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About Coral Reefs



Coral reefs are complex, biologically diverse ecosystems. Countless studies, books and papers have been devoted to exploring and understanding the nature of these unique marine environments. These four essays discuss some of the most important aspects of coral reefs. Many of their physical and biological characteristics are discussed in detail. Coral reef threats, both natural and anthropogenic, also are explored.

These essays are not meant to be exhaustive. For more information, the reader can refer to the literature cited at the end of each essay.

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Coral Reef Biology

There are over a thousand coral species exist worldwide. Stony (hermatypic) corals are the best recognized because of their elaborate and colorful formations. One trait of stony corals is their capacity to build reef structures that range from tens, to thousands of meters across. As they grow, reefs provide structural habitats for many different vertebrate and invertebrate species – a single reef may host tens of thousands different species.

Although corals are found throughout the world, reef-building corals are confined to waters that exhibit a narrow band of characteristics. The water must be warm, relatively clear, and saline. These waters are almost always nutrient-poor as well. Physiologically and behaviorally, corals have evolved to take advantage of this unique environment and thrive. Read About:

- Reproductive Behavior
- Spawning Events
- Feeding Behavior and <u>Reef Productivity</u>
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Not only are reef-building corals confined by a specific range of environmental conditions, but as adults, almost all of them are sessile. This means that for their entire lives, they remain on the same spot of the sea floor. Thus, reef-building corals have developed reproductive, feeding, and social behaviors that allow them to gain the maximum survival benefit from their situation.

Reproductive Behavior

Over the eons many corals have evolved with the ability to reproduce both asexually and sexually. In asexual reproduction, new clonal polyps bud off from parent polyps to expand or begin new colonies (<u>Sumich, 1996</u>). This occurs when the parent polyp reaches a certain size and divides. The process continues throughout the animal's life, forming an ever-expanding colony (<u>Barnes and Hughes, 1999</u>). It is worth noting that it is a judgement call whether to call this reproduction, since that implies that a polyp is an individual. In a coral, an individual could be either a polyp or the whole colony, and some lines of evidence indicate that the colony is the individual, not the polyp. Evidence for coral as the individual argument includes the polyps of a colony being connected by a nervous system and gastrovacular cavity, and becoming sexually reproductive when a

A spreading colony of asexually reproducing coral polyps provide shelter for a moray eel.

colony reaches a certain size, not when a polyp reaches a certain size (D. Fenner, personal communication, Jan 6, 2012).

Corals can also reproduce asexually by fragmentation – that is, when a portion of the colony (say, a branch), is detached from the rest and falls in suitable substrate. This can happen either naturally, when perhaps wave action from a storm breaks off a coral piece and settles it elsewhere, or when humans purposely take coral fragments and place them in other substrate areas (Highsmith, 1982).

The nature of sexual reproduction among corals varies by species. About three-quarters of all stony corals form hermaphroditic colonies. These colonies have the ability to produce both male and female gametes. The remainder form gonochoristic colonies which can produce either male or female gametes, but not both. The sexuality of corals';whether hermaphroditic or gonochoristic—tends to be consistent within species and genera, although there are exceptions (<u>Veron, 2000</u>).

As a predominantly sessile group of organisms, about three-quarters of all stony corals employ broadcast spawning to distribute their offspring over a broad geographic area. These corals release massive numbers of eggs and sperm into the water column (<u>Veron, 2000</u>). The gametes fuse in the water column to form planktonic larvae (planulae). A moderately-sized colony may produce up to several thousand planulae per year (<u>Barnes and Hughes, 1999</u>). Large numbers of planulae are produced to compensate for the many hazards they inevitably will encounter as they are carried through the water. The time between planulae formation and settlement is a period of exceptionally high mortality among corals (<u>Barnes and Hughes, 1999</u>). In contrast, some coral species brood planulae within their bodies after internal fertilization. While spawning is associated with high numbers of eggs and planulae, brooding results in fewer, larger and better-developed planulae (<u>Veron, 2000</u>).



A male star coral (Montastraea cavernosa) releases sperm into the water column.

Planulae swim upward toward the light (positive phototaxis) to enter the surface waters and be transported by the current. This behavior is observed not only in nature but in laboratory experiments as well (Jones and Endean, 1973). After floating at the surface for some time, the planulae swim back down to the bottom, where, if conditions are favorable, they will settle and begin a new colony (Barnes and Hughes, 1999). In most species, the larvae settle within two days, although some will swim for up to three weeks, and in one known instance, two months (Jones and Endean, 1973).

Once the planulae settle, mortality rates drop steadily as they metamorphose into polyps and form colonies which increase in size. The new colony becomes sexually mature at a minimum size,

depending on the species. Some massive species, like those in the genus *Favia*, reach sexual maturity when the colony grows to about 10 cm in diameter, which occurs when they are about eight years old. However, some faster-growing, branching corals, including species of *Acropora*, *Pocillipora*, and *Stylophora*, reach sexual maturity at a younger age (<u>Barnes and Hughes, 1999</u>).

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Spawning Events

Among sessile corals, the timing of the mass release of gametes into the water column (broadcast spawning event) is very important because males and females cannot move into reproductive contact. Spawning species must release their gametes into the water simultaneously. Because colonies may be separated by wide distances, this release must be both precisely and broadly synchronized, and is usually done in response to multiple environmental cues (Veron, 2000).

The long-term control of spawning (control of the maturation of gonads) may be related to temperature, day length and/or rate of temperature change (either increasing or decreasing). The short-term (getting ready to spawn) control is usually based on lunar cues. The final release, or spawn, is usually based on the time of sunset. Cues also may be biological (involving chemical messengers) or physical (<u>Veron, 2000</u>).



A star coral (Montastraea franksi), releasing egg and sperm bundles, with a feeding brittle star (Ophioderma rubicundum).

Brooding species can store unfertilized eggs for weeks, and thus, require less synchrony for fertilization. Spawning species require synchrony within a time frame of hours (<u>Veron, 2000</u>). This

regional synchrony varies geographically. In Australia's Great Barrier Reef, more than 100 of the 400 plus species of corals spawn simultaneously within a few nights during spring or early summer (<u>Willis, B.L. et al., 1997</u>). Studies have shown that coral species can form hybrids through mass spawning (<u>Hatta et al., 1999</u>). Such observations have led to the theory of reticulate evolution (<u>Veron, 1995</u>) whereas modern coral species came about not through the separation of new species along different lineages, but rather through a continual process of separation and fusion.

In western Australia and the Flower Garden Banks of the northern Gulf of Mexico, spawning occurs in late summer or fall (<u>Levinton, 1995</u>), and not necessarily simultaneously. In the northern Red Sea, none of the major coral species reproduce at the same time. In addition, individual corals do not necessarily breed every year (<u>Sumich, 1996</u>). Evidence indicates that slow-growing, longer-lived corals are less likely to spawn every year than faster-growing, shorter-lived species (<u>Barnes and Hughes, 1999</u>).

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Feeding Behavior and Reef Productivity



Zooxanthellae in the tissues of a coral polyp. (Photo: Scott Santos)

The unique mutualism between hermatypic corals and their photosynthetic zooxanthellae is the driving force behind the settlement, growth and productivity of coral reefs (Levinton, 1995).

Zooxanthellae are photosynthetic, single-celled dinoflagellates, living in the endodermal tissues of stony corals polyps (intracellularly). Often, zooxanthellae are concentrated in the polyps' gastrodermal cells and tentacles (<u>Levinton, 1995</u>). Deep water and some cold water corals lack zooxanthellae, but virtually all reef-building corals possess them (<u>Lalli and Parsons, 1995</u>).

During photosynthesis, zooxanthellae "fix" large amounts of carbon, part of which they pass on to their host polyp. This carbon is largely in the form of glycerol but also includes glucose and alanine. These chemical products are used by the polyp for its metabolic functions or as building blocks in the manufacture of proteins, fats and carbohydrates. The symbiotic algae also enhance the coral's ability to (Lalli and Parsens, 1005)

synthesize calcium carbonate (Lalli and Parsons, 1995).

Because of their intimate relationship with zooxanthellae, hermatypic corals respond to the environment in many ways reminiscent of plants. As a result, the distribution and growth of corals is strongly light-dependent, as is the overall growth of the reef (<u>Levinton, 1995</u>). The vertical distribution of living coral reefs is restricted to the depth of light penetration, which is why most coral reefs dwell in shallow waters, ranging to depths of approximately 60 to 70 meters. The number of species of hermatypic corals on a reef declines rapidly in deeper water; the curve closely follows that for light extinction (<u>Barnes, 1987</u>).

Because of their dependence on light, reef corals require clear water. Thus, coral reefs generally are found only where the surrounding water contains small amounts of suspended material, i.e., in water of low turbidity and low productivity. Thus, corals prefer waters that are nutrient-poor, yet paradoxically, are among the most productive of marine environments (<u>Barnes, 1987</u>).

Although the zooxanthellae supply a major part of their energy needs, most corals also require zooplankton prey. With some exceptions, most corals feed at night (<u>Barnes, 1987</u>). When capturing food particles, corals feed in a manner similar to sea anemones. Polyps extend their tentacles to capture prey, first stinging them with toxic nematocyst cells, then drawing them toward their mouths. In addition to capturing zooplankton, many corals also collect fine particles in mucous film or strands, which are drawn by cilia into the polyp's mouth. Some species are entirely mucous suspension feeders, such as the foliaceous ("leafy") agariciids, which have few or no tentacles. Prey ranges in size from small fish to small zooplankton, depending on



Coral polyps with extended tentacles feeding on

the size of the coral polyps (Barnes and Hughes, 1999).

zooplankton.

Prey supplies the coral and its zooxanthellae with nitrogen, an element essential to both organisms, but one that is not produced in sufficient amounts by either. The symbiotic relationship between corals and zooxanthellae facilitates a tight recycling of nutrients back and forth between the two (<u>Barnes, 1987</u>).

The degree to which the coral depends on zooxanthellae is species-specific (<u>Barnes, 1987</u>). Branching corals appear to be more self-nourishing (autotrophic) than some of the massive corals, largely because the multi-layered growth form of branching corals allows for a greater surface area to intercept light both horizontally and vertically. This enables corals to make maximal use of both incident and scattered light. In addition to these skeletal modifications, the polyps of branching corals tend to be small, thereby exposing the maximum area of zooxanthellae to light (<u>Barnes and Hughes, 1999</u>).

Corals that must obtain nourishment from outside sources (heterotrophic) typically are spheroidal and have a single-layered skeletal structure (<u>Barnes, 1987</u>). Less plant material exists in the thicker tissues of massive corals as well. Heterotrophic corals possess thicker, larger polyps that allow for the capture of more plankton. Their form also maximizes the surface area of plankton-intercepting tissue (<u>Barnes and Hughes, 1999</u>).

The amount of energy that corals derive autotrophically and heterotrophically varies by species and situations. However, estimates project that the proportion of energy ultimately derived from photosynthesis ranges from over 95% in autotrophic corals to about 50% in the more extreme heterotrophic species (<u>Barnes and Hughes, 1999</u>).

Evidence suggests that the phenomenally high productivity found on coral reefs is a complex function of the combination of light capture mechanisms and efficient nutrient recycling, as well as hydrodynamic processes (Hatcher, 1997; Hatcher, 1990).



Spreading formation of this Acropora palmata maximizes the utilization of sunlight by its zooxanthellae for photosynthesis.

<u>(top)</u>

Competitive Behavior

Corals require free substratum for settlement and free space for growth. Stony corals use two basic strategies to compete for space: indirect encounters (overtopping) and direct interactions (aggression) (Genin and Karp, 1994).

An overtopping strategy is used most often by fast growing species. For instance, stouter, slowergrowing corals are sometimes at a competitive disadvantage when they coexist with branching corals, which, by virtue of their upright, faster growth, gradually overtop their neighbors. The effects of overtopping are indirect. Underlying corals suffer light deficiency and come into contact with fewer food particles (<u>Glynn and Wellington, 1983</u>). Shaded from the necessary light, the overgrown species may die eventually, and recruitment of new colonies may be prevented, leaving a pure stand of branching corals (<u>Barnes and Hughes, 1999</u>).

Such a situation was observed on the Great Barrier Reef, where sequential photographs were taken over several years. Branched colonies of *Acropora* gradually extended over colonies of massive *Montipora*. When some of the *Acropora* branches were broken off in a hurricane, the underlying portions of the stouter colonies were dead (Barnes and Hughes, 1999).

In some situations, however, the fast, continued growth of branching corals may lead to their own demise. If environmental conditions allow it, branching coral colonies can become overcrowded and die, and eventually are overgrown by another species (<u>Barnes and Hughes, 1999</u>).

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Aggressive Behavior

While fast-growing corals often employ overtopping competitive strategies, other aggressive behaviors often are used by slow-growing species (Lang, 1973; Wellington, 1980; Bak et al., 1982). One type of aggressive behavior involves the use of extruded digestive filaments and sweeper tentacles (Lang and Chornesky, 1990). Typically, an attack by an aggressive coral on a subordinate neighbor will result in the death of some of the subordinate's polyps (Lang, 1973; Sheppard, 1982

Such behavior, however, also may allow for the coexistence of fastand slow-growing species. In an experiment conducted on Jamaican coral species in the early 1970s by Judith Lang, two coral species were placed adjacent to each other. The corals extruded digestive filaments orally and through temporary openings in the polyp walls. Usually, one species exhibited more aggression than the other, and its filaments penetrated the adjacent polyp walls of the subordinate



Corals reach out to their neighbors with long filaments which literally dissolve the coral tissue next door, making room for them to expand their surface area.

species. Within 12 hours, the tissue of the subordinate species in contact with the aggressor's filaments was completely digested, exposing the underlying skeleton. Though larger subordinate colonies suffered only local loss of tissue, colonies less than 3 cm in diameter perished after the attack (Barnes and Hughes, 1999).

Lang's experiments also revealed that each coral species attacked only certain species, and each was attacked itself by certain other species, suggesting an "aggressive pecking order" among the corals. Results suggested that the slow-growing massive corals belonging to the families Mussidae, Meandrinidae, and Faviidae were the most aggressive species. The fast-growing, branching acroporid corals were intermediately aggressive, and the foliose agariciids, also quick growers, were the least aggressive. Aggressors may attack more than one subordinate at a time, and intermediately aggressive coral even while being attacked on another side by a more aggressive coral (Barnes and Hughes, 1999).

Thus, it appears that at least on Jamaican reefs, fast- and slow-growing coral species can coexist because the speed at which branching corals grow is balanced by the aggressive nature of massive corals (Barnes and Hughes, 1999).

However, such a balanced competitive environment is not universal among reef ecosystems. Monospecific stands of corals do exist, and this may be due to a species being relatively fast growing while also aggressive. Other factors like spatial position, size and biological and physical disturbances also influence the outcomes of competition (<u>Connell and Keough, 1985; Cornell and Karlson, 2000</u>). These local processes, in addition to regional ones, contribute to the formation of species-diverse assemblages or a reef dominated by one or a few species (<u>Cornell and Karlson 2000</u>).

The coral reefs off the Pacific coast of Panama illustrate a low species diversity reef and the complex species interactions that can occur. The shallow reefs are dominated by species of fast-growing, branching *Pocillopora*. Species of the slow-growing, massive *Pavona* dominate in deeper waters. In the field, the distribution of scars left by tentacle encounters between neighboring corals suggests that *Pocillopora* is dominant over *Pavona*. However, in laboratory experiments, *Pavona* can damage the tissues of *Pocillopora* within 12 hours of tissue contact (Barnes and Hughes, 1999).

Fortunately, long-term experiments have explained the paradox. After placing *Pocillopora* and *Pavona* together on the reef, within two days *Pavona* extends its mesenterial filaments and kills the adjacent tissues of *Pocillopora*. *Pavona* then retracts its mesenterial filaments, and algae quickly cover the bare areas of *Pocillopora* skeleton. One to two months later, tissue regenerates over the bare patches, and the polyps on the peripheral branches of *Pocillopora* adjacent to *Pavona* convert some of their feeding tentacles into very elongated "sweeper" tentacles that sway passively in the surge, frequently dragging over the *Pavona* colony (<u>Barnes and Hughes, 1999</u>).

Contact with the sweeper tentacles damages or kills the affected *Pavona* tissue. The exposed skeleton is rapidly colonized by filamentous algae and later by encrusting coralline algae that

prevents further contact between the two corals. The sweeper tentacles of *Pocillopora* contract and resume their normal feeding function. Gradually, the faster-growing *Pocillopora* overtops the *Pavona* (Barnes and Hughes, 1999).

It is unclear why *Pavona* does not retaliate by extending its mesenterial filaments to counteract *Pocillopora* sweeper tentacles. Some researchers suggest that the sweeper tentacles are more powerful than the mesenterial filaments. Though previously thought to be used only for intercepting zooplankton, sweeper tentacles are structurally similar to the special tentacles of sea anemones that are used for aggression between clones (<u>Barnes and Hughes, 1999</u>).

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Disturbances

In addition to indirect encounters (overtopping) and direct interactions (aggression), the competitive advantage of one stony coral species over another may be affected by natural disturbances. Physical disturbances and predation can remove members of a community's dominant competitors, thus enhancing species diversity. However, disturbances do not necessarily increase species diversity. For instance, if a predator prefers a subordinate species, competitive exclusion is enhanced (Barnes and Hughes, 1999). Any kind of disturbance that disrupts the process of competitive exclusion, but does not eliminate competitors, will promote coexistence (Barnes and Hughes, 1999).

Finally, corals must contend with other competitors like soft corals and algae for reef space. Disturbances such as catastrophic low tides, predation and grazing affect the availability of space. Sea urchins and herbivorous fish prevent algae from monopolizing space. Soft corals can be overtopped by stony corals, but their rapid growth and distastefulness to many predators allow them to rapidly colonize any newly-opened space (Barnes and Hughes, 1999).



A variety of soft and hard corals compete for substrate and nutrients.

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Deep Water Corals

Many people are familiar with the coral reefs that thrive in shallow, well lighted, clear tropical waters where myriad colorful hard and soft corals provide habitat "infrastructure" for numerous invertebrates and fishes. The corals provide protection and cover, sources of nutrition, and sites for reproduction. Corals, however, also grow in the deep, cold sea. Although the existence of some of these deep-sea coral thickets has been known for several centuries, initially from pieces of broken corals brought up with fishing gear, scientists know little about their distribution, biology, behavior, and function as essential habitats for fishes and invertebrates.

Some deep-water corals (also called cold-water corals) do not form reefs exactly like those in tropical waters. Often, they form colonial aggregations called patches, mounds, banks, bioherms, massifs, thickets or groves. These aggregations are often still referred to as "reefs." While there are nearly as many species of deep-water corals as there are shallow-water species, only a few deep-water species develop "reefs." Deep-water corals also provide crucial habitat and reproductive grounds for commercially important fisheries including

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- General Distribution of Cold-water Corals
- <u>Two Important Deep-</u> water Corals
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sea bass, snapper, porgy, rock shrimp and calico shrimp, thus drawing the commercial fishing industry to these fragile areas.

Human activities constitute the most serious threat to these fragile corals. Destructive bottom fishing, as well as oil and gas exploration and exploitation have the potential to destroy large areas of coral habitat in a relatively short time. These activities create coral rubble, which is not a suitable habitat for fishes and invertebrates. In recent years, scientists have begun to study deep-water corals more closely, and some countries with deep-water corals in their territorial waters have begun to implement fishing restrictions in sensitive coral areas.

What are Deep-water Corals?

