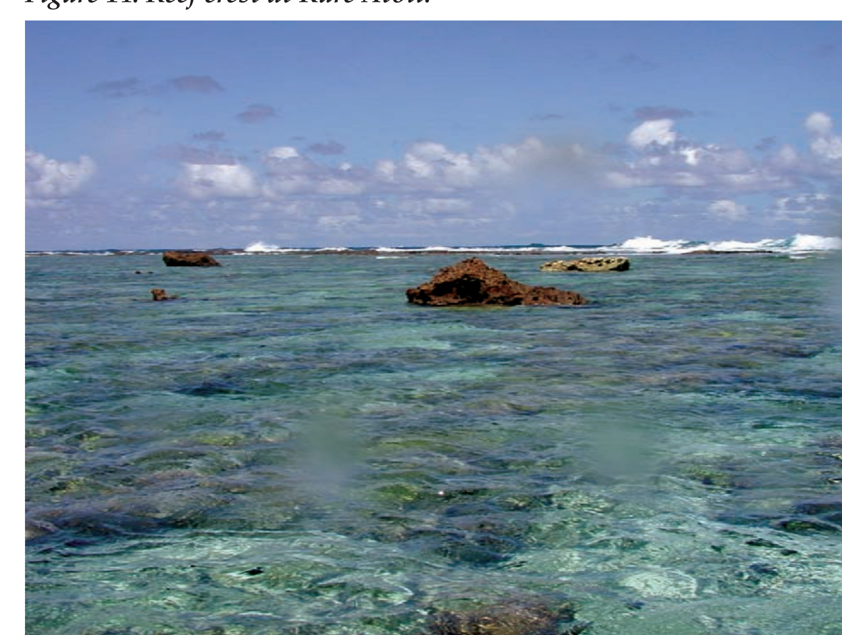
No data* (4000): Refers to areas within the geographic bounds of the habitat map that lie outside the bounds of the acquired imagery. This is not a habitat category in the classification scheme.

(* – This habitat category or other delineation was identified on a map within this Atlas.)

Figure 12. Hardbottom with crustose coralline algae at Lisianski Island.

Figure 13. Hardbottom with dense macroalgae at Kure Atoll.

Figure 14. Reef crest at Kure Atoll.



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Aggregated habitat cover classification descriptions

The aggregated habitat cover classification scheme was designed to provide information on substrate (hardbottom or unconsolidated) and habitat cover (coral, crustose coralline algae, macroalgae/seagrass, or uncolonized) found in the NWHI. By aggregating the detailed habitats into aggregated cover, analyses can be performed to assess, for example, the overall distribution of live coral cover, rather than whether it lies on a patch reef, pavement or volcanic rock structure. Areas that were classified only to the first or second level—meaning that specific cover was not identified—were combined into the aggregate class of indeterminate cover.

A brief description of each aggregate class is provided, along with an example of a class that is included in each category. The four-digit detailed habitat class numbers can be used to determine hardbottom cover groups, since the numbering is consistent with respect to cover. For example, a "1" in the third position (e.g., 21<u>1</u>0) always indicates live coral cover, a "2" always indicates uncolonized bottom, a "3" always indicates crustose coralline algal cover and a "0" always indicates indeterminate cover. Macroalgal cover is found in the fourth position (e.g. 272<u>2</u>), with a "1" indicating sparse (10–50 percent) coverage and a "2" indicating dense (>50 percent) coverage.

The Aggregated Habitat Cover Classification Scheme of the Northwestern Hawaiian Islands.

Hardbottom with >10 percent live coral: Included all classes in the hardbottom substrate category (linear reef, patch reef, pavement, etc.) that had more than 10 percent live coral cover. Hardbottom that was not classified with respect to structure (class 2020), but which had live coral, was also included in this category. Bottom habitat consisting of mixtures of live coral, crustose coralline algae and macroalgae also fell into this category as long as there was enough live coral to meet the 10 percent threshold. Example detailed class: Pavement with live coral (>10 percent cover) and dense (>50 percent cover) algae (2712).

Hardbottom with >10 percent crustose coralline algae: Included all classes in the hardbottom substrate category that had more than 10 percent live crustose coralline algal cover, but not more than ten percent live coral cover. Bottom habitats with a mixture of crustose coralline algae, live coral (not more than 10 percent) and macroalgae fell in this category if there was enough crustose coralline algae to meet the 10 percent threshold. Example detailed class: Linear Reef with crustose coralline algae (>10 percent cover) (2130).

Hardbottom (uncolonized): Included all classes in the hardbottom substrate category that had less than 10 percent live coral cover, crustose coralline algal cover or macroalgal cover. Example detailed class: Pavement with sand channels, uncolonized (2820).

Hardbottom with >10 percent macroalgae: Included all classes in the hardbottom substrate category that had more than 10 percent macroalgae, but not more than 10 percent live coral cover or 10 percent crustose coralline algal cover. Typically, these habitats also had a high percentage of turf algal cover. Example detailed class: Hardbottom with sparse (10–50 percent cover) algae (2001).

Hardbottom with indeterminate cover: Included all classes in the hardbottom substrate category for which a specific bottom cover was not identified. Included were all areas classified only to the first or second level of the detailed classification scheme. Example detailed class: Aggregated Patch Reef (2500).

Unconsolidated with 10 percent or less macroalgae or seagrass: Included all classes in the unconsolidated substrate category with not more than 10 percent cover of live submerged vegetation (macroalgae/seagrass). Example detailed class: Sand (1100).

Unconsolidated with >10 percent macroalgae or seagrass: Included all classes in the unconsolidated substrate category with more than 10 percent cover of live submerged vegetation (macroalgae/seagrass). Seagrass was very uncommon in NWHI (only a small area was found at Midway during the field survey) and was not identified on any of the habitat maps. Example detailed class: Sand with patchy (10–50 percent cover) macroalgae (1121).

Figure 15. An image of a portion of Kure Atoll showing typical benthic habitats. These benthic habitats are described in the classification scheme.