Three main groups of corals make up deep-water coral communities: hard (stony) corals of the Order Scleractinia, which form hard, ahermatypic reefs; black and horny corals of the Order Antipatharia; and soft corals of the order Alcyonacea, which includes the gorgonians (sea fans) (<u>Williams, 2001</u>). Deep-water corals are similar in some ways to the more familiar corals of shallow, tropical seas. Like their tropical equivalents, the hard corals develop sizeable reef structures that host rich and varied invertebrate and fish fauna. However, unlike their tropical cousins, which are typically found in waters above 70m depth and at temperatures between 23° and 29° C, deep-water corals live at depths just beneath the surface to the abyss (2000 m), where water temperatures may be as cold as 4° C and utter darkness prevails.

At these depths, corals lack zooxanthellae. These symbiotic algae provide food for many shallow-water corals through photosynthesis. They also assist in the formation of the calcareous skeleton, and give most tropical corals their coloration. By contrast, the polyps of deepwater corals appear to be suspension feeders. They capture and consume organic detritus and plankton that are transported by strong, deep-sea currents. These corals are commonly found along



This thicket of Paragorgia corals was viewed by the deep-sea submersible Alvin at 1,043 m depth. Photo: Barbara Hecker

bathymetric highs such as seamounts, ridges, pinnacles and mounds (<u>Southampton Oceanography</u> <u>Centre</u>).

Deep-water corals range in size from small solitary colonies to large, branching tree-like structures, which appear as oases of teeming life surrounded by more barren bathymetry. The gorgonians (sea fans) also range from small individuals to those with tree-like dimensions. The gorgonian, *Paragorgia arborea*, may grow in excess of three meters in length (<u>Watling, 2001</u>). Growth rates of branching deep-water coral species, such as *Lophelia* and *Oculina*, range from ~ 1.0 - 2.5 cm/yr, whereas branching shallow-water corals, such as *Acropora*, may exceed 10-20 cm/yr. Using coral age-dating methods, scientists have estimated that some living deep-water corals date back at least 10,000 years (<u>Mayer, 2001</u>). However, little is known of their basic biology, including how they feed or their methods and timing of reproduction.

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General Distribution of Cold-water Corals

Deep-water corals are found globally, from coastal Antarctica to the Arctic Circle. In northern Atlantic waters, the principal coral species that contribute to reef formation are *Lophelia pertusa*, *Oculina varicosa*, *Madrepora oculata*, *Desmophyllum cristagalli*, *Enallopsammia rostrata*, *Solenosmilia variabilis*, and *Goniocorella dumosa*. Four of those genera (*Lophelia*, *Desmophyllum*, *Solenosmilia*, and *Goniocorella*) constitute the majority of known deep-water coral banks at depths of 400 to 700 m (*Cairns and Stanley*, 1982).

Madrepora oculata occurs as deep as 2,020 m and is one of a dozen species that occur globally and in all oceans, including the Subantarctic (<u>Cairns, 1982</u>). Colonies of *Enallopsammia* contribute to the framework of deep-water coral banks found at depths of 600 to 800 m in the Straits of Florida (<u>Cairns and Stanley, 1982</u>).

Two Important Deep-water Corals

Two of the more significant deep-sea coral species are *Lophelia pertusa* and *Oculina varicosa*. These species form extensive deep-water communities that attract commercially important species of fishes, making them susceptible to destructive bottom trawling practices (<u>Reed, 2002a</u>). Increased sedimentation places additional stress on corals.

Oil and gas exploration structures and activities, particularly in the North Sea and adjacent areas, also damage *Lophelia* communities. Subsequent oil and gas production activities may also introduce noxious substances into these areas.

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Lophelia pertusa Distribution



Global distribution of Lophelia pertusa. Image: Southampton Oceanography Centre, UK.

vertebrate and invertebrate species.

Lophelia pertusa is the most common aggregate-forming deep-water coral. Typically, it is found at depths between 200 and 1,000 m in the northeast Atlantic, the Mediterranean Sea, along the mid-Atlantic Ridge, the West African and Brazilian coasts, and along the eastern shores of North America (e.g., Nova Scotia, Blake Plateau, Florida Straits, Gulf of Mexico) as well as in parts of the Indian and Pacific Oceans. Like tropical coral reefs, Lophelia communities support diverse marine life, such as sponges, polychaete worms, mollusks, crustaceans, brittle stars, starfish, sea urchins, bryozoans, sea spiders, fishes, and many other

Lophelia has been found most frequently on the northern European continental shelves between 200 and 1000 m, where temperatures range from 4° to 12°C, but it has also been found at depths greater than 2,000 m. Once a colonial patch is established, it can spread over a broad area by growing on dead and broken pieces of coral (coral rubble). *Lophelia* has a linear extension of the polyps of about 10 mm per year. The reef structure has been estimated to grow about 1 mm per year (<u>Fossa, 2002</u>). Scientists have also found *Lophelia* colonies on oil installations in the North Sea (<u>Bell and Smith, 1999</u>).

Lophelia pertusa can occur in a variety of structures and forms. DNA-based sequencing tests conducted at the University of Southampton Oceanography Centre, UK, have indicated that different morphological varieties of *Lophelia* all belong to the same species (<u>Rogers et al., on-line</u>).

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Noted Lophelia Areas

The world's largest known deep-water *Lophelia* coral complex is the Røst Reef. It lies in depths between 300 and 400 m west of Røst Island in the Lofoten archipelago, Norway. Discovered during a routine survey in May 2002, the reef is still largely intact. It covers an area approximately 40 km long by 3 km wide.

Relatively close by is the Sula Reef, located on the Sula Ridge, west of Trondheim on the mid-Norwegian Shelf, at 200 to 300 m depth. It is estimated to be 13 km long, 700 m wide, and up to 35 m high (<u>Bellona Foundation, 2001</u>), an area one-tenth the size of the 100 km² Røst Reef.

Discovered and mapped in 2002, Norway's 1,000-year-old and 2-km-long Tisler Reef lies in the Skagerrak -- the submarine border between Norway and Sweden at a depth of 74 to 155 m. The Tisler Reef contains the world's only known yellow *Lophelia pertusa* corals. At present, Norway is the only European nation to enact laws protecting its *Lophelia* reefs from trawling, pollution, and oil and gas exploration. However, the European Commission has introduced an interim ban on trawling in the Darwin Mounds area, west of Scotland, in August 2003. A permanent ban on trawling is expected to follow.

Elsewhere in the northeastern Atlantic, *Lophelia* is found around the Faroe Islands, an island group between the Norwegian Sea and the Northeast Atlantic Ocean. At depths from 200 to 500 m, *Lophelia* is chiefly on the Rockall Bank and on the shelf break north and west of Scotland (<u>Tyler-</u>

Walters, 2003).

One of the most researched deep-water coral areas in the United Kingdom are the Darwin Mounds. The mounds were discovered in 1998 by the Atlantic Frontier Environmental Network (AFEN) while conducting large-scale regional surveys of the sea floor north of Scotland. They discovered two areas of hundreds of sand and cold-water coral mounds at depths of about 1,000 m, in the northeast corner of the Rockall Trough, approximately 185 km northwest of the northwest tip of Scotland. Named after the research vessel *Charles Darwin*, the Darwin Mounds have been extensively mapped using low-frequency side-scan sonar. They cover an area of approximately 100 km² and consist of two main fields -- the Darwin Mounds East, with about 75 mounds, and the Darwin Mounds West, with about 150 mounds. Other mounds are scattered in adjacent areas. Each mound is about 100 m in diameter and 5 m high.



Two images of the deep sea coral Lophelia pertusa. The image on the left shows the complex growth structure of a small colony. On the right is a closeup of individual polyps. Photo: <u>John Reed, 2002a</u>.

The tops of the mounds are covered with Lophelia corals and coral rubble, which attract other marine life. Sidescan sonar images show that the mounds appear to be sand volcanoes, each with a unique feature -- a "tail." The tails are up to several hundred m long, all oriented downstream (ICES, <u>2001a</u>). The tails and the mounds are uniquely characterized by large congregations of deep-sea organisms called xenophyophores (*Syringammina fragilissima*), which are giant unicellular organisms that can grow up to 25 cm in diameter (ICES, 2002). Scientists are uncertain why these interesting

organisms congregate in these areas. In addition, the *Lophelia* of the Darwin Mounds are growing on sand rather than hard substrate, an unusual condition unique to this area. Usually, coral larvae almost always settle and grow on hard substrates, such as dead coral skeletons or rock.

Lophelia corals exist in Irish waters as well (<u>Rogers, 1999</u>). The Porcupine Seabight, the southern end of the Rockall Bank, and the shelf to the northwest of Donegal all exhibit large, mound-like *Lophelia* structures. One of them, the Theresa Mound, is particularly noted for its *Lophelia pertusa* and *Madrepora oculata* colonies. *Lophelia* reefs are also found along the U.S. East Coast at depths of 500 to 850 m along the base of the Florida-Hatteras slope. South of Cape Lookout, NC, rising from the flat sea bed of the Blake Plateau, is a band of ridges capped with thickets of *Lophelia*. These are the northernmost East Coast *Lophelia pertusa* growths. The coral mounds and ridges here rise as much as 150 m from the plateau plain. These *Lophelia* communities lie in unprotected areas of potential oil and gas exploration and cable-laying operations, rendering them vulnerable to future threats (<u>Sulak and Ross, 2001</u>).

Finally, *Lophelia* is known to exist around the Bay of Biscay, the Canary Islands, Portugal, Madeira, the Azores, and the western basin of the Mediterranean Sea. (<u>ICES, 2001a</u>).

<u>(top)</u>

Oculina varicosa Distribution

Oculina varicosa is a branching ivory coral that forms giant but slowgrowing, bushy thickets on pinnacles up to 30 m in height. The Oculina Banks, so named because they consist mostly of *Oculina varicosa*, exist in 50 to 100 m of water along the continental shelf edge about 26 to 50 km off of Florida's central east coast.

Discovered in 1975 by scientists from the Harbor Branch Oceanographic Institution conducting surveys of the continental shelf, *Oculina* thickets grow on a series of pinnacles and ridges extending from Fort Pierce to Daytona, Florida (<u>Avent et al, 1977;</u> <u>Reed, 1981; Reed, 2000a,b</u>).

Like the *Lophelia* thickets, the Oculina Banks host a wide array of macroinvertebrates and fishes. They also are significant spawning grounds for commercially important species of food fishes including gag, scamp, red grouper, speckled hind, black sea bass, red porgy, rock shrimp, and the calico scallop (Koenig et al., on-line).

Threats to Lophelia and Oculina Corals

Both *Lophelia* and *Oculina* corals face uncertain futures. Until recently, *Lophelia* habitats remained undisturbed by human activity. However, as traditional fish stocks are depleted from northern European waters, bottom trawling has moved into deeper waters, where the gear has affected the coral beds. The towed nets break up the reef structure, kill the coral polyps and expose the reef to sediment by altering the hydrodynamic and sedimentary processes around the reef (<u>Hall-Spencer et al., 2002</u>).

30' 80 W Cape Convictual 5 Fort Pierce West Palm

Chart of the Deep-water Oculina Coral Banks Marine Protected Area (MPA). The shaded area is the entire Oculina Habitat Area of Particular Concern (HAPC); the Experimental Oculina Research Reserve (EORR) is the smaller inset box. Recent dive sites from 2001 to 2003 include: 1) Cape Canaveral, 2) Cocoa Beach, 3) Eau Gallie, 4) Malabar, 5) Sebastian, and 6) Chapmans Lumps/ Jeff's Reef. (Courtesy of: Dr. John K. Reed, Harbor Branch Oceanographic Institution)

The fishes and invertebrates that depend on the coral structure lose their habitat and move out of the area. Damage may range from a decrease in the size of the coral habitat with a corresponding decrease in the abundance and biodiversity of the associated invertebrate and fish species, to the complete destruction of the coral habitat. The trawls also may resuspend sediments that, in turn, may smother corals growing downstream of the current. In addition, oil and gas exploration and extraction operations have begun to move into these deep-water areas, further threatening the resident corals.



Two images of the deep-sea coral Oculina varicosa. The image on the left shows the complex growth structure of a small colony. On the right is a closeup of an individual branch. Photo: <u>John Reed</u>, <u>2002a</u>.

Scientists estimate that within the Norwegian Exclusive Economic Zone, 30 to 50 percent of the total coral area of the Norwegian shelf has been damaged or destroyed by trawling (Fossa, 2002). Scientists from the International Council for the Exploration of the Sea, the main provider of scientific advice to the European Commission on fisheries and environmental issues in the northeast Atlantic, have recommended that to protect the remaining deep-water coral groves, all of Europe's deep corals must be accurately mapped and then closed to fishing trawlers (ICES, 2001b).

In 1999, the first complete mapping of the Sula Reef was carried out by the Norwegian Hydrographic Society, which used the latest available multibeam echosounder equipment to record both depth and backscatter data. The mapping was the product of joint cooperation between the Geological Survey of Norway and the Institute of Marine Research. That same year, the Norwegian Ministry of Fisheries issued regulations for the protection of the *Lophelia* reefs. An area of 1,000 km² at Sula, including the large reef, is now closed to bottom trawling. In 2000, an additional area, about 600 km² was

closed. The Røst Reef, an area of about 300 km², was closed to bottom trawling in 2002.

Florida's Oculina Banks, once teeming with commercially important fish, now appear to be severely depleted of fish stocks (<u>MPA, 2002</u>). Much of the *Oculina* coral has been reduced to rubble, probably the result of a combination of destructive bottom trawling and natural causes like bioerosion and episodic die-offs. Regardless of the cause, the Oculina Banks now support a drastically reduced fishery because most of the significant spawning grounds have been destroyed (<u>Reed, 2000a,b</u>).

Efforts to protect the Oculina Banks began in 1980, when scientists from Harbor Branch Oceanographic Institution initiated a call to implement protective measures for the area. In 1984, the South Atlantic Fishery Management Council established the 92-square mile Oculina Bank Habitat Area of Particular Concern (HAPC) in order to protect the fragile coral from damage by bottom-tending fishing gear, including bottom trawls, bottom longlines, dredges, and fish traps. Subsequent management measures provided further protection by prohibiting anchoring, trawling for rock shrimp, and by requiring vessel monitoring systems (VMS) on rock shrimp vessels.

In 1994, the 92-square mile OHAPC was declared the Oculina Experimental Closed Area, and possession of or fishing for snapper/grouper species was prohibited for a period of 10 years to allow for scientific studies. Having an area where deepwater species such as snowy grouper and speckled hind can grow and reproduce without fishing pressure provides a unique opportunity for study. The SAFMC has extended the closure indefinitely with periodic review for



This beautiful species of Madrepora oculata coral was collected off the coast of South Carolina.

further protection and research. The former Oculina Bank HAPC was expanded in 2000 to include an additional 300 square miles.

The Oculina Banks remain a hot spot for research and efforts to rehabilitate the coral (<u>MPA, 2002</u>). Scientists recently deployed concrete "reef balls" in the area in an attempt to attract fish and provide substrate for coral attachment, settlement and growth. They are cautiously optimistic about their initial restorative efforts in the reserve (<u>MPA, 2002</u>).

<u>(top)</u>

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<u>(top)</u>



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<u>Home</u> / <u>About Coral Reefs</u> / Major Reef-building Coral Diseases

Content on this page has not been updated in at least five years. Some of the content may be out of date. For more information: <u>http://coralreef.noaa.gov/</u>.

Major Reef-building Coral Diseases

Coral diseases and syndromes generally occur in response to biotic stresses such as bacteria, fungi and viruses, and/or abiotic stresses such as increased sea water temperatures, ultraviolet radiation, sedimentation and pollutants. One type of stress may exacerbate the other (Santavy and Peters, 1997).

The frequency of coral diseases appears to have increased significantly over the last 10 years, causing widespread mortality among reef-building corals. Many scientists believe the increase is related to deteriorating water quality associated with anthropogenic pollutants and increased sea surface temperatures. This may, in turn, allow for the proliferation and colonization of disease-causing microbes. However, exact causes for most coral diseases remain elusive. The onset of most diseases likely is a response to multiple factors (<u>Peters, 1997</u>).

Read About:

- Black-band Disease
- Coral Bleaching
- Dark Spots Disease
- Red-band Disease
- White-band Disease
- White Plague
- White Pox Disease
- Yellow Blotch Disease
- References

This section discusses, in alphabetical order, the most prevalent coral diseases and syndromes currently known and under study: black-band disease, coral bleaching, dark-spots disease, red-band disease, white-band disease, white-plague disease, white pox and yellow-blotch disease. Additional information on these diseases and others can be found on NOAA's <u>Coral Disease Identification and Information</u> Web site.

Black-band Disease

Black-band disease (BBD) is characterized by a blackish concentric or crescent-shaped band, 1 to 30 mm wide and up to 2 m long, that "consumes" live coral tissue as it passes over the colony surface, leaving behind bare skeleton. The disease is caused primarily by a cyanobacteria in combination with sulfide-oxidizing bacteria and sulfur- reducing bacteria, although other bacteria and opportunistic organisms such as nematodes, ciliate protozoans, flatworms and fungal filaments also are present in the mix (<u>Richardson et al., 1997</u>). The photosynthetic pigments of the dominant cyanobacteria gives the band its maroon to black color, but other bacteria are present in the mix. Often, the band has a white dusting of sulfur-oxidizing bacteria (<u>NMFS, 2001</u>).

The band, which is loosely anchored in the coral's living tissue and is easily dislodged by water motion, advances across the surface of the coral from a few millimeters up to 2 cm per day. The unaffected coral tissue appears normal in color, morphology and behavior (<u>McCarty</u> <u>and Peters, 2000</u>). However, exposed coral skeleton is rapidly colonized by filamentous algae and other organisms (<u>McCarty and</u> <u>Peters, 2000</u>).

Black-band disease was first discovered on the reefs of Belize and



Florida in 1972, and has since been identified in 26 countries including Fiji, Australia and the Philippines (<u>Green and Bruckner, 2000</u>). In the western Atlantic, BBD most commonly affects massive reef-building Black-band disease. (Photo: A. Bruckner)

corals, but other types of stony corals and sea fans can be affected as well. Caribbean staghorn and elkhorn coral appear to be resistant to the disease (<u>NMFS, 2001</u>), though acroporid corals in the Red Sea and Indo-Pacific are affected by BBD. A total of 16 species have been observed with BBD in the western Atlantic, and 26 species in the Red Sea and Indo-Pacific (<u>Green and Bruckner, 2000</u>).

The number of corals infected with BBD on a reef fluctuates, but BBD is often present on most reefs at low levels, to depths of over 100 feet. The incidence of BBD increases in late summer and early fall, when water is clear and temperatures reach their peak (<u>Green and Bruckner, 2000</u>). The incidence and prevalence may also increase when corals are stressed by sedimentation, nutrients, toxic chemicals and warmer-than-normal temperatures (<u>Richardson, 1998</u>). Although colonies often suffer only partial mortality, loss of live coral tissue reduces the number of reproductive coral polyps and opens up surfaces that can be colonized by bioeroding organisms (<u>Edmunds, 1991</u>).

<u>(top)</u>



Coral bleaching. (Photo: A. Bruckner)

Coral Bleaching

Healthy tissue of most stony corals ranges from yellow to brownish in color, a function of the photosynthetic pigments of their symbiotic zooxanthellae. When corals are inordinately stressed, they often expel their zooxanthellae, or the concentration of photosynthetic pigments declines. This response is known as bleaching (<u>Glynn, 1996</u>).

During a bleaching event, a coral's coloration disappears or becomes pale, and the white of the coral skeleton shows through the translucent coral tissue. In some species, such as the massive starlet coral *Siderastrea sidereal*, the tissue can appear pinkish or bluish, due to pigments within the animal tissue. Localized bleaching has been observed since at least the beginning of the 20th century. However, beginning in the 1980s, regional and global bleaching affecting numerous species has occurred on reefs worldwide. Bleaching usually

is not uniform over single coral colonies within coral communities or across reef zones, and some species are more susceptible to bleaching than others under the same conditions (Glynn, 1996). In some instances, only the upper surface or lower surface of the colony is affected. In others, bleached tissue appears as a circular patch or in the shape of a ring or wedge.