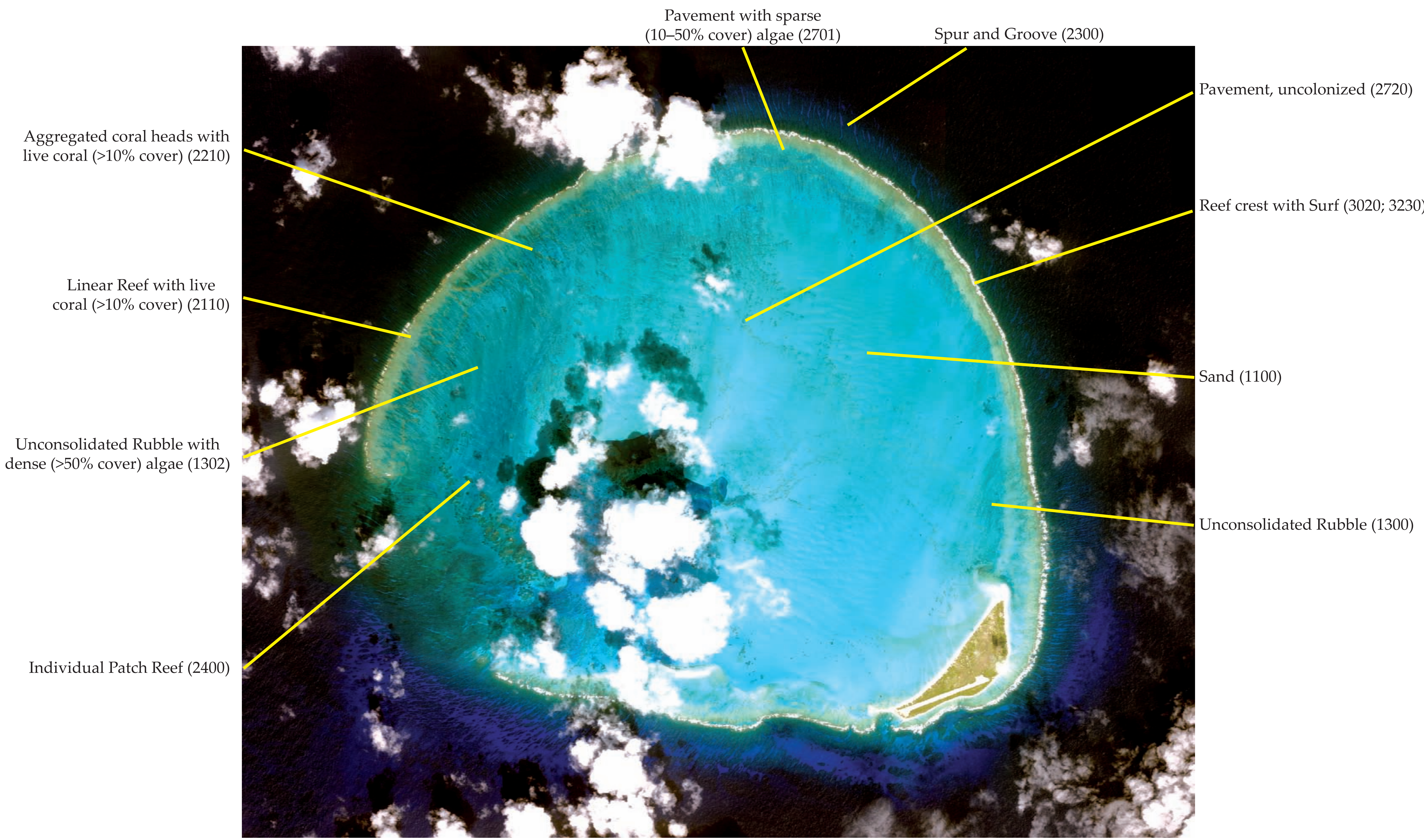


Figure 16. An image of a portion of Pearl and Hermes Atoll showing typical benthic habitats. These benthic habitats are described in the classification scheme.

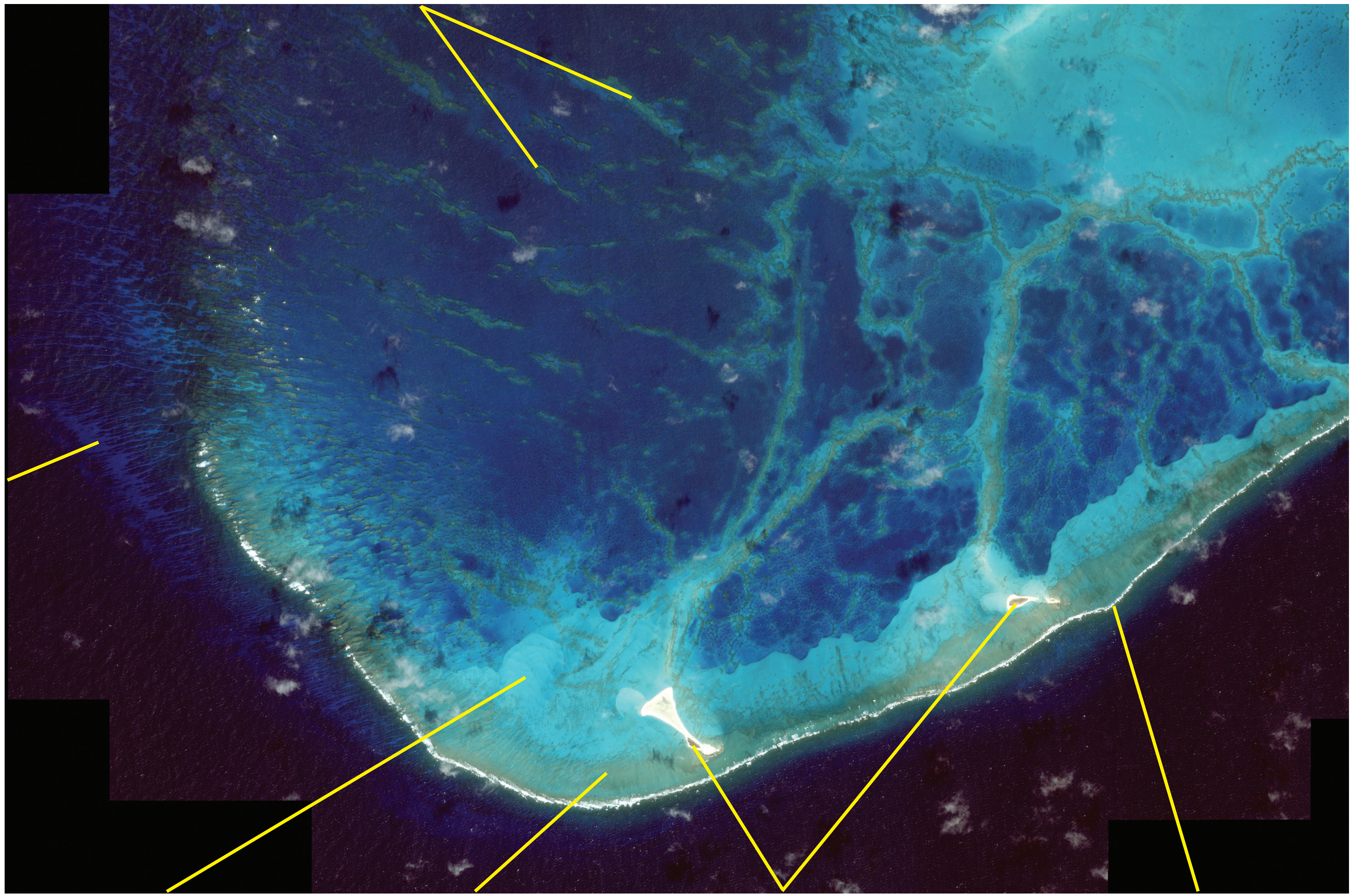


Table 3. Area Mapped by Aggregated Habitat Cover Type and Geographic Locale (sq. km)

	Kure Atoll	Midway Atoll	Pearl & Hermes Atoll	Lisianski Island	Laysan Island	Maro Reef	French Frigate Shoals	Necker Island	Nihoa Island	TOTAL
Hardbottom with >10% live coral	1.8	1.4	20.3	16.4	5.8	14.8	48.3	0.0	<0.1	108.8
Hardbottom with >10% crustose coralline algae	0.7	0.1	0.0	0.0	0.5	1.3	4.7	0.0	0.0	7.3
Hardbottom (uncolonized)	11.6	14.9	13.7	0.9	2.9	6.8	49.9	0.0	0.7	101.4
Hardbottom with >10% macroalgae	5.8	22.4	62.2	6.1	0.1	0.4	3.7	0.0	4.5	105.2
Hardbottom with indeterminate cover	8.4	6.7	49.3	183.5	81.7	180.1	46.1	208.1	58.9	822.8
Unconsolidated with 10% or less macroalgae or seagrass	38.8	49.9	226.2	231.8	36.2	295.7	241.5	19.5	10.0	1149.6
Unconsolidated with >10% macroalgae or seagrass	2.7	0.2	19.9	0.0	0.0	19.6	23.4	0.0	0.0	65.8
Total Habitat Area Classified	69.8	95.5	391.6	438.7	127.2	518.7	417.6	227.6	74.1	2360.8

No aggregated habitat cover maps were generated for Gardner Pinnacles and the bank areas found in the NWHI.

Table 4. Analysis of Mapped Areas, October 2002

This table presents a compilation of the best available information on area mapped within the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve. The values presented in the table are estimates derived from NOAA nautical charts and remotely sensed imagery.