Localized bleaching has been attributed to exposure to high light levels, increased ultraviolet radiation, temperature or salinity extremes, high turbidity and sedimentation resulting in reduced light levels, and other abiotic factors (Glynn, 1996). In addition, bleaching in some species has occurred in response to a bacterial infection (Kushmaro et al., 1996). However, the seven major episodes of bleaching that have occurred since 1979 have been primarily attributed to increased sea water temperatures associated with global climate change and el Niño/la Niña events, with a possible synergistic effect of elevated ultraviolet and visible light (Hoegh-Guldberg, 1999).

Debilitating effects of bleaching include reduced skeletal growth and reproductive activity, and a lowered capacity to shed sediments and resist invasion of competing species and diseases (<u>Glynn</u>, <u>1996</u>). Prolonged bleaching can cause partial to total colony death. If the bleaching is not too severe, and the stressful conditions decrease after a short time, affected colonies can regain their symbiotic algae within several weeks to months (<u>Glynn</u>, <u>1996</u>).

Dark-Spots Disease

Though only recently described as dark-spots disease (DSD), discolored spots or markings in the tissue of several massive reefbuilding corals from the western Atlantic have been noted for many years, but not studied. Dark-spots disease was first reported from Colombia during the late 1990s, but the condition appears to be widespread in the Florida Keys and throughout the wider Caribbean (Gil-Agudelo and Garzón-Ferreira, 2001).

The affected areas appear as dark purple, gray or brown patches of discolored tissue, circular or irregular in shape, that are scattered on the surface of a colony, or at the colony's margin. The discolored tissue increases in size and radiates outward as the area first affected



Dark-spots disease. (Photo: A. Bruckner)

dies. Darkened polyps often are depressed and appear smaller in size than normal polyps (<u>Bruckner, 2001</u>). DSD is most commonly observed on massive starlet coral (*Siderastrea siderea*) and blushing star coral (*Stephanocoenia intersepta*), but this condition also affects *Montastraea annularis* (species complex) (<u>Bruckner, 2001</u>).



<u>(top)</u>

Red-band Disease

Red-band disease (RBD) consists of a narrow band of filamentous cyanobacteria that advances slowly across the surface of a coral, killing living tissue as it progresses (<u>Bruckner, 2001</u>). Two types of RBD have been described. RBD-1 closely resembles BBD, but the band is reddish to maroon in color, and the cyanobacterial filaments are more loosely organized.

Close-up of red-band disease. (Photo: A. Bruckner)

RBD-2 is visibly different from RBD-1, in that the cyanobacterial filaments spread like a net over the colony's surface (<u>Richardson</u>,

<u>1992</u>). Like BBD, RBD is dominated by filamentous cyanobacteria, forming a soft microbial mat that is easily dislodged from the surface of the coral tissue. However, different species of cyanobacteria have been found to be associated with RBD (<u>Richardson, 1992</u>; <u>Santavy et al., 1996</u>). RBD affects massive and plating stony corals, and also sea fans throughout the wider Caribbean. Like in BBD, exposed skeletal surfaces are rapidly colonized by algae and other competing organisms.

White-band Disease

White-band disease (WBD) was first identified in 1977 on reefs surrounding St. Croix. It is now known to occur throughout the Caribbean where it is believed to only affect staghorn and elkhorn corals (Green and Bruckner, 2000). This disease is characterized by tissue that peels or sloughs off the coral skeleton in a uniform band, generally beginning at the base of the colony and working its way up to branch tips (Peters, 1997). The band ranges from a few millimeters up to 10 cm wide, and tissue is lost at a rate of about 5 mm per day (Gladfelter, 1991).

The effects of WBD can be devastating. In fact, WBD is thought to be a major factor in the decline of elkhorn and staghorn corals in the wider Caribbean (<u>Aronson and Precht, 2001</u>). Since the 1980s, *Acropora cervicornis* has been virtually eliminated from reef environments throughout the region. In the U.S. Virgin Islands, populations of *Acropora palmata* declined from 85 percent cover to 5 percent within 10 years, primarily as a result of WBD (<u>Gladfelter,</u> <u>1991</u>). WBD currently is the only coral disease known to cause major changes in the composition and structure of reefs (<u>Green and</u> <u>Bruckner, 2000</u>).



White-band disease. (Photo: A. Bruckner)

Scientists have distinguished two forms of WBD. Type II, first identified on staghorn corals in the Bahamas in 1997, differs from type I in that tissue adjacent to exposed skeleton bleaches before it dies. Type II WBD sometimes is mistaken for bleaching (Ritchie and Smith, 1998).

The cause of WBD is unknown. Though unusual aggregates of rod-shaped bacteria were found in the tissue of corals affected by WBD type I, scientists have not determined the role of this microorganism. To further complicate matters, some corals that contain these bacteria appear healthy, and other colonies that are affected by sloughing tissue do not contain the bacteria (<u>Richardson, 1998</u>). More recently, scientists reported a species of bacteria associated with type II (<u>Ritchie and Smith, 1998</u>).

WBD has also been found throughout the Red Sea and Indo-Pacific, including the Philippines, the Great Barrier Reef and Indonesia. Unlike reports of WBD from the Caribbean, this condition has been identified on 34 species of massive, plating and branching corals in nine countries in the Indo-Pacific (Green and Bruckner, 2000).



White plague disease. (Photo: A. Bruckner)

White Plague

White plague is similar in appearance to WBD, but it affects different species. The disease is characterized by an abrupt line or band of white, exposed coral skeleton that separates living tissue from algal-colonized skeleton, and often a narrow band of bleached tissue may be visible adjacent to exposed skeleton. Usually beginning at the base of a colony, it spreads quickly upward and outward.

White plague was first identified in the Florida Keys in 1977. A second form, type II, was identified on the same reefs in 1995, and a third form (type III) was reported in 2000 (<u>Richardson and Aronson, in press</u>). The three types of plague are similar in appearance, although a greater number of species are affected by type II. Additionally, the rate of tissue mortality is much greater in type II and type III than in type I (<u>Richardson, 1998</u>; <u>Richardson and Aronson, in press</u>).

Plague type I is reported to affect 10 species of corals, causing coral tissue mortality at a rate of about 3 mm/day. In Plague type II, up to 2 cm of tissue per day succumb to the disease, and small colonies can be decimated within one to two days. Thirty-two species are reported to be affected by this condition (<u>Richardson, 1998</u>). Plague type III affects the largest reef-building corals, including *C. natans* and *M. annularis*, and tissue loss is much greater than that observed in either plague type I or plague type II (<u>Richardson and Aronson, in press</u>).



White pox disease. (Photo: A. Bruckner)

White Pox Disease

White pox affects elkhorn coral in the Florida Keys and possibly throughout the Caribbean. First found in 1996, the disease is characterized by white circular lesions on the surface of infected colonies. The rate of tissue damage appears to be rapid, allowing for algal colonization within days. The cause of white pox remains a mystery, but a possible bacterial pathogen has been identified (<u>Porter, 2002</u>).

<u>(top)</u>

Yellow Blotch Disease

Affecting only star corals in the genus Montastraea and the brain coral *Colpophyllia natans*, yellow blotch disease (YBD) was first identified in 1994 in the lower Florida Keys. It is now known to occur throughout the Caribbean (<u>Green and Bruckner, 2000</u>). Yellow blotch disease begins as pale, circular blotches of translucent tissue or as a narrow band of pale tissue at the colony margin, with affected areas being surrounded by normal, fully pigmented tissue. As the disease progresses, the tissue first affected in the center of the patch dies,

and exposed skeleton is colonized by algae (Bruckner, 2001). The area of affected tissue progressively radiates outward, slowly killing the coral.

The rate of tissue loss by corals afflicted with YBD averages 5 t 11 cm per year, which is less than that of other coral diseases. However, corals can be affected for many years, and the disease can affect multiple locations on a colony. Moreover, some of the largest and oldest coral colonies have been affected by YBD (<u>Bruckner, 2001</u>). Though the cause of YBD remains elusive, histological studies in affected corals have shown degenerative changes in tissues and cells.



Yellow blotch /band disease. (Photo: A. Bruckner)

Scientists also have found unusual crystalline material in the coral's gastric cavity (Santavy and Peters, 1997).

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Content on this page was last updated in December 2012. Some of the content may be out of date. For more information: <u>http://coralreef.noaa.gov/threats/</u>.

Hazards to Coral Reefs

Coral reefs face numerous hazards and threats. As human populations and coastal pressures increase, reef resources are more heavily exploited, and many coral habitats continue to decline. Current estimates note that 10 percent of all coral reefs are degraded beyond recovery. Thirty percent are in critical condition and may die within 10 to 20 years. Experts predict that if current pressures are allowed to continue unabated, 60 percent of the world's coral reefs may die

Read About:

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completely by 2050 (<u>CRTF, 2000</u>). Reef degradation occurs in response to both natural and anthropogenic (human-caused) stresses. Threats to coral reefs can be also classified as either local or global: local threats include overfishing, destructive fishing practices, nutrient runoff, sedimentation, and coral disease while global threats include mass coral bleaching produced by rising sea surface temperature (worsened by climate change), and ocean acidification. Together, these represent some of the greatest threats to coral reefs.

Coral reef threats often do not occur in isolation, but together, having cumulative effects on the reefs and decreasing its overall resiliency. Following destructive natural events such as hurricanes, cyclones or disease outbreaks, reefs can be damaged or weakened, but healthy ones generally are resilient and eventually recover. In many cases, however, natural disturbances are exacerbated by anthropogenic stresses, such as pollution, sedimentation and overfishing, which can further weaken coral systems and compromise their ability to recover from disturbances. Conversely, a reef directly or indirectly affected by anthropogenic stresses may be too weak to withstand a natural event. In addition, many scientists believe that human activities intensify natural disturbances, subjecting coral reefs to stronger, more frequent storms, disease outbreaks and other natural events.

Natural Threats

Reefs are now, and always have been, vulnerable to destructive natural events. In fact, weather-related damage occurs frequently. The large, powerful waves that accompany hurricanes and cyclones can break apart or flatten large coral heads and scatter fragments (Barnes & Hughes, 1999; Jones & Endean, 1976). Branching corals, which tend to be more delicate and become increasingly unstable as they grow, are more vulnerable to storm damage than massive forms such as brain coral or the stouter branching forms. A single storm seldom kills off an entire colony, but slow-growing corals may be overgrown by algae before they can recover—a circumstance that may be aggravated by increased nutrient output from runoff and sedimentation (UVI, 2001).

Reefs are dependent on specific environmental conditions. Most require a specific water temperature range (23 to 29 °C) for optimal growth.



GOES 8 weather satellite's image of Hurricane Mitch, October 26, 1998. Coral reefs are vulnerable to hurricane damage.

Some can tolerate higher temperatures, but only for limited periods of time. When temperatures fall

outside this preferred range, corals can "bleach," when they lose their symbiotic zooxanthellae and begin to effectively starve. If the temperatures are too high or continue unabated long enough, it results in mass coral mortality. In addition, specific levels of salinity (32 to 42 parts per thousand), water clarity and light levels generally must be consistent throughout the year for corals to grow optimally. Impacts associated with global climate change, such as increased concentrations of carbon dioxide and other greenhouse gases, are disrupting the delicate balance of the ocean's chemistry, a worrying phenomenon called "ocean acidification." Warming trends can elevate seawater temperatures and levels as well, rendering conditions unfit for coral survival (<u>NMFS, 2001</u>).

Coral reefs also are vulnerable to disease outbreaks. The onset of disease generally is a response to biotic and/or abiotic stresses. Biotic stress factors include the presence of bacteria, fungi, protozoa and possibly viruses. Abiotic stress factors—physical and chemical changes—include increased seasurface temperatures, ultraviolet radiation, and nutrient input or other pollutants (<u>NMFS, 2001</u>).

According to many coral researchers, rates of disease outbreaks are increasing and affecting more reef species (<u>NMFS, 2001</u>). Scientists believe that the presence of certain stress factors can create environmental conditions favorable to disease microbes, while rendering corals weaker and more vulnerable to colonization. Currently, the most common diseases affecting coral in the Caribbean are white-band disease, black-band disease, white plague and yellow-blotch disease (<u>NMFS, 2001</u>), while in the Pacific white syndrome may be most common and lethal.



Corals are susceptible to exposure during periods of low tide. They may become so stressed that they eject their zooxanthellae, bleach and possibly die.

Tidal emersions—low-tide occurrences that leave coral heads exposed —are natural phenomena which also can damage shallow-water reefs, particularly along the reef flat and on the reef crest. The amount of damage incurred depends on the time of day and the weather conditions that coincide with low tide. Chronic emersions that occur during the day, when heat and sun are strongest, generally are more damaging to coral systems than other emersion events. During the day, corals are exposed to the most ultraviolet radiation, which can overheat and dry out the coral. Corals may become so stressed that they begin to expel their symbiotic zooxanthellae—a circumstance that can lead to a phenomenon known as "coral bleaching" (<u>Barnes &</u> <u>Hughes, 1999</u>).

Prolonged exposure to cold and rainy weather also can damage corals (<u>Barnes & Hughes, 1999</u>). In some cases, corals exposed to such conditions become covered with a grayish fuzz that consists primarily of decomposing coral tissue (<u>Jones & Endean, 1976</u>). Coral reefs have been exposed to natural disturbances like hurricanes, low tides, and El Niño events, for as long as coral reefs have been in existence. Coral reefs are well adapted to recover from natural events, if they weren't, there would be none left. By themselves they are not really a cause for great concern. However, human impacts are probably making reefs less "resilient," that is, able to recover from such events, and that is a cause for concern.

In addition, natural phenomena, such as the El Niño weather pattern, can have lasting, and sometimes devastating, effects on coral reefs. During an El Niño season, easterly trade winds weaken, which depresses normal oceanic upwelling processes and affects the climate. Rainfall increases along the eastern Pacific, while Indonesia and Australia experience drought conditions. El Niño can lead to increased sea-surface temperatures, decreased sea level, and altered salinity due to excessive rainfall (Forrester, 1997). During the 1997-1998 El Niño season, extensive and severe coral reef bleaching occurred, especially in the Indo-Pacific region, and the Caribbean.

Approximately 70 to 80 percent of all shallow-water corals were killed on many Indo-Pacific reefs (<u>NMFS, 2001</u>). During the same year, coral reefs in the Florida Keys experienced bleaching events ranging from mild to severe (<u>NMS, 2001</u>). The increased sea surface temperatures



Massive coral infected with Black Band disease. The white area is the exposed coral skeleton where the living coral tissues have died.

during recent El Niño events comes on top of gradually rising temperatures which are part of global warming. It is the combination that produces the temperatures high enough to cause mass coral

bleaching. The cause for concern is primarily the global warming, not the El Niño by itself.



Damage caused by a single feeding parrotfish. The polyps have been killed and eaten, and the underlying skeleton is exposed. The polyps adjacent to the exposed skeleton are vulnerable to algal colonization.

Finally, corals are vulnerable to predation. Numerous species, including parrotfish, polychaetes, barnacles, crabs and gastropods, prey on coral polyps, destroying the substrate in the process and preventing other corals from settling (Jones & Endean, 1976). Recent outbreaks of one predator, the crown-of-thorns starfish (*Acanthaster planci*), devastated reef systems in Guam, along Australia's Great Barrier Reef and others.

A. planci is a multirayed starfish covered with long, sharp, mildly venomous spines. A full-grown specimen ranges in size from .25 to .5 m in diameter, and feeds by attaching itself to a coral head, inverting its stomach, and digesting the underlying coral tissue. When it detaches, it leaves behind a large, white, dead skeletal patch that is rapidly colonized by filamentous algae. Colonies of calcareous algae and soft corals soon follow (Barnes & Hughes, 1999).

When *A. planci* infestations occur at low densities, coral colonies can recover relatively easily. However, heavy infestations, as great as 15 adults per square meter, can devastate a coral colony (<u>Barnes, 1987</u>). In 1978 and 1979, for example, a massive *A. planci* outbreak devastated as much as 90 percent of the coral reefs of Fagatele Bay in American Samoa (<u>NMS, 2001</u>).

Scientists are unsure of the causes for heavy outbreaks, but evidence suggests that the removal of the starfish's predators in many areas, particularly the overfishing of giant triton and other predator fish, has allowed starfish populations to boom (<u>Barnes & Hughes, 1999; Jones & Endean, 1976</u>). Other evidence suggests that larval periods of high population outbreaks may coincide with plankton blooms (<u>Barnes, 1987</u>).



The crown-of-thorns sea star (A. planci) consumes and ingests corals' soft tissues as it slowly craws over the reef. In high concentrations, these organisms can quickly decimate a reef system, leaving it a barren wasteland.

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Anthropogenic Threats

In addition to natural threats, human activities pose grave threats to the viability of coral reefs. One of the most significant threats to reefs is pollution, a term used to describe numerous types of human-induced marine discharges.



Marine debris like this discarded plastic bag are ubiquitous near heavily populated near-shore areas. Plastic bags can quickly kill corals by surrounding and "suffocating" them.

Excessive runoff, sedimentation, and pollutant discharges can result from dredging and shoreline modifications, coastal development activities, agricultural and deforestation activities, and sewage treatment plant operations. In addition, hot-water discharges from water treatment plants and large power plants can significantly alter the water chemistry in coastal areas (UVI, 2001).

When pollutants are discharged, nutrient levels (nitrates and phophates) in the water can increase. This can lead to an excessively nutrient-rich environment (eutrophic), which encourages algae blooms and the growth of other organisms that can stifle corals or outcompete them for space (Jones & Endean, 1976). In addition, direct sedimentation can smother a shoreline reef, or it may increase the water's turbidity, which, in turn, obscures the light on which corals thrive. Light deprivation ultimately will starve a coral, which is dependent on its symbiotic algae (zooxanthellae) to generate food photosynthetically (UVI, 2001; Bryant *et al.*, 1998).

In many other areas, coral reef habitats are overfished and/or overexploited for recreational and commercial purposes (UVI, 2001).

Coral heads and brightly colored reef fishes are collected for the growing aquarium and jewelry trade. Reef fishes also are collected for food. Careless or untrained divers often can trample fragile corals. In addition, their fishing techniques can be destructive not only to fish but to the coral habitat. Blast fishing, for example, in which dynamite or other heavy explosives are detonated to stun fish for easy capture. This fishing method cracks coral heads apart and stresses nearby coral colonies so much that they expel their symbiotic algae. As a result, large sections of reefs can be destroyed.

Cyanide fishing, which involves spraying or dumping cyanide onto reefs to stun and capture live fish, also kills coral polyps, and degrades the reef habitat. In addition, one-third to one-half of all fish collected this way die soon after they are removed—either sometime along the trade process or, ultimately, in captivity (<u>NMFS, 2001</u>). According to some estimates, more than 40 countries are affected by blast fishing, and more than 15 countries have reported cyanide fishing activities (<u>ICRI, 1995</u>).

Other damaging fishing techniques include deep-water trawling, which involves dragging a fishing net along the sea bottom, and muroaminetting, in which reefs are pounded with weighted bags to startle fish out of crevices (<u>Bryant *et al.*</u>, 1998). Often, fishing nets left as debris. Live corals become entangled in nets and in areas of wave disturbance are torn away from their bases (<u>Coles</u>, 1996). Moreover,



Destructive fishing practices such as the use of cyanide, blast fishing, and deep-water trawling destroy both fish and reef habitat.

the impact of anchors dropped from fishing vessels onto reefs can break and destroy coral colonies (Bryant *et al.*, 1998).

Finally, coral reefs are directly impacted by marine-based pollution. Leaking fuels, anti-fouling paints and coatings, and other chemicals can leach into the water, adversely affecting corals and other species (<u>UVI, 2001</u>). Petroleum spills also are a concern. It is uncertain how much petroleum spills directly affect corals - oil usually stays near the surface of the water, and much of its volume evaporates into the atmosphere within days. However, the timing of a spill is crucial. Corals that are spawning at the time of an oil spill can be damaged because the eggs and sperm, which are released into the water at very precise times, remain at shallow water depths for various times before they settle. In addition, it is not yet fully known how dispersants used to combat oil spills might affect corals, as this results in more oil being suspended in the water column instead of the surface.

As coastal populations swell and marine resources continue to be exploited, coral reefs face an uncertain future. An International Coral Reef Initiative has been established to address and mediate the hazards that threaten the survival of coral reef ecosystems.

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Cumulative Threats

Globally, the most pressing threats to coral reef ecosystems are climate change and ocean acidification, adverse impacts from fishing, and land-based sources of pollution. All three of these are anthropogenic, and impact not only the reefs directly, but also indirectly, by worsening the impact of natural threats. As such, human activity is increasingly difficult to separate threats to coral reefs as either natural or anthropogenic. Hurricanes are a natural phenomenon – but they are being made stronger and more frequent by increased temperatures that result global warming linked to human activities. There is evidence that coral reef disease has become more prevalent, and that this is thought to be linked to human activities. Likewise, crown of thorn sea stars are natural predators to coral reefs in many areas, but there is increased evidence that this is linked to nutrient run-off, removal of sea star predators, or both. Finally, the concept of ecosystem resiliency is important to understand the cumulative effects of threats: both natural and anthropogenic; and local and global. For instance, hurricanes and disease have occurred ever since coral reefs have existed, and historically the reefs have thrived in spite of them - that is, the ecosystem was resilient, and able to "bounce back" and recuperate from disturbances. Nowadays, however, the cumulative impact of several stressors has reduced the resiliency of many coral reefs ecosystems. For instance, corals which have suffered from bleaching events might succumb more readily to an encroaching disease,

and ocean acidification might slow the calcification rate, thus delaying recovery from a destructive hurricane event.

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Northwestern Hawaiian Islands

Introduction

Hundreds of miles northwest of the eight Main Hawaiian Islands (MHI) are ten little known, remote, and rarely visited tiny islands, atolls and shoals that span more than 1,200 miles (1,931 km) of the North Pacific Ocean. These are the Northwestern Hawaiian Islands (NWHI). With coral reefs in general decline around the populated regions of the world, the NWHI reefs provide a unique opportunity to study and assess how coral reef ecosystems function when not affected by major human activities.

The coral reefs of the NWHI are spectacular and pristine ecosystems covering thousands of square miles in the United States. These coral reefs are the healthiest and most undisturbed of the United States reefs, and unlike most other present-day coral reefs, the NWHI reefs comprise possibly the last, large-scale, apex predator-dominated coral reef ecosystem on Earth.

The NWHI coral reefs and associated habitats harbor more than 7,000 species that include corals and other invertebrate animals, algae, plants, fishes, sea turtles, birds, and marine mammals. Many of these species are rare, threatened, or endangered; many are endemic, found nowhere else on Earth; and many more remain unidentified or even undiscovered to science.

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A chart depicting the distribution of the Estimated 36,813 sq km of Potential shallow-water Coral Ecosystems in U.S. Tropical and Subtropical Waters. (Ref. 13 Rohmann etal. , 2005)

Research and surveys from several scientific expeditions to the NWHI over the past five to six years, have shown the coral reefs to be in good to excellent condition. The corals were healthier and more vigorous than expected. In some areas, the abundance and number of species of stony coral were much higher, even double, than researchers had been led to believe from previous literature (<u>Ref. 7</u>). Some single coral colonies were found to be very old, indicating long-term stability of the ecosystem. Coral scientists also observed the presence of a wide variety of unique growth forms which are uncommon in MHI. Also, some rare species of coral in the main islands are abundant in the NWHI. From a fisheries' perspective, the most important finding was the abundance of large apex predators, such as sharks and jacks, compared to the MHI. Not surprisingly, unique and specialized habitats in some areas harbored undescribed, and possibly endemic, species of sponge. Initial surveys found no invasive marine invertebrates in the NWHI except in the inhabited Midway Atoll. This is in dramatic contrast to the MHI where many marine invertebrates have been introduced via shipping traffic. However, terrestrial alien insects were found on all islands, and terrestrial alien plants were found on all islands except Gardner Pinnacles. Scientists noted an uneven distribution of corals, fishes and marine plants across the NWHI. For example, there seemed to be a higher number of gray sharks (*Carcharhinus amblyrhinos*) in the southern NWHI, whereas Galapagos sharks (Carcharhinus galapagensis) were more abundant in the north. There were marked differences in percentages of coral cover and kinds of species between the basaltic volcanic islands and the carbonate atolls.

A Presidential Order in the year 2000 designated nearly 100,000 square nautical miles (342,990 km²) in the NWHI area as a marine reserve, restricting both commercial and recreational fishing. The islands, shoals, atolls and reefs in this reserve is the largest nature preserve ever established in the United States and the second largest marine protected area in the world (after the Australian Great Barrier Reef). Limiting fishing has helped this ecosystem thrive, but it's still not immune from outside threats. NOAA's National Marine Sanctuary Program (NMSP) has begun the process to designate the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve (Reserve) as a National Marine Sanctuary under the National Marine Sanctuaries Act (NMSA). On June 15, 2006, President George W. Bush used his authority under the Antiquities Act to designate the Northwestern Hawaiian Islands a national monument. On March 2, 2007, First Lady Laura Bush joined Hawaii Governor Linda Lingle in announcing a new Hawaiian name for the Northwestern Hawaiian Islands Marine National Monument. The name is Papahanaumokuakea, which refers to Hawaiian genealogy and the formation of the Hawaiian archipelago. The name was adopted through consultation with the Native Hawaiian Cultural Working Group. This national monument will enable nearly 140,000 square miles of the Northwestern Hawaiian Islands to receive our Nation's highest form of marine environmental protection. The monument is managed by the Department of the Interior's U.S. Fish and Wildlife Service and the Commerce Department's National Oceanic and Atmospheric Administration (NOAA), in close coordination with the State of Hawaii.

The Papahanaumokuakea Marine National Monument will:

- Preserve access for Native Hawaiian cultural activities;
- Provide for carefully regulated educational and scientific activities;
- Enhance visitation in a special area around Midway Island;
- Prohibit unauthorized access to the monument;
- Phase out commercial fishing over a five-year period; and
- Ban other types of resource extraction and dumping of waste

This characterization of the Northwestern Hawaiian Islands touches upon the geography, cultural history, comparative biology, and conservation efforts to preserve the area. Recent scientific expeditions and methods of data capture are described, along with summary descriptions of individual islands, atolls, shoals, and banks. Links are provided to metadata and data catalogued with the NOAA Coral Reef Information System (CoRIS) The final statement is a 2005 assessment of the status and health of the coral reef ecosystem of the NWHI.

<u>Quicktime Movie Slideshow</u> of images taken in the NWHI during the 2002 Northwestern Hawaiian Islands Coral Reef Assessment and Monitoring Program (NOWRAMP) expedition. Images taken by professional wildlife photographer, James Watt. (39 MB, requires Apple <u>QuickTime</u> free viewer)

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Hawaiian Archipelago

The Hawaiian Islands form an archipelago that extends over a vast area of the North Pacific Ocean. The archipelago is made up of 132 islands, atolls, reefs, shallow banks, shoals, and seamounts stretching 1,523 miles (2,451 km) from the island of Hawai'i in the southeast to Kure Atoll in the northwest. The archipelago lies across the Tropic of Cancer between 1540 40' to 1780 25' W longitude, and 180 54' to 280 15' N latitude. It has a total land area of approximately 6,425 square miles (16,642 km2) (*Ref 1*). The archipelago represents the exposed peaks of an undersea mountain range, formed by volcanic activity over a hotspot in the Earth's mantle.



Northwestern Islands and Banks of the Hawaiian Archipelago

The inhabited eight Main Hawaiian Islands (MHI) are separated from the southernmost of the mostly uninhabited Northwestern Hawaiian Islands (NWHI) by approximately 155 miles (250 km) of open ocean. This is the distance between Kaua'i in the south and Nihoa Island in the north.

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The Northwestern Hawaiian Archipelago

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Geography and history

The NWHI is an archipelago which consists of a series of islands, atolls, reefs, shallow water banks, and seamounts that start with Nihoa Island and stretch 1,193 miles (1,920 km) west-northwest to Kure Atoll. They are part of the Hawaiian Ridge-Emperor Seamounts chain that extends approximately 3,700 miles (6,000 km) from the island of Hawai'i to the Aleutian Trench off the coast of Siberia.

The named islands, shoals , banks and atolls (from east to west) are: Nihoa, Necker, French Frigate Shoals, Gardner Pinnacles, Maro Reef, Laysan Island, Lisianski Island, Pearl and Hermes Atoll, Midway Island, and Kure Atoll.



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Table coral (Acropora) at French Frigate Shoals (Photo: James Watt)

The NWHI were formed by volcanic action over the past 70-75 million years as the Pacific tectonic plate moved slowly northwestward over a stationary magmatic hotspot in the Earth's crust (a location on the Earth's surface which has had volcanic activity for a long period of time). This hotspot has its origin in the convection of molten lava from the upper mantle (<u>Ref. 2</u>). Kure is the oldest island in the Hawaiian Archipelago; the Main Hawaiian Islands (MHI) are the youngest.

A significant percentage of reef-building corals within the waters of the United States are contained within the NWHI. While elsewhere in the world coral reefs are threatened and stressed by human activities such as coastal development, pollution, and resource over-exploitation, the remote location of the NWHI has helped protect its coral reefs from adverse human impact. The shallow-water coral reefs of the NWHI are truly unique. They are still pristine ecosystems with a much greater diversity in reef habitats than in the MHI.



A beautiful coral in the NWHI (Photo: Bishop Museum/ NOWRAMP Expedition)

Algae

Scientists have recorded 366 described species of algae from The NWHI, with new endemic species (species native to the area) more recently discovered. The NWHI provide habitats for many Indo-Pacific algal species that are not found in the MHI.

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Birds, mammals, and turtles

A distinctive group of marine mammals, fishes, sea turtles, birds, and invertebrates inhabit the NWHI. They include species that are endemic, rare, threatened, and endangered, including the Hawaiian monk seal and the green, leatherback, and hawksbill sea turtles. The majority of the highly endangered Hawaiian monk seals breeds and feeds in the NWHI, as do over 90 percent of the Hawaiian population of threatened green sea turtles. Four other species of sea turtles are sometimes seen in the waters of the NWHI. The NWHI also provide the nesting habitats for more than 14 million Pacific seabirds. Nearly all of the world's Laysan albatross and black-footed albatross reproduce there. Seventeen other species of seabirds also nest in the islands. Many of these birds rely on the coral reefs for food. Many of these atolls also provide protection for Hawaiian spinner dolphins to safely rest during daylight hours. Other marine mammals, such as the Hawaiian humpback whale, also travel through this region.

Corals

More than 7,000 marine species have been recorded from the Hawaiian Islands, including corals and other benthic (bottomdwelling) invertebrates, algae, plants, fishes, sea turtles, and marine mammals. It has been estimated that as many as one quarter to one half of the species in some of these groups exist only in the NWHI. These islands


also serve as a source of marine species that helps restock the MHI. Among the 57 recorded stony coral species in the NWHI, 11 were first records and 29 were species range extensions. Coral endemism is high (30 percent), with three genera accounting for 88 percent of the endemic species and

A pristine coral reef in the NWHI (Photo: Bishop Museum/ NOWRAMP Expedition)

most of the endemic abundance in the NWHI. Live coral cover is highest on Maro Reef and lowest on Necker Island. Coral abundance and diversity are highest on the large open atolls (French Frigate Shoals, Maro Reef, Lisianski/Neva Shoals) and decline through the remaining atolls to the northwest.

<u>A list of NWHI coral species</u> (pdf,30kb) adapted from: Maragos, J., G. Aeby, D. Gulko, J. Kenyon, D. Potts, D. Siciliano, and D. VanRavensway. 2004. The 2000-2002 Rapid Ecological Assessment of Corals in the Northwestern Hawaiian Islands, Part I: Species and Distribution. Pacific Science 58(2):211-230.

Fishes

The average fish standing stock (the total biomass of fishes in a given area) in the NWHI was almost 300 percent greater than in similar habitats of the MHI. The deeper waters surrounding these islands support commercially important fishes such as large sea basses and deep sea snappers. Remarkably, the NWHI have an abundance of sharks and other large apex predators, species at the top of the food chain. More than 54 percent of the total fish biomass on forereef habitats in the NWHI consisted of apex predators, compared to less than 3 percent in the MHI. About 30 percent of the fish species are endemics. Most of the dominant species by weight in the NWHI are



Squirrelfish inhabiting crevices and holes in a reef in the NWHI (Photo: Bishop Museum/ NOWRAMP Expedition)

either rare or absent in the MHI.. Overfishing has not taken a devastating toll on these species as it has done on most coral reef ecosystems that are more accessible to humans.

Online Encyclopedia for Flora and Fauna of the Northwestern Hawaiian Islands <u>http://www8.nos.noaa.gov/onms/park/parks/?pID=12</u>

Early human influences

The NWHI also possess a great cultural significance to native Hawaiians. During their trans-Pacific voyages, ancient Polynesians sailed these waters and used these islands for centuries as places of residence and worship. By the time European explorers discovered these islands, the early Polynesians had already stopped visiting them. Some of the island ecosystems, for example, Laysan, suffered in the late 1800's and early 1900's when humans exploited seabird guano deposits for use as fertilizers. They also introduced rabbits and guinea pigs as food supplements and for business ventures. Soon the island was overrun with rabbits which ate most of the vegetation, nearly turning the island into a desert. Without vegetation for shelter, the great populations of birds on the islands were threatened with extinction. The great numbers of birds also attracted poachers, which slaughtered hundreds of thousands of birds for their feathers. As a result of this wholesale slaughter of birds, President Theodore Roosevelt, on February 3, 1909, by executive order, set aside all of the islands from Kure to Nihoa, with the exception of Midway, as the Hawaiian Islands Bird Reservation, Within this Sanctuary it is unlawful to kill or molest the birds.

NOAA's Remote Sensing Team led development of the first benthic habitat maps made for the Northwest Hawaiian Islands. The satellite data used was IKONOS multispectral (blue/green/red/near-infrared bands) and panchromatic imagery from Space Imaging, collected between 2000 and 2002. Landsat 7 Enhanced Thematic Mapper Plus (ETM+) imagery was also obtained for all ten atolls as well as for most of the bank areas

NWHI: Maps and Imagery

NOAA's Remote Sensing Team led development of the first benthic habitat maps made for the Northwest Hawaiian Islands. The satellite data used was IKONOS multispectral (blue/green/red/near-infrared bands) and panchromatic imagery from Space Imaging, collected between 2000 and 2002. Landsat 7 Enhanced Thematic Mapper Plus (ETM+) imagery was also obtained for all ten atolls as well as for most of the bank areas

http://ccma.nos.noaa.gov/ecosystems/coralreef/nwhi/

Bathymetry of the Northwestern Hawaiian Islands

The Pacific Islands Benthic Habitat Mapping Center provides an assortment of bathymetric maps for the Northwestern Hawaiian Islands.

http://www.soest.hawaii.edu/pibhmc/pibhmc_nwhi.htm

NWHI Multi-Agency Education Project

This site provides educational materials and web reports from NWHI expeditions.

http://www.hawaiianatolls.org/

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The Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve



On December 4, 2000, the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve (Reserve) was created by Executive Order 13178. The Reserve encompasses an area of the marine waters and submerged lands of the Northwestern Hawaiian Islands extending approximately 1200 nautical miles long (2,222.4 km) and 100 nautical miles (185.2 km) in width. As part of the establishment of the Reserve, Executive Order 13178 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. On January 18, 2001, after the close of a 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 National Marine Sanctuary Program (NMSP) has begun the process to designate the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve (Reserve) as a National Marine Sanctuary under the National Marine Sanctuaries Act (NMSA).

Executive Order 13178

Executive Order 13196: Amendment to Executive Order 13178

Reserve Preservation Areas (RPA)

This page provides a set of maps on individual Reserve Preservation Areas (RPA). Selected RPA maps are supplemented with images taken by the Landsat 7 Satellite. The satellite images are provided to depict how these areas appear from space, not to delineate their boundaries. http://www.hawaiireef.noaa.gov/imagery/rpa.html

Reserve Preservation Areas of the NWHI Coral Reef Ecosystem

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http://oceanexplorer.noaa.gov/explorations/02hawaii/ background/ecosystem_reserve/ecosystem_reserve.html

NWHI Coral Reef Ecosystem Reserve List Serve

The purpose of this list is to announce Reserve activities and events pertaining to education, research and monitoring, enforcement, sanctuary designation, and the Reserve Advisory Council and other items of interest.

http://www.papahanaumokuakea.gov/education/listserve.html

Sanctuary Designation

The National Marine Sanctuary Program (NMSP) has begun the process to designate the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve as a National Marine Sanctuary under the National Marine Sanctuaries Act. Answers are given to commonly raised questions about the proposed designation for the NWHI.

http://www.papahanaumokuakea.gov/about/faq.html

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out of date. For more information: <u>http://coralreef.noaa.gov/</u>.

Cultural History of the NWHI

Early settlers

The Pacific Ocean covers one-third of the surface of the earth and is comprised of thousands of islands that are scattered over a vast expanse of water with shifting winds, and strong currents. The movement of ancestral Oceanic people, or kanaka maoli, across remote Oceania was one of the most remarkable feats of open-ocean voyaging and settlement in all of human history. In the Hawaiian archipelago, the northwestern region contained the most peripheral islands that relied heavily on interaction and networking between core islands (the Main Hawaiian Islands) as a social mechanism to help reduce the possibility of extinction of their geographically isolated populations.

The Northwestern Hawaiian Islands (NWHI) were explored, colonized, and in some cases, permanently settled by Native Hawaiians in pre-contact times. Nihoa and Mokumanamana (Necker Island), the islands that are closest to the Main Hawaiian Islands, have archaeological sites which with agricultural, religious, and habitation features. Based on radiocarbon data, it's been estimated that Nihoa and Mokumanamana could have been inhabited from 1000 A.D. to 1700 A. D. (Ref. 4). These islands pose the same dilemma as a score of other islands in Oceania, which were small targets for voyaging, and often at some distance from their nearest



One of a number of stone ki'i, or images, that were found on Necker Island, NWHI. They are remarkable in that they look more like the artwork found in central Polynesia, like the Marquesas Islands, than the art of Hawai'i. (Photo: Bishop Museum)

occupied neighbor. All of these islands were either empty at contact or abandoned, having been occupied some time previously. Due to the environmental constraints of being small, geographically isolated, and not having sufficient resources to allow self-sustainability, demographic stability (in initial and later stages of colonization) is thought to be among the main reasons why interaction was so vital to these regions.

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2004 cultural expedition of the voyaging canoe Hokule'a at Nihoa Island (Photo credit: Na'alehu Anthony)

Archeology

Nihoa and Mokumanamana Islands are recognized as culturally and historically significant and are listed on the National and State Register for Historic Places. They are protected by the U. S. Fish and Wildlife Service in accordance with the National Wildlife Refuge System Administration Act of 1966, as amended. Archaeological surveys on Nihoa and Mokumanamana have documented numerous cultural sites and materials (Emory 1928; Cleghorn 1988; Graves and Kikiloi, in prep.). Nihoa Island, where there is significant soil development, has over 88 cultural sites, including ceremonial, residential, and agricultural features. Mokumanamana Island has 52 cultural sites, including ceremonial and temporary habitation features. Several archaeological surveys have collected cultural artifacts from both these islands. These are curated at the Bernice Pauahi Bishop Museum and University of Hawai'i at Manoa Archaeological Laboratory. The range in types of cultural artifacts stored in these collections is testimony to the various uses these islands and surrounding waters served for Native Hawaiians.