	Area Within:				
Location in the NWHI	100-fathom isobath (digitized from NOS chart) in sq. km	20-fathom isobath (digitized from NOS chart) 97 in sq. km	10-fathom isobath (digitized from NOS chart) in sq. km	Landsat (visible bottom) in sq. km	IKONOS (mapped habitat) in sq. km
Kure Atoll	341	133	–	–	– 70
Midway Islands	361	–	– 99	–	– 96
Ladd Seamount	146	–	–	–	–
Gambia Shoal	15			–	
Salmon Bank	155	528	–	–	–
Pearl and Hermes Atoll	744	–	– 387	–	– 392
Unnamed Bank ESE of Pearl and Hermes Atoll	5	–	–	–	–
Unnamed Bank SSE of Pearl and Hermes Atoll	5				
Unnamed Bank SW of Lisianski Island	105	–	–		–
Lisianski Island	1,225	1,151	– 211	972	– 439
Pioneer Bank	428			369	
Northhampton Seamounts	394	516		269	
Laysan Island	578	1,590	26	453	– 127
Maro Reef	1,900		1 189	1,648	– 519
Raita Bank	561	1,297	– 16	503	–
Gardner Pinnacles	2,398	–	–	–1,934	–
St. Rogatien Bank	380	–	–	– 315	–
Brooks Bank (NW of St. Rogatien)	67	–	–		–
Brooks Bank 1 (very small bank E of St. Rogatien Bank)	3	–	–		–
Brooks Bank 2 (just SE of St. Rogatien)	70	–	2	85	–
Brooks Bank 3 (more SE of St. Rogatien)	66			65	
Brooks Bank 4 (most SE of St. Rogatien)	6	237	–	– 11	–
French Frigate Shoals	933	–	3 464	– 712	– 418
Unnamed Bank NE of French Frigate Shoals	12		9		
Unnamed Bank N of Necker Island	7	1,200	3		–
Necker Island	1,541	8	6	1,314	228
Bank SW of Nihoa Island	342	–	–	247	–
Nihoa Island	579			487	74
Bank E of Nihoa Island	–			91	
Total	13,367	7,257	1,416	10,045	2,363
Percentage of Reserve Area represented	3.9	2.1	0.4	3.0	0.7

NOTES:

1. Approximiate area of entire Reserve (as currently defined) = 340,000 sq. km
2. All areas digitized from charts include all polygons within the respective isobath contours, and so include small amounts of land area.
3. The 100-, 20-, and 10-fathom areas are based on digitized isobaths depicted on nautical charts and obtained from several sources. They should be considered approximations of actual area.
4. Landsat areas were calculated using computerized image analysis of polygons drawn around bottom habitat visible in the imagery.
5. Areas shown for IKONOS reflect actual mapped habitat, rather than the amount of visible bottom.
6. Total area includes 70 sq. km for Kure Atoll, 96 sq. km for Midway Atoll, and 389 sq. km for Pearl and Hermes Atoll mapped using IKONOS; and 15 sq. km for Gambia Shoal estimated from a nautical chart.

Table 5. Overall Accuracy Assessment of Aggregated Habitat Cover for all NWHI Islands

Mapped Habitat Type	Actual Habitat Type: Hardbottom with >10% live coral	Hardbottom with >10% crustose coralline algae	Hardbottom (uncolonized)	Hardbottom with >10% macroalgae	Unconsolidated with 10% or less macroalgae or seagrass	Unconsolidated with >10% macroalgae or seagrass	Row Total	User Accuracy
Hardbottom with >10% live coral	**50**	3	5	5	0	0	63	79%
Hardbottom with >10% crustose coralline algae	0	**11**	0	0	1	0	12	92%
Hardbottom (uncolonized)	6	0	**33**	2	3	0	44	75%
Hardbottom with >10% macroalgae	1	2	11	**16**	3	6	39	41%
Unconsolidated with 10% or less macroalgae or seagrass	9	1	18	14	**161**	6	209	77%
Unconsolidated with >10% macroalgae or seagrass	3	0	1	1	3	**1**	9	11%
Column Total	69	17	68	38	171	13	376	
Producer Accuracy	72%	65%	45%	42%	94%	9%		

Overall Accuracy	**72%**
Kappa Statistic	**0.59**
Tau Coefficient	**0.62**

Mapped Structure Type	Actual Structure Type: hardbottom	unconsolidated	Row Total	User Accuracy
hardbottom	**221**	18	239	92%
unconsolidated	47	**171**	218	78%
Column Total	268	189	457	
Producer Accuracy	82%	90%		

The accuracy assessment was performed on the aggregated cover benthic habitat maps only. This was due to the relatively few site-specific benthic characterization data (1,130 points) available for the NWHI. The overall accuracy of the aggregated cover maps was 72 percent, and ranged from 94 percent accuracy for unconsolidated sediment with little or no algae or seagrass to 9% for unconsolidated sediment with seagrass present. [Note: A subset of the 1,130 points (376) was used in the accuracy assessment]

Correctly classifying benthic habitats that include algae and live coral was challenging. For example, it is difficult to separate Unconsolidated Rubble with dense (>50 percent cover) algae from Pavement with dense (>50 percent cover) algae. Also, it is difficult to separate Unconsolidated Rubble and Sand and Rubble from Pavement habitats. These challenges also were encountered when differentiating between the various habitats with live coral cover.