Site Complex, East Palm Valley, Nihoa Island (Photo credit: Dave Boynton). <u>Click here</u> to view the large version.



Site 45 on Nihoa Island, possible habitation (Photo credit: Dave Boynton). <u>Click here</u> to view the large version.



Map of Nihoa Archaeological Sites, Emory 1928. <u>Click here</u> to view the large version.



Map of Site 45 on Nihoa Island, Emory 1928. <u>Click here</u> to view the large version.

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Cleghorn, Paul. 1988. The Settlement and Abandonment of Two Hawaiian Outposts: Nihoa and Necker Islands. Bishop Museum Occasional Papers Vol. 28, p.35-49.

Graves, Michael and Kekuewa Kikiloi. in prep. Preliminary Reconnaissance of Archaeological Sites on Nihoa Island, August 2005. Prepared for U. S. Fish and Wildlife Service, Honolulu.

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Marine Field Surveys and Data Collection

The first scientific expeditions to the Northwestern Hawaiian Islands (NWHI) were in the early 1920's. The Tanager Expeditions, which took their name from the First World War minesweeper, the USS *Tanage*r, surveyed the NWHI, and collected archaeological, meteorological, and biological data and specimens. Prominent scientists from the Bishop Museum and the Smithsonian Institution participated in these surveys. In 1984, Bishop Museum scientists discovered additional archeological sites on Nihoa and Necker Islands.



USS Tanager

In 2000, the Northwestern Hawaiian Islands Reef Assessment and Monitoring Program (NOWRAMP) multiple-year expedition was launched as a multi-agency and institutional partnership that brought together the best field resources (people, equipment, and funding) of both the resources trustees (state and federal management agencies) and the academic community. The major goal of NOWAMP is to map and rapidly assess the shallow coral reefs of the NWHI for their biodiversity, status, health, and management needs. NOWRAMP involved the U.S. Fish and Wildlife Service (USFWS), NOAA's National Ocean Service (NOS) and National Marine Fisheries Service (NMFS), Hawai'i Division of Aquatic Resources, Bishop

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Museum, Oceanic Institute, and the Universities of Hawai'i and California. The NOWRAMP expeditions are the most comprehensive coral reef assessments of the NWHI to date. Most of the information on NWHI coral reefs in this essay was obtained from the NOWRAMP expedition reports and publications.

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NOAA CoRIS - Northwestern Hawaiian Islands: Data Collection Scope and Methods



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Data Collection Scope and Methods

Read About:

Conductivity, temperature and depth, or "CTD" measurements

Water samples Solar radiation Time series measurements

Night observations Water movement Benthic habitat mapping

Physical and chemical oceanography(Ref. 8)

Physical and chemical oceanographers study the movement of ocean water (currents) and the physical and chemical characteristics of that water (e.g., temperature, salinity, density, dissolved gasses, nutrients, geochemistry, fluxes, light penetration and distribution, and other primary and derived physical and chemical parameters). Data are collected by taking direct measurements on site, by instrumented moored buoys that telemeter their data back by satellite or are retrieved at a later time, and by aerial surveys and satellite imagery.

Conductivity, temperature and depth, or "CTD" measurements

The CTD is a device that can reach 1,640 ft (500 meters) in depth, taking up to five water samples at different depths, and making other measurements on a continuous basis on descent and ascent. Temperature and pressure are measured directly. Salinity is measured indirectly by measuring the conductivity of water to electricity.

> Chlorophyll, a green photosynthetic pigment, is measured indirectly by a fluorometer that emits purple light and measures fluorescence in response to that light. These measurements are made continuously, providing a profile of temperature, salinity, and chlorophyll as a function of depth.

> Shipboard CTD measurements are typically taken at three locations around a given island or atoll: the windward and leeward sides, and at a standard oceanographic "station" assigned to each

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Scientists preparing to lower a shipboard CTD unit (Photo: NOAA/PMEL)

island or atoll that is being surveyed over a long period of time. There is one such station per each major island or atoll in the NWHI: Nihoa, Necker, French Frigate Shoals, Gardner, Maro Reef, Laysan Island, Lisanski Island, Pearl and Hermes Atoll, MidwayAtoll, and Kure Atoll (<u>*Ref.*</u><u>6</u>).

Shallow, handheld water CTD

measurements are taken to understand the local reef ecosystem. These measurements are taken from a small jet boat every mile or two around the island/atoll between the 80 and 120 foot (24 to 37 m) isobath (a contour of equal depth in a body of water), and in a few places inside the atolls. Data are needed at more locations than just three, and at depths shallower than a ship can operate. A handheld CTD includes a temperature sensor, a depth sensor, and a conductivity sensor. It also has a transmissometer that measures the level of particulate matter in the water (a proxy for turbidity). These measurements are also made continuously as the device descends and ascends. Unlike the larger version, the small boat CTD does not take water samples and does not have a fluorometer. Separate devices are used for these purposes.

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Water samples

Water samples are taken by a handheld water bottle consisting of a tube with spring loaded caps at both ends. The caps are set in the open position so water can flow through the tube as it descends. A weight is then slid down the supporting rope to hit a trigger and close the caps. Water samples are typically taken at three depths, 5, 30, and 60 feet (1.5, 9, and 18 meters). The sampler is then taken to the surface, where the water is used to first rinse out a sample bottle (to avoid contamination from other water), and then to fill the sample bottle.



A handheld CTD (Photo: NOWRAMP)

The bottle is opaque to prevent further modification of the chlorophyll content by light. (Water from the large CTD is also stored in these same bottles).

Solar radiation

A radiometer on the jet boat replaces the fluorometer, and also gives

important information about available solar radiation. Two radiometers are coupled together to take readings above and below the surface. An instrument on the boat reads the amount of light arriving at the ocean surface. Another instrument is put in the water to read the light reflected back from the water. This is compared to the former surface measurement for reference. These measurements are made at light frequencies relevant to photosynthesis. The concentration of chlorophyll can be measured by reading reflected light at certain wavelengths.

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Time series measurements

In order to understand variability of an ecosystem, it needs to be monitored over many years. The instruments described below record a series of measurements of water characteristics over time. They include NOAA Coral Reef Early Warning System (CREWS) buoys, Sea Surface Temperature (SST) buoys, and SST "pipe bombs".





Sea Surface Temperature (SST) buoys (Photo: NOWRAMP)

scientists as soon as possible of an unusual change taking place in the coral reef environment. These buoys have sensors both below and above the water surface that measure water and air temperature, salinity, wind speed, and barometric pressure. A few of them also have radiometers to measure solar radiation, but these can only be located where staff can get to them every few weeks to clean the sensors. There is one at French Frigate Shoals, serviced by U.S. Geological Survey staff on Tern Island.

CREWS buoys are large and expensive, so other instruments are also used that measure fewer parameters but can be deployed in more locations. Sea Surface Temperature (SST) buoys are round floating buoys that are anchored in a specific location. They measure water temperature and telemeter these data back to a data receiving station at regular intervals via satellite. SST pipe bombs are strapped to the reef at different depths and locations around an atoll. These are set to measure temperature every half an hour, and record it on a data chip. Divers must retrieve these devices in order to obtain the data.



A CREWS Buoy installed in the lagoon at Rose Atoll, American Samoa. (Photo: NOAA)

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Night observations

In order to maximize ship use, after dark operations are conducted during which various sensors are deployed as the ship follows designated tracks in deeper water locations. Night operations include shipboard CTD deployment, and Towed Optical Assessment Device (TOAD) surveys. TOAD



consists of a video camera and lights on a frame designed to be towed just above the bottom. TOAD video is used to certify or ground truth acoustic habitat sensing. Specifically, the TOAD videos show the composition of the bottom in a few locations, such as sand, rubble, sea grass,

A Towed Optical Assessment device (TOAD) being readied (photo: NOWRAMP)

coral, etc. TOAD allows interpretation of broad area acoustic data by comparing it to the video information.

Water movement

Several instruments are used to measure water movement: Wave and Tide Recorders (WTDs) measure the tide 48 times a day, and record wave height eight times a day in the process. They are deployed at 50 to 100 feet (15.2 to 30.5 meters); The Acoustic Doppler Current Profiler (ADCP) generates a 3-dimensional current profile by analyzing the Doppler-shift of fixed-frequency acoustic echos. The ADCP is typically mounted to the bottom of a ship, or tied to a mooring and uses sound waves to detect the motion of particles in the water. Sound waves are emitted into the water column at a frequency of around 150 KHz and the echo of the sound bouncing off small particles in the water can be used to determine the motion of the particles; Drifting buoys follow water at 49.2 feet (15 m) depth, measuring Global Positioning System (GPS) position and water temperature over time.

Benthic habitat mapping

The Pacific Islands Benthic Habitat Mapping Center (PIBHMC), located on the University of Hawaii Manoa campus, is tasked with the delineation of the benthic habitat of coral reef ecosystems throughout the U.S. Pacific Islands, including the Hawaiian and Mariana archipelagos, American Samoa and remote, U.S.- affiliated islands such as Johnston and Palmyra Atolls. PIBHMC was established as a result of a long-standing relationship between the University of Hawaii's School of Ocean and Earth Science and Technology (SOEST) and NOAA.

Using acoustic and optical techniques, PIBHMC extends shallow-water maps into deeper waters where satellite and diver-based techniques are not feasible. Products such as gridded bathymetric maps of the NWHI (<u>http://www.soest.hawaii.edu/pibhmc/pibhmc_nwhi.htm</u>) were created using data gathered from multibeam soundings. The data are also being used for benthic habitat mapping, for locating Essential Fish Habitat, and for studying geologic features of the area. These products provide resource managers with comprehensive habitat maps on which to base decisions about Pacific coral reef ecosystems.

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NOAA CoRIS - Northwestern Hawaiian Islands: Rapid Ecological Assessment (REA)



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Rapid Ecological Assessment (REA)

Read About:

Towboard team Fish team Benthic team Sediments team

Remote sensing team Land team

Geography and history

In order to maximize the intercomparability and coverage of field in situ surveys, Rapid Ecological Assessment (REA) operations are organized into specialist teams which provide baseline data for improved decision making and planning for the ecological management of the Northwestern Hawaiian Islands (NWHI) coral reef ecosystem. REAs are like "snapshot " assessments of the reef ecology. The teams are the (1) Towed Diver (Towboard) Team, (2) Fish Team, (3) Benthic Team, (4) Sediments Team, (5) Remote Sensing Team, and the (6) Land Team. The Teams take a global positioning position (GPS)) reading on each site so they can return in later years to determine the status and health of the reefs.

Towboard team

The **Towboard team** protocol used in the Northwestern Hawaiian Islands Coral Reef Assessment and Monitoring Program (NOWRAMP) involves two divers, each holding onto a separate towboard being towed behind the same small boat at a constant speed (1.5 knots). A towboard is a board with a bridle for attaching the towline and handles for the diver to hold on to. Each towboard has a temperature and depth sensor that records continuously during each towboard survey. Paired lasers project a scale onto the video. The towboard also has attachments for affixing watches and dive computers, and a signaling system to the boat operator.

A global positioning system (GPS) on the boat records latitude and longitude. A digital video camcorder is mounted to each board, with one camcorder pointing down (90⁰) and the other pointing at a forward angle (20⁰) to capture a broader swath of habitat and ocean bottom information. The "forward-looking" board records information about habitat complexity and relative abundance of fish that are larger than 1.6 Hawaiian Archipelago

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feet (50 cm) in length along a 33 feet (10 m) swath. The "downward-looking" board captures information about the composition of the substrate. The divers maintain the cameras one to two meters from the bottom. Tows are conducted in multiple habitats around the reef system. Most

Marine biologists conducting a survey of the benthic community (Photo: Bishop Museum/NOWRAMP Expedition)

surveys focus on depths between 33 and 49 feet (10 and 15 m), except where the water is shallower.

The divers also utilize charts on which they record visual observations. One diver records all species of fishes over 1.6 feet (50 cm). The other diver records types of benthic habitat every 5 minutes and identifies and counts large invertebrates, such as sea stars, lobsters, octopi, sea cucumbers, and bivalves, etc. These records are important because the cameras may not record fishes and invertebrates out of camera range.

Towed diver surveys provide an effective method for rapid broad overview monitoring of reef health.

Marine biologist recording data on a coral reef in the NWHI (Photo: Bishop Museum/NOWRAMP Expedition)

Towboard Diver collecting data (QuickTime

Movie, 1.5 mb) These videos were taken in the NWHI by researchers aboard the National Marine Fisheries Service Research Vessel, the *Townsend Cromwell* in 2001.

Fish team

The **Fish team** consists of three divers who are fish specialists. Two of the divers swim three 82 feet (25 m) transects per dive. During the "swim out" leg of the transect, both divers record size class-specific counts of all fishes greater than 20 cm in length, within two meters on each side of the transect line. Small and cryptic fishes are enumerated by size class during the "swim back" leg. The third diver of the fish team completes stationary point counts, each within a cylinder having a radius of 32.9 feet (10 m), to estimate the size and abundance of fishes larger than 9.8 inches (25 cm), and the more mobile fishes. This diver also uses a video camcorder to gather information on fish assemblages and size information using attached lasers. Upon completion of transect surveys, fish teams swim freely and randomly over the reef to record rare species.

Benthic team

Benthic teams survey Fish team transects for corals, algae, and other invertebrates. Initial NOWRAMP projects used two broad-scale approaches to study benthic organisms: towed divers who videotaped and estimated

NOAA CoRIS - Northwestern Hawaiian Islands: Rapid Ecological Assessment (REA)

characteristics of long transects, and teams of taxonomic specialists who worked at the same finite sites to conduct extensive REAs. They focused on recording the presence, abundance, and population/community characteristics of all observable species in four main groups: corals, fishes, algae, and other invertebrates (Maragos *et al*, 2004).Some scientists employ a photoquadrat method during REAs to quantitatively survey benthic organisms. This technique utilizes a digital camera and computer software for photographic analysis.

Sediment team

The **Sediment team** focuses on the collection of sediments for later analysis of microorganisms and chemical contaminants, e.g. polychlorinated biphenyls (PCBs).

Remote sensing team

The **Remote sensing team** collects data remotely sensed by instrumentation on satellites and aircraft. Aerial and satellite images of coral reefs can assist mapping and ecological characterization of coral reefs. Different components of a reef, such as carbonate, basalt, organisms, sand, and soft mud bottoms, reflect radiance differently. Specialized instrumentation captures these differences and groups them by type, from which a first estimation map can be derived. A critical step in this process is to capture *in situ* groundtruthing data in order to determine if the reflected radiance images accurately portrays the composition of the reef.



Scientists conducting a photoquadrat survey of benthic organisms (Photo: James Watt)

Land team

The **Land team** lands on island surfaces while submerged REAs are conducted and makes surveys of algae, plants, insects, and other arthropods, such as spiders and mites, and birds, seals, and turtles.

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REA Land Team biologist conducting a survey for insects and other arthropods on Necker Island (Photo: NOWRAMP)



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NOAA CoRIS - Northwestern Hawaiian Islands: Nihoa Island



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Nihoa Island (23° 04' N - 161° 55' W)

Read About:

Geography Terrestrial plants and animals Shallow water habitats

Corals and algae Other invertebrates and fishes

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Nihoa Island (23° 04' N - 161° 55' W)

Geography

The island closest to the Main Hawaiian Islands (MHI) is Nihoa.

This small basalt island lies 160 nautical miles (296 km) east southeast of Necker Island and 155 nautical miles (287 km) west northwest of Kauai and 250 nautical miles (463 km) from Honolulu.

Nihoa is the largest volcanic island in the northwestern chain, with approximately 171 acres (0.7 km^2) of land. It is about a mile long and a quarter mile wide, and it is the tallest of the Northwestern Hawaiian Islands (NWHI) at 903 feet (275 m) on its easternend.

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IKONOS satellite image of Nihoa (Photo: NOAA)

Nihoa's submergent coral reef habitat totals approximately 570 km² (140,554 acres). It was designated a wildlife refuge by President Theodore Roosevelt in 1906. Nihoa is also called "Bird Island", which translates from its ancient name, Mokumanu.



Map of Nihoa Island.



Nihoa Island (23° 04' N - 161° 55' W) is the highest island in the Northwestern Hawaiian Island chain with Miller's Peak reaching to an elevation of 910' (277 meters) (Photo: NOAA/ George H. Balazs)

Although seemingly inhospitable, between 1000 and 1700 A.D this remote and rugged island was visited and inhabited by Hawaiians. More than 80 cultural sites have been discovered, including religious shrines, habitation terraces and bluff shelters, agricultural terraces, and burial caves. Artifacts found included fishhooks, sinkers, cowry shell lures, hammerstones, grindstones, and adzes (ax - like tools).



NOAA vessel approaching Nihoa Island (Photo: NOAA)



Nihoa Island - Tanager Peak (852ft) (Photo: NOAA)

Terrestrial plants and animals

The terrestrial fauna include monk seals (*Monachus schauinslandi*), 72 species of arthropods including giant crickets and earwigs, two species of endemic land birds, the endangered Nihoa finch (*Telespyza ultima*) and the endangered Nihoa millerbird (*Acrocephalus familiaris kingi*), and several species of seabirds, such as terns, shearwaters, petrels, boobies, albatrosses, tropic birds, and frigate birds. Endemic endangered plants include the Nihoa fan palm (*Pritchardia remota*), the only species of tree on the island, and the leguminous 'ohai shrub (*Sesbania tomentosa*). Most of the ridges are covered with two species of grass and the valleys are densely covered with shrubs and bushes.



The endangered Nihoa Finch (Telespyza ultima) is an endemic that lives only on the island of Nihoa. It prefers open but vegetated habitat, nesting in small holes in rock outcrops



The endangered Nihoa Millerbird (Acrocephalus familiaris kingi) is an endemic bird found only on Nihoa. The population size of the Nihoa Millerbird has fluctuated between 300 and 700 individuals in the last 30 years. Threats to the Millerbird include introduced plants and animals, and fire. The Nihoa Millerbird got its name because of its appetite for the miller moth (Photo: USFWS/Craig Rowland)

100 to 800 feet (30.5 to 244 meters) above sea level (Photo: USFWS/Craig Rowland)

Shallow water habitats

Basalt underlies most shallow water habitats surrounding Nihoa. These basaltic habitats consist of submerged portions of sea cliffs close to shore, caves and lava tubes, ledges, overhangs, basalt pinnacles, boulders, cobbles, sand deposits, basalt benches and slopes, trenches, and shelves which are constantly punished by swells and currents. Consequently, there are few suitable habitats for strong and extensive coral colonies to grow and flourish.

Corals and algae

Coral cover is not greater than 25 percent in any habitat. Around Nihoa and the next island in the NWHI chain, Necker Island, there are only submerged reefs, no emergent ones. Most of the reefs are found at 40 ft or deeper. On the North side of



The Nihoa fan palm (Pritchardia remota), is an endemic endangered plant. It is the only species of tree on Nihoa (Photo: Botany Dept., U. Hawaii/Sheila Conant)

Nihoa, few corals were found at depths shallower than 70 feet. Most of the corals observed are low growing encrusting species (Maragos and Gulko, 2002). Seventeen species of scleractinian (stony) coral were found at Nihoa. Small encrusting forms of the lobe coral, *Porites lobata*, and rose coral colonies (*Pocillopora meandrina*) were the most common. Encrusting pink coralline algae covered many rocky surfaces in very shallow water. Some red, brown and green algae were common around the island. The red alga, *Asparagopsis taxiformis*, is an edible species that is no longer common in the Main Hawaiian Islands (MHI).



The cauliflower coral, Pocillopora meandrina. (Photo: National Park Service/ Eva DiDonato)



The edible marine red alga, Asparagopsis taxiformis, while common in Nihoa, has become uncommon in the main Hawaiian islands (Photo: R. Cavaliere, Biology Department, Gettysburg College, PA)

Other invertebrates and fishes

The most common invertebrates found (excluding corals and other cnidarians) are the smaller encrusting species, such as sponges, ectoprocts (*bryozoans*), and tunicates. Large invertebrates were uncommon, except for a couple of species of rock-boring sea urchins and a starfish, the spotted linckia (*Linckia multifora*). Sharks, jacks, monk seals, and other apex predators (predatory animals which are at the top of their food chain and are not normally preyed upon by other predators) are common to the island. However, due to the limited number of habitat types, species diversity of



The spotted linckia, Linckia multifora (photo: www.edge-ofsea.com/Alberto Romero)

reef fishes is low when compared to other atolls and islands in the NWHI. Fishes uncommon or rare in the MHI but typical of the NWHI, such as the spotted knifejaw, *Oplegnathus punctatus*, are often found. Nihoa supports a small population of endangered Hawaiian monk seals with limited reproduction, probably maintained by immigration from other breeding colonies.

<u>A list of NWHI coral species</u> (pdf,30kb) adapted from: Maragos, J., G. Aeby, D. Gulko, J. Kenyon, D. Potts, D. Siciliano, and D. VanRavensway. 2004. The 2000-2002 Rapid Ecological Assessment of Corals in the Northwestern Hawaiian Islands, Part I: Species and Distribution. Pacific Science 58(2):211-230. In order to protect the island's fragile ecosystem, few visitors are allowed on Nihoa and strict protocols are required. Approval must be given by the U.S. Fish and Wildlife Service and is mostly granted to those doing cultural and scientific research.

Link to metadata and data held by CoRIS

Click on the following URL to locate metadata and data in the CoRIS holdings on Nihoa Island. When the query screen comes up, enter Nihoa in the window, and then click on Search.

http://coris.noaa.gov/geoportal/



Fishes uncommon or rare in the Main Hawaiian Islands, but typical of the NWHI, such as the spotted knifejaw, Oplegnathus punctatus, are often found in Nihoa (Photo: NOWRAMP)

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Necker Island (23° 35' N - 164° 42' W)

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<u>Geography</u> Early human visitation <u>Terrestrial vegetation</u> <u>Reef biology</u> <u>Link to metadata and data held by CoRIS</u> <u>More photos</u>

Geography

Necker Island is a small, fish hook-shaped basalt island, about 155 miles (250 km) northwest of Nihoa Island and 90 miles (145 km) east of French Frigate Shoals, with a land area of about 45 acres (0.16 km²). The main portion of the island has a profile with five hills, the highest being about 276 feet (84 m) above sea level. A narrow spur extends about 200 yards (183 m) northward from the western end of the island. Where it joins with the main land mass, the spur, whose highest elevation is 156 feet (48 m) above sea level, forms a shallow, rocky cove called Shark Bay.

Necker Island is the second smallest of the Northwestern Hawaiian Islands (NWHI), but its surrounding marine habitats to depths of 328 feet (100 m) totals 380,048 acres (1538 km2), the second largest in the NWHI. Shallow water marine habitats to depths of 66 feet (20 m) are limited to the vicinity of the island. Deeper shelves, which are offshore commercial fishing grounds, extend many miles from the island, especially in the southeastern direction.



IKONOS Satellite image of Necker Island (photo: NOAA)



Map of Necker Island (Photo: NOAA)

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Early human visitation

Necker Island was visited by Polynesians sometime before 1300 A.D. Over 50 cultural sites were discovered on the island, which include ruins of ceremonial stone structures (heiau) and over a dozen carved stones. It was "rediscovered" and named in 1786 by Jean Francois de Galaup.



These upright stones still remain in place from several hundred years ago when Polynesian visitors used these sites on Necker Island for spiritual or navigational purposes (Photo: NOAA)



Stone idols discovered on Necker Island in 1894. Thirteen idols have been found and eight are housed in the Bishop Museum. The largest image weighs 25 pounds (11.3 kg) and stands over 18 inches (46 cm) high (Photo: Bishop Museum

Terrestrial vegetation

In suitable locations, the island is sparsely carpeted with five species of low, nearly prostrate plants: a species of goosefoot shrub (Chenopodium sandwicheum), a bunch grass (Panicum torridum), purslane (Portulaca lutea), pickle weed (Sesuvium portulacastrum), and the ohai shrub (Sesbania tomentosa). Necker Island provides a nesting spot for thousands of sea birds.



The purslane (Portulaca lutea) on Necker Island (Photo: Botany Dept., U. Hawaii)

Reef biology

With regard to reef and coral development, Necker Island somewhat resembles Nihoa. It is a small island, vulnerable to strong wave action from any direction. The scoured shallow flat surfaces are unfavorable for coral growth. Most corals were found in habitats which are at least partially protected from wave scour, such as caves, overhangs, and trenches. Sixteen species of stony coral have been reported from Necker Island, a number somewhat comparable to Nihoa. The most commonly encountered species of stony coral were *Pocillopora meandrina* and *Porites lobata*. Corals found at Necker and not reported from Nihoa were *Porites compressa*, *Pocillopora ligulata*, and the corrugated coral, *Pavona varians*.

Shark Bay hosts a benthic community dominated by a variety of large, abundant algae. Reef fish assemblages at Necker appear healthy and abundant, very similar to those found at Nihoa and the Main Hawaiian Islands. Grey reef sharks, giant Trevally jacks, gray snappers, monk seals, and other predators have been reported. Several large manta rays have also been observed. Numerous limpets inhabit the island's rocky surf zone. Necker also supports a small population of endangered Hawaiian monk seals with limited reproduction, probably maintained by



The finger coral, Porites compressa (Photo: Keoki and Yuko Stender)

immigration from other breeding colonies. Necker Island also provides a nesting spot for thousands of sea birds.

Link to metadata and data held by CoRIS

Click on the following URL to locate and access metadata and data in the CoRIS holdings on Necker Island. When the query screen comes up, enter "Necker" in the window, and then click on "Search."

http://coris.noaa.gov/geoportal/

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NOAA CoRIS - Northwestern Hawaiian Islands: Gardner Pinnacles



Gardner Pinnacles (25° 01' N - 167° 59' W)

Read About:

Geography Reef biology Birds and plants

Link to metadata and data held by CoRIS More photos

Geography

Rising out of the ocean are two small, steep, basalt outcroppings, named Gardner Pinnacles. They are all that remain of a former volcanic island. The highest point is 190 feet (58 m). The pinnacles are approximately 690 nautical miles (1,278 km) from Honolulu and 150 nautical miles (278 km) from Maro Reef.

This five acre area comprises the smallest land area of any of the Northwestern Hawaiian Islands (NWHI). Underwater shelves, however, extend outward from the pinnacles over an area of approximately 604,000 acres (2,446 km2), the most of any island or bank in the NWHI.



IKONOS Satellite image of Gardner Pinnacles (photo: NOAA)



Map of Gardner Pinnacles (Photo: NOAA)

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Gardner Pinnacles abrupyly rise from the sea (Photo: J. McVey/NOAA)

Reef biology

Gardner Pinnacles' rocky intertidal areas are known for their abundance of giant opihi, Cellana talcosa, the endemic Hawaiian limpet. The opihi has all but disappeared from the Main Hawaiian Islands and is also very rare in the NWHI. Twenty-seven documented species of stony coral are distributed throughout the Pinnacles' reef system, many more species than observed at the comparable basalt islands of Nihoa and Necker. *Acropora* table corals have been noted on the more sheltered leeward (western) side, while tube (*Tubastraea*, *Balanophyllia*), stony, and soft corals have been found throughout the reef system.



Cellana sandwicensis, the endemic Hawaiian limpet (opihi), has been a popular food source in Hawaii for centuries.

Stony coral cover is poorly developed on the more shallow basalt slopes and flat pavements, probably due to strong abrasive wave action. Live coral cover ranges from 1 to 15 percent.



The orange cup coral, Tubastraea coccinea (Photo: Keoki, Yuko Stender)



The Hawaiian oval coral, Balanophyllia hawaiiensis (photo: Keoki, Yuko Stender)

Gardner Pinnacles underwater shelves provide habitats for some of the highest recorded numbers of fish species in the NWHI. Also, many species of fishes found in the MHI, but not found at other NWHI areas, are found here.

Birds and plants

In general, Gardner Pinnacles has among the highest diversities of marine life in the entire NWHI. However, only a single species of plant, a purslane, clings to its rocky surface. Gardner Pinnacles is also home to seabirds, insects, spiders, and mites. Scientists have observed 19 species of seabirds, 12 of which breed on the steep cliffs, including the rare blue gray noddy. Other birds include terns, boobies, frigate birds, and two species of migratory shore birds, the ruddy turnstone (*Arenaria interpres*) and the golden plover (*Pluvialis fulva*).

Click here for a description of Gardner Pinnacles land vegetation from the <u>S.S.</u> <u>Midway Expedition.</u>

Reference: Starr, F. and K. Martz. 1999. S.S. Midway Expedition. Trip report prepared for U. S. Fish and Wildlife Service, Honolulu, Hawai'i.

Link to metadata and data held by CoRIS



Sea approach to Gardner Pinnacles. Bird guano covers the steep cliffs (Photo: NOAA)

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NOAA CoRIS - Northwestern Hawaiian Islands: French Frigate Shoals



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French Frigate Shoals (23° 45' N - 166° 10' W)

Read About:

Geography Birds, mammals, and turtles Corals Algae Fishes

Marine debris Terrestrial plants of Tern Island

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Geography

French Frigate Shoals is a large 18-mile (29 km) wide, crescent-shaped atoll on a circular platform, approximately 718 miles (1,330 km) northwest of Honolulu and 702 miles (1,300 km) southeast of Kure Atoll. The Shoals' lagoon contains two exposed volcanic rocks and 12 low, sandy islets. While the land area is only 67 acres (0.2 km2), the total coral reef area of the shoals is over 232,000 acres (938 km2), which makes it the largest atoll in the Northwestern Hawaiian Islands (NWHI).



Map of French Frigate Shoals (NOAA)



Satellite image of French Frigate Shoals (Photo: NOAA)

The reef forms a barrier against winds and currents around the north and east sides of the platform. The south and west sides of the platform are submerged, averaging about 98 feet (30 m) depth. Near the center of the platform is a small basalt pinnacle about 121 feet (37 m) high, La Perouse Pinnacle, which is the last remnant of the volcano still above sea level that formed the original foundation of the atoll. The pinnacle was named after

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Compte de La Pérouse, who visited the atoll in 1786. La Perouse supports a large number of seabirds. The bird guano provides high nitrogen levels in the surrounding waters, which promote the growth of algae in the pinnacle's intertidal zone, including species of the green algae, Caulerpa and Cladophoropsis, and the red alga, Asparagopsis.

Some of the sandy islets have some sparse growth of grass and other low vegetation. East Island and Whale-Skate are the two largest naturally occurring islands. From 1944 to 1952, East Island was the site of a now-abandoned U.S. Coast Guard station. Tern Island, located 6 miles (11 km) to the northwest of East Island, is a reconstructed island that was enlarged by dredging and landfill. It was formed into a runway to serve as a refueling stop for planes en route to Midway during World War II. The original seawall, runway, and some of the buildings still remain. The U.S. Fish and Wildlife Service maintains a field station there, which is staffed year-round by two permanent employees and a few volunteers.



La Perouse Pinnacle, French Frigate Shoals (Photo: NOAA)

Birds, seals, and turtles

The islets' highest elevation is about three meters (9.8 ft). Most of the islets are lower. Their population consisted of thousands of nesting sea birds, most of them terns. Six different species of terns have been recorded from Tern Island. The islets attract the largest breeding colony of the endangered monk seal in the NWHI, while also serving as the breeding ground for 90% of threatened green sea turtles in the Hawaiian Islands. Satellite tagging of these turtles indicates that most of them migrate to the Main Hawaiian Islands (MHI) to feed and reach sexual maturity before returning to French Frigate Shoals to breed. Some of these turtles, however, migrate in a northwest direction to feed, while others migrate as far south as Johnston Atoll.



Tern Island, French Frigate Shoals (Photo: George H. Balazc/NOAA)



Sea turtles at French Frigate Shoals (Photo: Tom Ordway/ Ocean Futures Society)

Corals

French Frigate Shoals' substrate is primarily reef carbonate, which provides an abundance of diverse habitats, such as deep ocean reef slopes, terraces, spur and groove formations, pinnacles and mounds, caves and overhangs, and shallow perimeter reef flats. The Shoals' semi-enclosed lagoon gives protection from the destructive effects of storms and waves and provides many other reef habitats not found in exposed ocean reef environments. Due to the diversity and quantity of its habitats, coral species diversity and abundance is spectacular. The Shoals support the greatest variety of coral species in the NWHI, with 41 species of stony corals documented. These include table, finger, and lobe corals. Rare table corals of the genus *Acropora*, which are common throughout reefs of the central and south Pacific, are essentially absent in the Main Hawaiian Islands, but are common at French Frigate Shoals. Observed at almost all survey sites were *Acropora cytherea*, *A. cerealis*, *A. gemmifera*, *A. nasuta*, *A. valida*, and *A. paniculata*.

The best coral development occurs near the lagoon ends of the reef where exposure to waves and storms is reduced, and where the flow of clean ocean water promotes habitat diversity and good water quality. Poorer reef habitats were concentrated in the shallow eastern lagoon, which is dominated by shallow sediment deposits, strong currents, high turbidity, and poor water quality. However, reticulated reefs with protected habitats are concentrated in this area with finger and lobe corals (*Porites*) thriving. The



Giant tabletop coral

western portion of the lagoon is open and live coral cover is higher in the transition zone between the two halves of the lagoon. Live coral cover is also high on patch reefs and on the deep reefs at the northern and southern ends of the lagoon. Table, finger, lobe, rose (*Pocillopora*), and other corals in the genera *Cyphastrea* and *Leptastrea* are abundant.

Algae

Many macro and turf algae find suitable habitats within the lagoon. The bottom of lagoon reef slopes provide habitat for large mats of the green alga, *Halimeda*. More than 150 species of algae are components of the reef community, including red, green and brown algae. Especially rich and diverse algal communities are found immediately adjacent to La Perouse Pinnacle. Pink and purple encrusting coralline algae cover much of the shallow pavement habitats and reef crests.

Fishes

The outer reef waters support gray reef sharks, butterfly fish, and large schools of jacks and groupers. Endemic masked angelfish (*Genicanthus personatus*) are occasionally seen here at scuba diving depths. In the MHI, they are rarely seen shallower than 295 feet (90 m). The chevron butterflyfish (*Chaetodon trifascialis*), which feeds exclusively on polyps of Acropora corals, is also rare or absent in the MHI, but common at French Frigate Shoals. The Shoals' many and diverse habitats also support more than 600 species of invertebrates, many of which are endemic.





The rare Chevron butterflyfish, Chaetodon fascialis, is almost absent from the Hawaiian Islands, except for French frigate shoals. (Photo: Keoki and Yuko Stender) A male masked angelfish, Genicanthus personatus. This species is rare except in the NWHI, where it is found at scuba diving depths. In the Main Hawaiian Islands, they are found at 300 feet depths. (Photo: Keoki and Yuko Stender)

Marine debris

Derelict fishing gear and other types of marine debris have a major impact on the reefs and associated fauna of the French Frigate Shoals, especially the monk seals. Over the past several years, efforts have been undertaken to lessen the threat of this problem.

Terrestrial plants of Tern Island

Click here for a description of the terrestrial plants of French Frigate Shoals: <u>S.S. Midway Expedition</u>

Reference: Starr, F. and K. Martz. 1999. S.S. Midway Expedition. Trip report prepared for U. S. Fish and Wildlife Service, Honolulu, Hawai'i.

Link to metadata and data held by CoRIS

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http://coris.noaa.gov/geoportal/

Fish links

Checklist of the near shore fishes of Tern Island, French Frigate Shoals, Northwestern Hawaiian Islands. Ian L. Jones and Daniel Mitchell.

http://www.mun.ca/serg/checklist.pdf

Annotated list of the near shore fishes of Tern Island, French Frigate Shoals, Northwestern Hawaiian Islands. Ian L. Jones and Daniel Mitchell.

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http://www.mun.ca/serg/FishofTern.pdf

More photos



IKONOS Satellite imagery of French



Tern Island, French Frigate Shoals



Endangered monk seals fight for territory on



Endangered green sea turtles bask in the sun

http://www.coris.noaa.gov/about/eco_essays/nwhi/ffshoals.html[12/1/2014 3:10:31 PM]

Frigate Shoals

the beach at French Frigate Shoals on the beach at French Frigate Shoals

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NOAA CoRIS - Northwestern Hawaiian Islands: Maro Reef



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Maro Reef (25° 22' N - 170° 35' W)

Read About:

Geography Corals Fishes Marine debris

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Geography and habitats

Maro Reef is the largest coral reef in the Northwestern Hawaiian Islands (NWHI), with approximately 746 square miles (478,000 acres or over 1,934 km2) of reef area. Maro Reef is an open atoll without any emergent land except for about an acre of large coral blocks on the reef crest at low tide. Much of the reef habitat is composed of an intricate network of reef crests and surrounding lagoons. Unlike the familiar circular atoll, Maro Reef has a complex geometry of linear reefs that radiate outward from a series of lagoons, like spokes of a wheel. Channels of deep water with highly irregular bottom topography lie between the shallow reef structures. The lagoon is the second largest in the archipelago, after French Frigate Shoals. Many large gaps in the reef's perimeter expose regions of the lagoon area to wave action and resuspension of fine bottom sediments, which makes the water silty and murky. The habitats of Maro Reef include shallow sandy lagoon bottoms, steep reef slopes, large coral heads, pinnacles, and patch reefs.



Maro Reef is a largely submerged atoll with only about one acre of land that is sometimes submerged. The surrounding reef habitat is about 475,000 acres in size



IKONOS satellite imagery of Maro Reef (Photo: NOAA)

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(Illustration: Bishop Museum)

Corals

The eastern side of Maro Reef has little coral cover. Scientists observed that many pinnacles were covered with an algal "fuzz." Boring bivalve mollusks also covered many of the pinnacles. Few sea urchins were found at Maro. The lack of these grazers may account for the amount of algal "fuzz." In contrast, the western side of the reef has a high live coral cover. Maro Reef has a greater abundance and diversity of coral than most any other reef system in the NWHI. Rapid environmental assessment teams have recorded 37 species of stony



Rice Coral (Montipora Capitata) (Photo: UCSC-LLNLOHyperspectral Imageing Project)

corals, and live coral cover ranging from zero to 95 percent. The northwestern pinnacles and reticulated reefs are characterized by high coral species diversity. The rice coral, Montipora capitata, dominated the reef slopes and bases, and finger coral (*Porites compressa*), disc coral (*Pavona duerdeni*), and sheet-like growths of *Porites lobata* and *Montipora* species are common near the top of the reef slope. The large table coral, Acropora cytherea, and other smaller table corals are also quite common. A new species of *Montipora* was also discovered. Non reef-building tube corals were found under overhangs and caves.

One prominent coral reef scientist feels that Maro Reef is "surviving on the edge" because the reefs are narrow and not consolidated, making them vulnerable to storm surges and waves. Others suggest that Maro Reef is a healthy complicated reef system on a large seamount, living in balance with the environmental forces.

Fishes

Maro Reef has a large amount of crustose coralline algae which lay down a cement that holds the coral together in rough water. The reef supports several species of butterflyfish and large numbers of surgeonfish. Large jacks, such as the giant trevally or ulua (*Caranx ignobilis*) and the bluefin trevally or omilu (*Caranx melampygus*) have been seen in the reef's open waters, along with white-tip and gray reef sharks. Large schools of Galapagos sharks are also a common in the shallow waters. Large manta rays and eagle rays have also been observed.