The aggregated cover category **Hardbottom with indeterminate cover** was not included in the accuracy assessment. The aggregated **Hardbottom with indeterminate cover** includes those detailed habitat categories where a specific cover was not identified on the map, and no comparison to the field-based benthic characterization information could be performed.

An assessment of the overall accuracy of the **hardbottom** and **unconsolidated** was performed (see the bottom of Table 5). That analysis included habitat catgories with indeterminate cover and their associated field-based benthic characterization data. That analysis revealed that these two habitats were correctly identified 82 percent and 90 percent of the time, respectively.

The Kappa Statistic is a measure of map accuracy relative to a map with classifications randomly assigned, expressed as a percent.

The Tau Coefficient measures the accuracy of the entire map across all major categories. The Tau Coefficient is valuable because it indicates how many more habitat polygons were correctly classified than would be expected by chance alone.

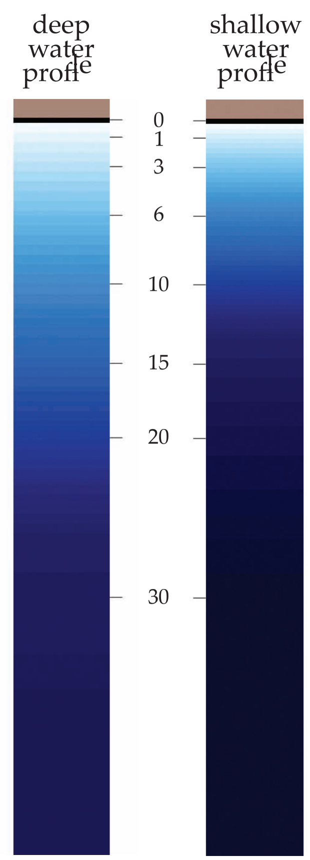
Tau Coefficients were not generated for the individual detailed habitat maps because only a small number of field-based benthic characterizations were available at each NWHI locale.

Table 6. Area Mapped by Detailed Habitat Cover Type and Geographic Locale (sq. km)