The bluefin trevally or omilu, Caranx melampygus.



On an Ocean futures Society expedition to NWHI, Jean-Michel Cousteau and a dive team member examine the divisity of " macro " life clinging to the underside of the ledge. (Photo: Tom, Ocean Future Society)



Maro Reef (Photo: Phycology Dept., University of Hawaii at Manoa/L. Preskitt)

Seals, birds, and Marine debris

Monk seals are occasionally seen hunting in the area, but Maro Reef provides very few suitable mating sites and therefore is not considered a breeding area. Derelict fishing gear and other types of marine debris have a major impact on the shallow reefs and fauna. Birds are the only terrestrial animals that inhabit Maro Reef.

Link to metadata and data held by CoRIS

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http://coris.noaa.gov/geoportal/

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NOAA CoRIS - Northwestern Hawaiian Islands: Laysan Island



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Laysan Island (25° 46' N - 171° 44' W)

Read About:

Geography Reef habitats and biology Birds and monk seals

Terrestrial plants Human activities

Link to metadata and data held by CoRIS

Geography

Laysan Island, located approximately 940 miles (1,741 km) from Honolulu, is a low lying sand island, basically oval in shape, about a mile wide and just under two miles long, with a highest elevation of about 40 feet (12 m). It is approximately 1,000 acres in size (3.7 km2), which makes it the largest natural island in the Northwestern Hawaiian Islands (NWHI). Laysan Island is surrounded by a 1,119,387 acre (4,530 km2) shallowwater coral reef ecosystem. The island and its surrounding coral reefs were formed approximately 17 million years ago, when the underlying shield volcano and a portion of the associated coral reef bank were lifted above sea level. The surface of the island is composed of loosely packed coral sand, with beds of coral reef and phosphate rock on the southern and western sides. The beaches rise from the water's edge to a height of 15 to 18 feet (4.6 to 5.5 m), then flatten out to a maximum height of 30 to 40 feet (9.0 to 12.0 m), and then slope gradually downward to a central depression, part of which is occupied by a shallow, land-locked, 173 acre (0.7 km2) hypersaline lake (water with a salinity above 35 percent). It is the only lake in the NWHI, and one of only five natural lakes in all of Hawai`i.

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Reef habitats and biology

Most of the shallow water reef habitat is in a protected embayment on the southwestern side of the island, while most other reef areas are in deeper waters. These reef habitats are mostly spur and groove formations. The northern section is heavily eroded with many caves, overhangs, and large holes on a sloping reef with small sand channels. Twenty-seven species of reef-building stony corals are recorded from Laysan. There are some large massive and encrusting corals (*Porites* and *Pavona*) found on the sandy floor of the sub-lagoon of the shallow embayment on the southwestern side of the island. Several species of branching corals in the genus *Pocillopora* are common. Some rare species of coral are also found in the Laysan reefs. Some common invertebrates, other than corals, include rock-boring sea urchins and encrusting coralline algae in all shallow wavewashed habitats. Of the 75 native invertebrate species found on Laysan Island, 15 are endemic.



The large black area is a shallow



Aerial view of Laysan Island

IKONOS satellite imagery of Laysan Island (Photo: NOAA)

(Photo: George H. Balazs/NOAA)

land-locked hypersaline lake (0.7 km2). It is the only lake in the NWHI, and one of only five natural lakes in all of Hawai'i. (Photo: NOAA)

Birds and monk seals

The island is home to an estimated two million birds, including thousands of boobies, frigatebirds, terns, shearwaters, and two endangered endemic land birds, the Laysan finch and the Laysan duck. The island is also an important breeding ground for Hawaiian monk seals.



Terrestrial plants

The Hawaiian monk seal, Monachus schauinslandi.

Native species of plants include *Eragrostis* (a bunch grass important for supporting bird

burrows), *Chenopodium* (goosefoot), *Ipomea* (a morning glory), *Sesuvium*, and Makaloa (*Cyperus*), in which the laysan ducks and finches like to hide, and *Mariscus*, an endemic sedge on the endangered species list.



Eragrostis growing on Laysan Island (Photo: Bishop Museum)



Laysan's endangered endemic plant, Mariscus.

Human activities

Laysan's ecosystem was severely altered by the effects of human habitation and exploitation in the late 19th century. The island was extensively mined for bird guano, used as a fertilizer. Later, feather collectors killed birds by the hundreds of thousands. Rabbits released in 1903 ate the island's plants, driving to extinction three species of land birds that relied upon these plants: the Laysan Rail, the Laysan Honeycreeper, and the Laysan Millerbird. These events caused a public outcry which led to the creation of the Hawaiian Islands Bird Reservation by President Theodore Roosevelt in 1909. Successful efforts by the U.S. Fish and Wildlife Service have eliminated most pests, such as rats, rabbits, and weeds, and restored much of the native vegetation. As a result, Laysan finch and Laysan duck populations are increasing.



A shy Laysan duck protects her brood in long grass near the interior lake (Photo: Tom Ordway, Ocean Futures Society [http://www.oceanfutures.org])



Albatross amidst native grass and sand on Laysan Island (Photo: Nan Marr, Ocean Futures Society [http://www.oceanfutures.org])



Jean-Michel Cousteau is seen walking along the beach at Laysan Island, littered with marine debris. In the background are remnants of a shipwreck and rusting Japanese long liner that sank, but is still visible in the sand lake. (Photo: Tom Ordway, Ocean Futures Society [http://www.oceanfutures.org])



Scientists carry jugs of fresh water up the Laysan beach to the camp they will occupy for several months. The NOAA ship OSCAR ELTON SETTE sits at anchor three quarters of a mile west of the island. (Photo: NOAA)

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NOAA CoRIS - Northwestern Hawaiian Islands: Lisianski Island and Neva Shoals



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Lisianski Island and Neva Shoals (26° 4' N - 173° 58' W)

Read About:

Geography and history Corals and algae Fishes, seals, turtles and birds

Terrestrial vegetation Human impacts

Link to metadata and data held by CoRIS

Geography

Lisianski Island lies about 905 nautical miles (1,676 km) northwest of Honolulu and 115 miles (213 km) west of Laysan Island, its nearest neighbor. It is a low, flat sand and coral island, with an area of about 381 acres (1.5 km2). The island is encircled by a white sandy beach. Most of the interior is covered by native plants. Its highest point is a sand dune about 40 feet (12.19 m) above sea level on the northern side of the island,while a ridge of sand on the southern side of the island reaches to about 20 feet (61 m) elevation. Within the center of the island is a depression which might have been a lake in ancient times.



Bathymetric map of Lisianski Island and Neva Shoal (NOAA)



IKONOS satellite imagery of Lisianski Island and Neva Shoals (Photo: NOAA)

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Corals and algae

The species richness of hermatypic (reefbuilding) stony corals appears to be lower than those reported from the other atolls, but investigators suggest that this may just reflect inadequate survey coverage. About 24 species of stony corals have been recorded from Lisianski-Neva Shoals. Massive coral heads of *Porites lobata* and Porites evermanni were dominant at most of the Northwestern Hawaiian Islands Coral Reef Assessment and Monitoring Program (NOWRAMP) survey sites. Coral cover was lower in deeper and more exposed waters. Encrusting pink coralline algae cover the tops of the reefs just below the surface at low tides. Shallow reef habitats closer to Lisianski Island have prominent mounds of



Porites lobata coral colony at Lisianski Island (Photo: James Watt)

the encrusting corals, *Montipora turgescens* and *Montipora capitata*. Fleshy algae are more abundant at shallow depths adjacent to the shoreline and overgrow corals and other hard surfaces. It has been suggested that dissolving nutrients from bird guano deposits have promoted the growth of these algae.

Fishes, seals, turtles and birds

Reef fishes of the shallow nearshore waters are abundant and diverse. Researchers have found predators, such as sharks and trevalley jacks (ulua), near Lisianski's reefs to be very aggressive. Large numbers of Hawaiian monk seals, frequently visit Lisianski Island. Green turtles are also quite common on the beaches. Large numbers of seabirds nest on the island and migratory shore birds, which include the golden plover (kolea), wandering tattler (ulili), and bristlethighed curlew (kioea) are frequent visitors.



A Bonin petrel in its nesting burrow in Hawai'i (Photo: E. Kridler/ USFWS)

The island also has the largest breeding colony of Bonin petrels in Hawai'i. Three-fourths of all breeding pairs in the entire state breed here. In some years more than a million sooty terns visit Lisianski.

Terrestrial vegetation

In general, the land vegetation of Lisianski Island extremely intact and pristine. Only three alien species occur on Lisianski, (possibly four, if *Solanum americanum* is treated as alien) sand bur (*Cenchrus echinatus*), a few dead ironwood trees (*Casuarina equisetifolia*), and tree heliotrope (*Tournefortia argentea*). Otherwise, the vegetation is completely native, 10 species are indigenous and 3 species are endemic.

Starr, F. and K. Martz. 1999. <u>S.S. Midway Expedition</u>. Trip report prepared for U. S. Fish and Wildlife Service, Honolulu, Hawai'i.

Human impacts

A ship picking up survivors of a shipwreck introduced rodents to Lisianski island in 1844. Rabbits were introduced later, and along with the rodents, they devastated the land ecology. Feather collecting began on Lisianski Island in about 1904, resulting in the wholesale slaughter of birds. Reports of such slaughter stirred up extensive interest in bird protection. In 1909 President Theodore Roosevelt initiated a joint resolution in Congress, which set aside the islands from Nihoa to Kure Atoll, with the exception of Midway, as the Hawaiian Islands Bird Reservation. At present, with bird poaching at an end, the rabbits exterminated, and vegetation again spreading over its surface, Lisianski Island is a populous bird sanctuary.



The remote and deserted shores of Lisianski Island are littered with marine debris, including colorful floats from fishing nets (Photo: Jen Schorr, Ocean Futures Society)

Link to metadata and data held by CoRIS

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NOAA CoRIS - Pearl and Hermes Atoll



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Pearl and Hermes Atoll (27° 50' N - 175° 50' W)

Read About:

Geography Reef habitats Algae and corals and other invertebrates Fishes Seals, turtles, and spinner dolphins Terrestrial vegetation Birds Human activities Marine debris Link to metadata and data held by CoRIS

Geography

Pearl and Hermes Atoll lies about 216 nautical miles (400 km) eastsoutheast of Midway Atoll and approximately 1,080 nautical miles (2,000 km) northwest of Honolulu. Pearl and Hermes Atoll was discovered when the whaling ship Pearl ran aground in 1822. It is a huge oval coral reef with several internal reefs and seven sandbar/islets above sea level along the southern half of the atoll. The land area is small (88 acres or 0.36 km2) and the highest point above sea level is about three meters. The islets are periodically washed over when winter storms pass through. Its coral reef area, however, is huge. It is the second largest (about 1,166 km2 or 288,125 acres to depths of 100 m) among the six atolls in the Northwestern Hawaiian Islands (NWHI).



Map of Pearl and Hermes atoll (Map: NOAA)



IKONOS satellite image of Pearl and Hermes Atoll (Photo: NOAA)

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Reef habitats

The fringing reef encloses a lagoon that measures about 43 miles (69 km) in circumference, and open to the west. The reef is continuous on the east side but there are some breaks on the south side that allow entrance for small vessels a short way into the lagoon. The northwestern third of the rim consists of a line of coral heads and patch reefs, interspersed with deeper water. Some extensive reef formations are found within the lagoon, some extend 1.6 to 2.7 nautical miles (three to five km) in a nearly straight line. Others form miniature atolls. The lagoon is large with amazing variety and abundance of reef habitats.

Survey teams reported that carbonate pavement and spur and groove habitat dominated the ocean-facing reefs. Live coral cover was low, but there were large populations of macroinvertebrates, such as boring sea urchins in the genera *Echinometra* and *Echinostephus*. Other habitats included holes, overhangs, mounds of coral rubble, shallow sand depressions, pinnacles, deep vertical canyons, sea grass meadows, rubble flats, and sand flats. The pinnacle reefs show both high coral cover and diversity. The spur and groove habitat of the north and northwest outer barrier reefs is unique among NWHI atolls in that it contains extremely deep and narrow canyons. The southern outer reef slopes, dominated by fleshy algae cover, contain numerous large holes, overhangs and caves, which contribute to the abundance and diversity of fishes at the atoll. The east and south reef slopes had a very high numbers of crown-of-thorns sea stars that preyed on *Pocillopora* corals.

Algae and corals and other invertebrates

Circular reef formations surround deep lagoon holes which have isolated populations of invertebrates, such as lobsters, moon-snails, and sponges. Ten new species of sponges for Hawai'i were collected from this type of habitat.

Pearl and Hermes has a moderately diverse assemblage of coral species, but probably not as high as in French Frigate Shoals. It has been suggested that this difference may



The rare black-lipped pearl oyster, Pinctada margaritifera (Photo: Cal Hirai)

be attributed to the lack of table corals (*Acropora*) at Pearl and Hermes, while up to six or more species are present at French Frigate Shoals. Thirty-three species of stony corals have been documented at Pearl and Hermes Atoll. Gardens of the finger coral, *Porites compressa*, flourished on patch reefs in the north central lagoon. The southern, central, and eastern lagoon areas contain reticulated reefs. Southern back reef habitats and northwestern and open lagoon pinnacles are covered with several species of *Pocillopora*. The bottom habitats of the lagoon were dominated by the green alga, *Microdictyon setchellianum* and the red alga, *Stypopodium hawaiiensis*. These algae provide food and cover protection for small invertebrates and juvenile fishes, and also provide a substratum for turf algae and other invertebrate animals.

Black-lipped pearl oysters, at one time very common, were harvested in the late 1920s to make buttons from their shells. Over-harvested, the oysters were nearly eliminated, and today only a handful remain even long after their harvesting was declared illegal in 1929.



The red alga, Stypopodium hawaiiensis, on the lagoon bottom (Photo: J.Smith/U. Hawai'i)



The green alga, Microdictyon sp. (Photo: J.Smith/ U. Hawai'i)

Fishes

It is reported that Pearl and Hermes Atoll has the highest standing stock and species richness of fishes in the NWHI. These include large predators, such as sandbar sharks, Galapagos sharks, and Trevalle Jacks. In addition, angelfishes considered rare in the rest of the Hawaiian archipelago, such as the masked angelfish (*Genicanthus personatus*) and the Japanese angelfish (*Centropyge interrupta*), are commonly encounted at Pearl and Hermes Atoll.



A male masked angelfish, Genicanthus personatus, at Pearl and Hermes Atoll (Photo: Tom Ordway, Ocean Futures Society)



The Japanese angelfish (Centropyge interrupta) is commonly seen at Pearl and Hermes Atoll (Photo: Keoki and Yuko Stender)

Seals, turtles, and spinner dolphins

Pearl and Hermes Atoll supports a breeding population of endangered monk seals. Sea turtles also breed and feed there. The atoll is also a mating area for spinner dolphins.

Terrestrial vegetation

The sandbar islets support a number of coastal dry grasses, vines, and herbal plants, including 13 native species and 7 introduced species. The plants survive because they are salt-tolerant and able to recover from frequent flooding. The islets are devoid of trees, except for some ironwoods (*Casuarina*) planted in 1928, and which may not have survived.

Click here for a description of the terrestrial vegetation of Pearl and Hermes Atoll and other NWHI: <u>S.S. Midway Expedition</u>.

Reference: Starr, F. and K. Martz. 1999. S.S. Midway Expedition. Trip report prepared for U. S. Fish and Wildlife Service, Honolulu, Hawai'i. [<u>Text only</u>]

Birds

The islands of Pearl and Hermes Atoll provide resting and nesting areas for an estimated 160,000 birds of approximately 22 species. They include Black-footed albatrosses, Tristram's storm petrels, and one of two recorded Hawaiian nest sites of little terns. Over the years, several of the NWHI's rare endemic birds have been introduced to Pearl and Hermes. The Laysan Finches brought to the Atoll appear to have survived, but not Laysan ducks and Laysan rails.

Human activities

Pearl and Hermes Atoll was discovered in 1822 when the whaling ships *Pearl* and *Hermes* went aground. A century later, pearl oysters were found, and a brief industry developed, with Filipino divers collecting tons of shell that were sold to button manufacturers on the Mainland. The pearl oyster population never recovered.

Pearl and Hermes Atoll continues to be a danger to ships. On July 2, 2005, the charter vessel, *Casitas*, ran aground on the northern reef. The *Casitas* was on its way from Midway, roughly 90 miles (167 km) to



The Casitas, a 145-foot charter vessel, is grounded on a reef at the Pearl and Hermes Atoll. It was successfully refloated then scuttled (Photo: USCG)

the west, to conduct marine debris removal work first at Pearl and Hermes, and then later at Maro Reef and French Frigate Shoals. The extent of the long term damage to the reef ecosystem has not been determined.

Marine debris

Pearl and Hermes Atoll has been extensively impacted by marine debris washing ashore and fouling the Atoll's reefs. In 2003, over 90 tons (81.7 metric tons) of marine debris was removed from the reefs. The debris appears to be coming from the North Pacific Gyre, a slow-moving current that traps discarded nets and other waste. Pearl and Hermes appears to be the most affected of the NWHI The debris damages reefs, entangles fish and marine mammals, and may be introducing alien marine organisms to the NWHI.

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NOAA CoRIS - Northwestern Hawaiian Islands: Midway Atoll



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Midway Atoll (28° 15' N - 177° 20' W)

Read About:

Geography Human activities Terrestial vegetation Biodiversity Algae and urchins Terrestrial plants Insects and spiders Birds Corals, other invertebrates, and algae Fishes Seals, turtles, and dolphins Link to metadata and data held by CoRIS

Geography

Midway Atoll, the second most northern atoll in the world, is a circularshaped atoll with three small islets (Sand, Eastern, and Spit) on the southern end of a lagoon. It is situated near the northwestern end of the Hawaiian Islands archipelago about 60 nautical miles (111 km) east southeast of Kure Atoll. While its land area is small, about 1532 acres (6.2 km2), the atoll has approximately 55,105 acres (223 km2) of reef area to depths of 328 feet (100 m).



Aerial view of Sand Island at Midway Atoll (Photo: J. David Rogers)



Aerial view of Eastern Island at Midway Atoll (Photo: J. David Rogers)

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NOAA CoRIS - Northwestern Hawaiian Islands: Midway Atoll





Map of Midway Atoll (Map: NOAA)

IKONOS satellite imagery Midway Atoll (photo: NOAA)

Human activities

Midway Atoll was discovered in 1859 by N.C. Brooks, captain of the sealing ship, *Gambia*. By claiming Midway for the United States under the Guano Act of 1856, Midway became the only island in the entire Hawaiian archipelago that was not part of the State of Hawai'i. Midway is the most frequently visited locale in the Northwestern Hawaiian Islands (NWHI). Its geographical position as a "stepping stone across the Pacific," made the island a critical link in cable communications (1903) and as an early transpacific seaplane stop (1935). Midway lies about 2,800 miles (5,186 km) west of San Francisco and 2,200 miles (4,074 km) east of Japan.

Midway served as a major U.S. military base and submarine refit base during the Second World War. The atoll's reefs were substantially degraded during the war as reef areas were dredged and filled in to enlarge land areas for airfields. Reef areas were also excavated to construct a deep harbor, navigation channels, and military fortifications and facilities. Bombing during the World War II Battle of Midway caused further destruction of the reefs and islands. The post-war era saw Midway with up to 6,000 inhabitants. Introduction of alien species, sewage discharge, chemical contamination, oil spills, and recreational



A marine biologist observing a Hawaiian grouper at Midway Atoll (Photo: Keoki and Yuko Stender)

fishing pressure further degraded the reef and land habitats. In 1996, the naval base was turned over to the U.S. Fish and Wildlife Service to be managed as the Midway Atoll National Wildlife Refuge. A massive U.S. Navy clean up prior to their departure removed tons of debris, leaky fuel tanks, and lead paint, as well as rats.