	Kure Atoll	Midway Atoll	Pearl & Hermes Atoll	Lisianski Island	Laysan Island	Maro Reef	French Frigate Shoals	Necker Island	Nihoa Island	TOTAL
Unconsolidated (1000, refer to classification scheme for habitat description)	0.0	0.0 49.2 0.2	141.9	75.4	0.0	245.4	0.0	0.0	7.2	469.9
Sand (1100)	25.5	0.0	60.4	72.3	35.0	43.4	98.4	19.5	2.8	406.5
Sand with macroalgae (1120)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Sand with patchy (10–50% cover) macroalgae (1121)	0.0	0.0	0.0	0.0	0.0	0.0	22.3	0.0	0.0	22.3
Dense (>50%) macroalgae on sand (1122)	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	1.0
Unconsolidated Rubble (1300)	12.6	0.0	14.5	16.9	1.1	6.9	0.3	0.0	0.0	52.3
Unconsolidated Rubble with sparse (10–50% cover) algae (1301)	0.0	0.0	14.2	0.0	0.0	19.6	0.0	0.0	0.0	33.8
Unconsolidated Rubble with dense (>50% cover) algae (1302)	2.7	0.7	5.6	0.0	0.0	0.0	0.0	0.0	0.0	8.3
Sand and Rubble (1400)	0.0	0.0	7.0	67.2	0.0	0.0	142.8	0.0	0.0	217
Groove (1500)	0.7	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	3.9
Hardbottom (2000)	0.0	0.6	8.3	155.7	81.7	176.4	0.0	205.5	58.3	685.9
Hardbottom with sparse (10–50% cover) algae (2001)	0.0	6.5	52.3	6.0	0.0	0.0	0.0	0.0	0.0	58.3
Hardbottom with live coral (>10% cover) (2010)	1.0		0.0	7.1	0.0	1.0	0.0	0.0	0.0	9.7
Hardbottom, uncolonized (2020)	9.5	<0.1 0.2	0.0	0.0	0.0	<0.1	0.0	0.0	0.0	16
Hardbottom with crustose coralline algae (>10% cover) (2030)	0.0	0.0	0.0	0.0	0.5	<0.1	0.0	0.0	0.0	0.6
Linear Reef (2100)	0.3	0.0	2.9	0.0	0.0	0.1	3.9	0.0	0.0	7.4
Linear Reef with live coral (>10% cover) (2110)	0.2	0.0	6.7	0.0	0.0	10.5	0.0	0.0	0.0	17.4
Linear Reef, uncolonized (2120)	0.0	0.0	0.0	0.0	0.0	1.6	5.3	0.0	0.0	6.9
Linear Reef, uncolonized with sparse (10–50% cover) algae (2121)	0.0	0.0	0.0	0.0	0.0	0.2	3.4	0.0	0.0	3.6
Linear Reef with crustose coralline algae (>10% cover) (2130)	0.0	2.9	0.0	0.0	0.0	0.2	1.3	0.0	0.0	1.5
Aggregated Coral Heads with live coral (>10% cover) (2210)	0.5	2.4	0.0	0.0	0.0	0.0	1.6	0.0	0.0	2.1
Spur and Groove (2300)	5.1	0.1	6.8	0.0	0.0	0.0	0.0	0.0	0.0	14.8
Patch Reef (2400)	3.0	0.0	11.0	0.0	0.0	3.4	8.5	0.0	0.0	28.3
Patch Reef with live coral (>10% cover) (2410)	0.0	0.0	0.5	0.0	0.4	3.4	0.0	0.0	0.0	4.4
Patch Reef, uncolonized (2420)	0.0	0.0	0.0	0.0	0.0	5.2	0.0	0.0	0.0	5.2
Patch Reef, uncolonized with sparse (10–50% cover) algae (2421)	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.2
Patch Reef with crustose coralline algae (>10% cover) (2430)	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.0	0.0	0.4
Aggregated Patch Reef (2500)	0.0	0.0	6.2	18.4	0.0	0.0	0.0	0.0	0.0	24.6
Aggregated Patch Reef with live coral (>10% cover) (2510)	0.0	0.9	0.0	8.7	0.0	0.0	0.0	0.0	0.0	8.7
Scattered Coral/Rock in Sand with live coral (>10% cover) (2610)	0.0	3.4	0.0	0.0	0.0	0.0	2.0	0.0	0.0	2.0
Pavement (2700)	0.1	19.0	13.8	9.4	0.0	0.2	21.2	0.0	0.5	46.1
Pavement with sparse (10–50% cover) algae (2701)	2.9	0.6	3.5	0.0	0.1	0.0	0.0	0.0	0.0	9.9
Pavement with dense (>50% cover) algae (2702)	2.9	0.0	1.3	<0.1	<0.1	0.0	0.3	0.0	0.0	23.5
Pavement with live coral (>10% cover) (2710)	<0.1	7.5	7.9	0.5	5.4	0.0	27.8	0.0	0.0	42.3
Pavement with live coral (>10% cover) and dense (>50% cover) algae (2712)	0.0	0.0	5.1	0.0	0.0	0.0	0.0	0.0	0.0	5.1
Pavement, uncolonized (2720)	2.1	0.0	13.7	0.9	2.9	0.0	44.5	0.0	0.0	71.6
Pavement, uncolonized with dense (>50% cover) algae (2722)	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	4.5	4.5
Pavement with crustose coralline algae (>10% cover) (2730)	0.7	0.1	0.0	0.0	0.0	0.0	3.1	0.0	3.1	6.9
Pavement with sand channels (2800)	0.0	0.8	0.4	0.0	0.0	0.0	12.4	0.0	12.4	25.4
Pavement with sand channels and live coral (>10% cover) (2810)	0.0	0.0	0.0	0.0	0.0	0.0	16.9	0.0	16.9	33.9
Pavement with sand channels, uncolonized (2820)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8
Volcanic Rock (2900)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	<0.1	2.7
Volcanic Rock with dense (>50% cover) algae (2902)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	<0.1	0.0	<0.1
Volcanic Rock with live coral (>10% cover) (2910)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	<0.1	<0.1
Volcanic Rock, uncolonized (2920)	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7
Other Delineations (3000)	0.0	57.8	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.7
Deep water (3010)	131.5	<0.1 0.4	156.7	59.3	33.0	100.4	196.7	78.3	39.1	852.8
Reef crest (3020)	0.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	<0.1
Dredged channel (3030)	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
Land (3100)	0.9	12.4 0.0	0.5	1.5	3.5	0.0	0.2	0.1	0.7	13.4
Cloud, Shadow, Surf, and No image data (3210, 3220, 3230, and 4000)	2.7		19.2	93.3	7.6	60.4	90.7	11.1	6.3	303.7
Unclassified (3300)	0.0	95.5	0.0	0.0	0.2	0.1	113.3	0.0	113.3	226.9
Total Habitat Area Classified	69.8	172.2	381.6	438.7	137.2	518.7	417.6	237.6	74.1	2360.8
TOTAL Area in IKONOS image	205.0		562.9	592.8	172.2	679.6	818.3	317.2	120.2	3640.4

Legend for the estimated depth maps of the Northwestern Hawaiian Islands. Units of depth are meters.

The deep water bathymetric profile was used at Lisianski Island, Laysan Island, Maro Reef, Necker Island, and Nihoa Island.



The shallow water bathymetric profile was used at Kure Atoll, Midway Atoll, Pearl and Hermes Atoll, and French Frigate Shoals.

Legend for the aggregated cover benthic habitat maps of the Northwestern Hawaiian Islands. A summary of which detailed habitat categories were combined to create these aggregations can be found in the classification scheme.

- Hardbottom with >10% live coral
- Hardbottom with >10% crustose coralline algae
- Hardbottom (uncolonized)
- Hardbottom with >10% macroalgae
- Hardbottom with indeterminate cover
- Unconsolidated with 10% or less macroalgae or seagrass
- Unconsolidated with >10% macroalgae or seagrass
- Deep Water

Legend for the detailed benthic habitat maps of the Northwestern Hawaiian Islands. Refer to the classification scheme for habitat descriptions.

- Unconsolidated sediment (1000)
- Sand (1100)
- Sand with macroalgae (1120)
- Sand with patchy macroalgae (1121)
- Sand with dense macroalgae (1122)
- Unconsolidated Rubble (1300)
- Unconsolidated Rubble with sparse algae (1301)
- Unconsolidated Rubble with dense algae (1302)
- Sand and Rubble (1400)
- Groove (1500)
- Hardbottom (2000)
- Hardbottom with sparse algae (2001)
- Hardbottom with live coral (2010)
- Hardbottom, uncolonized (2020)
- Hardbottom with crustose coralline algae (2030)
- Linear Reef (2100)
- Linear Reef with live coral (2110)
- Linear Reef, uncolonized (2120)
- Linear Reef, uncolonized with sparse algae (2121)
- Linear Reef with crustose coralline algae (2130)
- Aggregated Coral Heads with live coral (2210)
- Spur and Groove (2300)
- Individual Patch Reef (2400)
- Patch Reef with live coral (2410)
- Patch Reef, uncolonized (2420)
- Patch Reef, uncolonized with sparse algae (2421)
- Patch Reef with crustose coralline algae (2430)
- Aggregated Patch Reef (2500)
- Aggregated Patch Reef with live coral (2510)
- Scattered Coral/Rock in sand with live coral (2610)
- Pavement (2700)
- Pavement with sparse algae (2701)
- Pavement with dense algae (2702)
- Pavement with live coral (2710)
- Pavement with live coral and dense algae (2712)
- Pavement, uncolonized (2720)
- Pavement, uncolonized with dense algae (2722)
- Pavement with crustose coralline algae (2730)
- Pavement with Sand Channels (2800)
- Pavement with sand channels and live coral (2810)
- Pavement with sand channels, uncolonized (2820)
- Volcanic Rock (2900)
- Volcanic Rock with dense algae (2902)
- Volcanic Rock with live coral (2910)
- Volcanic Rock, uncolonized (2920)
- Other Delineations (3000)
- Deep water (3010)
- Reef crest (3020)
- Dredged channel (3030)
- Land (3100)
- Unclassified (3300)
- No data, cloud cover (3210), cloud shadow (3220), surf (3230), missing data (3240), and no image data (4000)