Today a fulltime Refuge staff of about 40 people administers a habitat restoration program, cares for the atoll's wildlife, and protects historic resources.

Terrestial vegetation

Prior to human settlement, Midway's islands consisted primarily of large sand dunes and a small variety of native plants, which included beach naupaka (*Scaevola sericea*), native bunch grass (*Eragrostis variabilis*), and beach morning glory (*Ipomea pes-caprae*). Over 200 plant species were introduced after human settlement, including many ornamental plants and crops. Approximately 75 percent of Midway's plant species were introductions. These include weeds, ornamental shrubs, exotic vegetables, and trees such as coconut palms and ironwood. The most common, and in most cases, invasive/noxious, introduced species include ironwood (*Casuarina equisetifolia*), golden crown-beard (*Verbesina enceloides*), wild poinsettia (*Euphorbia cyanospora*), haole koa (*Leucaena leucocephala*), sweet alyssum (*Lobularia maritima*), buffalo grass (*Stenotaphrum secundatum*), peppergrass (*Lepidium virginicum*), and Bermuda grass (*Cynodon dactylon*). Approximately 249 plant species have been reported on Midway from the time it was first discovered through 1992. Of these, 119 were known only from cultivation, 104 were intentional or accidental alien species, and 24 were indigenous. Fifteen of the native species are indigenous, or found elsewhere beyond the Hawaiian Islands, and nine are endemic to the Hawaiian Islands. None of the endemic species are restricted to Midway Atoll (*Ref. 12*).



The plant, Sesuvium portulacastrum, growing amidst coral, on Eastern Island, Midway Atoll (Photo: Forest and Kim Starr)



Beach morning glory or pohuehue, Ipomea pes-caprae, on Midway Island. It is one of the most abundant species on rocky and sandy beaches of high islands, but is uncommon on atolls (Photo: Midway Atoll National Wildlife Refuge)

Biodiversity

Midway Atoll lies near the most northern limit of coral growth. Although coral diversity is less than in more tropical climates, some species (e.g., Pocillopora, Porites) are abundant. Live coral cover is low. The blue encrusting coral, *Montipora turgescens* is common in the lagoon and back reef habitats. Deep chasms, spur-andgroove formations, overhangs, caves, rubble and sand-filled flats, and channels in the reef create habitats for a wide variety of fishes, several of which are unique to Midway. The Hawaiian grouper (Epinephelus *quernus*) is reported from Midway. Large jacks (ulua) are present, but less common than in other NWHI atolls. Boarfish and knifejaws find shelter under overhangs, and large school of goatfish and bluestripe snapper have been observed. Adult and juvenile cleaner wrasses are found in the lagoon, as well as many juvenile fishes of several species. Pods of dolphins also inhabit the lagoon.



The blue encrusting coral, Montipora turgescens, is common in the lagoon and back reef habitats of Midway Atoll (Photo: Keoki and yuko Stender)

The bluestripe snapper or ta'ape (Lutjanus

kasmira) forms large schools by day and forages at night. The ta'ape is an alien species intentionally introduced to the Main Hawaiian Islands from the Marquesas Islands in 1958. The species has now spread as far as Midway.

The whitesaddle goatfish, *Parupeneus porphyreus*, rests in small caverns and under overhangs during the day.



The whitesaddle goatfish, Parupeneus porphyreus (photo: Keoki and Yuko Stender)



The bluestripe snapper, or Ta'ape (lutjanus kasmira) (photo: Keoki and Yuko Stender)

Algae and urchins

It is reported that Pearl and Hermes Atoll has the highest standing stock and species richness of fishes in the NWHI. These include large predators, such as sandbar sharks, Galapagos sharks, and Trevalle Jacks. In addition, angelfishes considered rare in the rest of the Hawaiian archipelago, such as the masked angelfish (*Genicanthus personatus*) and the Japanese angelfish (*Centropyge interrupta*), are commonly encounted at Pearl and Hermes Atoll.



A patch reef in Midway Atoll's lagoon (Photo: USFWS/ J. Maragos)

Terrestrial plants

Click on the following links for data on terrestrial vegetation:

Midway Atoll National Wildlife Refuge (

<u>http://www.fws.gov/midway/midwaywildlifeplants.html</u>) Starr, F. and K. Martz. 1999. <u>Botanical Survey of Midway Atoll 1999</u> <u>Update</u> In: 1995-1999 Baseline Surveys for Alien Species in Marine and Terrestrial Habitats on Midway Atoll National Wildlife Refuge U.S. Fish and Wildlife Service, Honolulu, Hawaii. [<u>Text only</u>] [<u>GPS shapefiles</u> (.zip)]

Martz, K. and F. Starr. 1999. <u>Native Plant Propagation Midway Atoll</u> <u>National Wildlife Refuge</u>. Report prepared for U. S. Fish and Wildlife Service, Honolulu, Hawai'i. Starr, F. and K. Martz. 1999. <u>S. S. Midway</u> <u>Expedition</u>. Trip report prepared for U. S. Fish and Wildlife Service, Honolulu, Hawai'i. [<u>Text only</u>]

Starr, F. and K. Martz. 2000. <u>New plant records for Midway Atoll.</u> Bishop Mus. Occas. Pap. 64:10-12.

Insects and spiders

Terrestrial insects and spiders from Midway Atoll include beetles (Coleoptera); flies (Diptera); bugs (Heteroptera); aphids and scales (Homoptera); bees; wasps; and ants (Hymenoptera); butterflies and moths (Lepidoptera); and spiders (Araneae).

Click here for a list of Midway insects and arachnids identified from Midway Atoll between 1997 and 1998. Compiled by Dr. Gordon Nishida, Bishop Museum, Honolulu, HI: <u>http://hbs.bishopmuseum.org/pdf/op68-04.pdf</u>

Birds

Nearly two million birds of 19 species nest on Midway Atoll. The atoll has the largest Laysan albatross or "gooney birds," colony in the world, with nearly 300,000 nesting pairs. Other birds include brown noddies, shearwaters, Bonin petrels, black-footed albatross, and the largest colonies of red-tailed tropic birds, black noddies, and white terns within the Hawaiian archipelago. One of the rarest visitors is the endangered shorttailed albatross. The bird species nesting at Midway divide the limited habitat by selecting different sites to lay their eggs, such as burrows, open surfaces, under the vegetation, and perches within shrubs or taller trees. Midway's native indigenous bird fauna also includes a small variety of arctic nesting shorebirds, such as bristle-thighed curlews and ruddy Turnstones, and a long list of vagrant species that have been observed in small numbers over the years.



A patch reef in Midway Atoll's lagoon (Photo: USFWS/ J. Maragos)

Click here for a checklist of birds of Midway Atoll

Corals, other invertebrates, and algae

Only 16 species of stony corals have been reported from Midway from the NOWRAMP surveys. This number is probably low because of incomplete surveys of the atoll. The blue encrusting coral, *Montipora turgescensis*, is common in the lagoon and back reef habitats. NOWRAMP surveys reported that the back and fore reef areas hosted a moderate level of abundance of mobile invertebrate species, and low levels of encrusting species. They reported unusually large numbers of Christmas tree worms (*Spirobranchus sp*) on the reefs. Seagrass meadows, dredged areas, and patch reefs are common within the lagoon.



The native plant, naupaka(Scaevola sericea) (Photo: Frest and Kim Starr)

Rock-boring urchins (*Echinometra and Echinostrephus*), calcareous green algae (*Halimeda*), and brown turban algae (*Turbinaria*) are also abundant. Common habitats on the ocean-facing reef slopes include coral spur and groove formations with overhangs and holes, and coral rubble and sand filled flats and channels. In general, live coral cover is low, although pink encrusting coralline algae are abundant.

Fishes

Over 250 species of fishes inhabit the Midway Atoll lagoon and surrounding waters. Among them are *hapu`upu`u*, the Hawaiian grouper, usually caught at depths exceeding 148 feet (45 m) in the Main Hawaiian Islands (MHI), but often seen at diving depths at Midway. Ulua (jacks) were less common relative to other NWHI atolls. Large schools ofkumu (goatfish) and ta'ape (bluestripe snapper) were reported. Large numbers of adult and juvenile cleaner wrasses were observed in the lagoon. The lagoon seemed to support a large number of juvenile fishes. The NOWRAMP surveys reported boarfish (*Evistias acutirostris*) and knifejaws (*Oplegnathus*) under many of the overhangs. Beyond the reefs are large pelagic fishes such as sharks, tuna and marlin.

Click here for: Checklist of Reef Fishes of Midway Atoll (434 k)



The Hawaiian grouper (hapu'upu'u) at Midway Atoll. (Photo: Keoki and yuko Stender)



The crosshatch triggerfish, Xanthichthys mento, is rare in very deep water except at Pearl and Hermes, Midway, and Kure Atolls . In the NWHI it is common along current-swept reefs in as little as 20 feet (Photo: Keoki and Yuko Stender)

Seals, turtles, and dolphins

The waters of Midway abound with dolphins, monk seals, and green sea turtles. Midway's beaches provide critically important habitat where monk seals raise their pups. Threatened green sea turtles are most common offshore of Sand Island's beaches, but they have been observed throughout the lagoon and surrounding nearshore waters. A population of about 300 spinner dolphins also inhabit Midway's lagoon during daylight hours. They exit the lagoon each evening to feed in deeper waters.



Spinner dolphins swim in the Midway Atoll Iagoon (Photo: Tom Ordway/ Ocean Futures Society)

Click here for a list of marine life by common names:

(http://midway.fws.gov/wildlife/marine.html)

Click here for a list of algae, marine invertebrates and vertebrates: <u>Other</u> <u>Marine Life</u>

Click here for current research projects on Midway Atoll: (<u>http://www.fws.gov/midway/research.html</u>)

Click here for more on: <u>Hawaiian Green Sea Turtle</u> Click here for more on: <u>Hawaiian Spinner Dolphin</u> Click here for more on: <u>Hawaiian Monk Seal</u>

Link to metadata and data held by CoRIS

Click on the following URL to locate metadata and data of Pearl and Hermes Atoll in the CoRIS holdings. When the query screen comes up, enter "Pearl and Hermes Atoll" in the window and then click on "Search" <u>http://coris.noaa.gov/geoportal/</u>

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NOAA CoRIS - Northwestern Hawaiian Islands: Kure Atoll



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Kure Atoll (28° 25' N - 178° 20' W)

Read About:

Geography Terrestrial vegetation Birds Monk seals, turtles, and insects Corals and other invertebrates Fishes Marine debris Biological data report Link to metadata and data held by CoRIS

Geography

Kure Atoll is the most remote of the Northwestern Hawaiian Islands (NWHI), and the northern-most coral atoll in the world. It lies close to what is called the Darwin Point, the latitude at which reef growth just equals reef destruction by various physical forces. It is 1,200 miles (2,222 km) northwestward of Honolulu and 56 miles (104 km) west of Midway Atoll. Kure is a small oval-shaped atoll with a land area of 0.86 km2 (213 acres) and reef areas to 100 m depth totaling 167 km2 (41,267 acres). The barrier reef is about 15 miles (28 km) in circumference and 6 miles (11 km) in greatest diameter. There is an opening on the southwest side through the reef to the shallow lagoon, but only small craft can enter. Along the south side of the lagoon are one small island and two sand banks. The somewhat crescent-shaped island, Green Island, is approximately one mile long by less than half a mile wide. It is located in the southeast corner of the lagoon.

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Map of Kure Atoll (NOAA)

It is believed that Kure Atoll was discovered in 1825 by B. Morrell, Jr., the captain of the schooner *Tartar*. Over the years, many ships have crashed into Kure Atoll's fringing reefs. The U.S. Coast Guard operated a long-range navigation (LORAN) station there for many years.



The IKONOS satellite imagery of Kure Atoll (Photo: NOAA)



Green Island reaches a maximum height of 25 feet and is about 1.5 miles long and .5 mile wide (Photo: Space Imaging/ NOAA)

Terrestrial vegetation

Kure Atoll is bordered all around by sand dunes, which rise steeply from the waters edge to a height of eight to 20 ft above sea level. The dunes and most of the interior are covered with a dense growth of beach *Scaevola*, a branching shrub with large, glossy green leathery leaves, small white flowers, and small white fruit. This shrub reaches a height of five to six feet. There is a large open grassy area toward the eastern end of the island surrounded by *Scaevola*. Most of the other 13 species of the island's

vascular plants are found here. The two other islets, lying close to the southern reef, between Green Island and the entrance into the lagoon, are sandy and usually devoid of vegetation.

Click here for a botanical inventory and annotated checklist of the plants of Kure Atoll: Botanical Inventory of Kure Atoll Reference: Starr, F., K. Martz, and Lloyd Loope. 2001. Botanical Inventory of Kure Atoll. Report prepared for State Department of Land and Natural Resources, Honolulu, Hawai'i.

Birds

Green Island is a habitat and nesting area for hundreds of thousands of seabirds which include shearwaters, petrels, tropic birds, boobies, frigate birds, albatrosses, terns, and noddies. It is also a wintering area for a variety of migratory bird species from North America and Asia. Bird life is less abundant on Kure than on other islands of the NWHI.

Click here for a Checklist of the Birds of Hawaii - 2002

Monk seals, turtles, and insects

Kure Atoll is an important pupping and resting area for Hawaiian monk seals. The monk seal population size at Kure is currently about 100-125 individuals. Sea turtles are common on the beaches. Thirtyfive species of insects were identified in 1923 from specimens collected by the Tanager Expedition, which made a careful biological survey of the island. Unfortunately, an invasive species, the big-headed ant (*Pheidole megacephala*), has overrun the ecosystem on Green Island. The density sampling, recorded on average, 26,500 ants per square meter on the surface at the sample sites. To complicate matters, these alien ants feed on the nectar of another introduced insect, a scale, that is also very common on island. The scale breeds on an



The big-headed ant, Pheidole megacephala (Photo: Hirotami T. Imai and Masao Kubota, Japanese Ant Database Group)

introduced plant, *Verbesina encilioides*, which has also overrun the island. As the plant continues to spread so does the scale population, which assists in the population explosion of big-headed ants.

Corals and other invertebrates

The reef habitats of Kure Atoll include outside reef slopes, wave-scoured spur and groove habitats, overhangs and holes, passes, carbonate platforms, patch reefs, coral rubble, and sand flats. Considering water temperatures and latitude, Kure Atoll hosts a surprising diversity and numbers of corals and other large invertebrates, particularly echinoderms, crustaceans, and mollusks.

Twenty-seven species of stony corals have been documented at Kure Atoll. Northwestern Hawaiian Islands Coral Reef Assessment and Monitoring Program (NOWRAMP) recorded high live coral cover in some of the back reef and lagoon areas. Live coral cover is low on the ocean-facing reefs, but coralline algae are abundant. Large massive colonies of *Porites*



compressa, Porites evermanni, Pavona duerdeni, and Montipora turgescens were found at many locations within the lagoon. The highest concentration of crown-ofthorns sea stars in the NWHI were recorded on the outer barrier reefs of the eastern rim.

Corals at Kure Atoll (Photo: Bishop Museum)

Common bottom invertebrates included rock-boring urchins, macroalgae, and branching *Pocillopora*. Many spiny lobsters (*Panulirus marginatus*) were also observed.

Fishes

The lagoon and near-shore reefs support large schools of fishes, including jacks, sharks, dolphins, goatfish, and chub, as well as non-schooling species such as dragon morays, knifejaws, masked angelfish, and the rare native grouper, *Epinephelus quernus* (*hapu'upu'u*). Adult and juvenile cleaner wrasses were in the lagoon in large numbers. The lagoon supported many juvenile fishes. Many rare fishes which have seldom been observed in the Main Hawaiian Islands have been recorded at Kure Atoll.

Marine debris

A significant threat facing Kure Atoll is the accumulation of marine debris washing up on the beaches and reefs. The atoll lies in the path of a major ocean current which deposits tons of fishing nets and other debris, creating an entanglement hazard for monk seals, turtles, seabirds, fishes and lobsters. Approximately 2700 pounds (1,225 kg) of marine debris was removed from Kure in 2003, including 997 pounds (452 kg) removed from accumulation study areas that were cleaned of all marine debris just the year before.



Diver examining the anchor of a wreck at Kure Atoll. (Photo: Van Tilburg)

Biological data report

Click here for a report of biological data on marine algae, benthic invertebrates, coral cover and species, a list of fishes and their relative abundance, and other data. <u>Northwestern Hawaiian Islands/Kure Atoll</u> <u>Assessment and Monitoring ...</u> Reference: Northwestern Hawaiian Islands/Kure Atoll Assessment and Monitoring Program. Final Report. March 2002. Grant Number NA070A0457. By William j. Walsh, Ryan Okano, Robert Nishimoto1, and Brent Carman.

Link to metadata and data held by CoRIS

Click on the following URL to locate metadata and data in the CoRIS holdings of Kure Atoll. When the query screen comes up enter "Kure Atol"I in the window and then click on "Search". <u>http://coris.noaa.gov/geoportal/</u> (<u>top</u>)



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NOAA CoRIS - Northwestern Hawaiian Islands: NWHI Deeper Submerged Banks



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NWHI Deeper Submerged Banks

Read About:

Raita Bank Pioneer Bank Link to metadata and data held by CoRIS

Links to fishes observed at various seamounts

There are approximately 30 deeper, partially explored, submerged banks and seamounts with coral formations in addition to the coral reefs which surround the main 10 Northwestern Hawaiian Islands (NWHI). These submerged areas are feeding grounds for seabirds and Hawaiian monk seals. The banks lack the protection provided by barrier reefs, and don't have much live coral cover. Some scientists hypothesize that the banks may serve as stopping-off points or bridges for marine species as they move from island to island. NOAA's National Marine Fisheries Service investigated several of these formations by using an acoustic seabed classification system and a Tethered Optical Assessment Device (TOAD) towed camera. Preliminary assessments indicate that in general, all of the banks have very rough bottoms with numerous outcroppings, protuberances, and rocky areas. Generally, they are biologically nearbarren and dominated by sand and algal beds. However, the bank areas provide extensive habitat for bottom fishes and a few are known to provide foraging habitats for Hawaiian monk seals. Large precious corals, such as gold, pink, and black corals, are also found in the deep waters of the banks.

The banks consist of Raita Bank; St. Rogatien Bank; the first bank west of St. Rogatien Bank and east of Gardner Pinnacles (Bank Number 7, which remains unnamed); Pioneer Bank; Southeast Brooks Bank, which is the first bank immediately west of French Frigate Shoals; and the first bank immediately east of French Frigate Shoals.

Raita Bank

A significant percentage of reef-building corals within the waters of the United States are contained within the NWHI. While elsewhere in the world coral reefs are threatened and stressed by human activities such as coastal development, pollution, and resource over-exploitation, the remote location of the NWHI has helped protect its

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coral reefs from adverse human impact. The shallow-water coral reefs of the NWHI are truly unique. They are still pristine ecosystems with a much greater diversity in reef habitats than in the MHI.

Pioneer Bank



Map view of Brooks Bank, NWHI. <u>Click here</u> to view the large version.

3D perspective view of Brooks Bank. <u>Click here</u> to view the large version.

Pioneer Bank is only 22 nautical miles (37 km) from Neva Shoals, and their features combine to form a major coral reef ecosystem rich in biodiversity and marine habitats. The bank west of St. Rogatien lies at about 197 feet (60 m) and is approximately 2.7nautical miles (5 km) in diameter. Pioneer Bank is another oval seamount that sits at about 112 feet (34 m) and extends 11 nautical miles (20 km) east-west and 6 nautical miles (11 km) north-south. At St. Rogatien Bank, the top of the seamount is covered by about 79 feet (24 m) of water. It also is a large oval seamount and extends

approximately 4 nautical miles (7 km) east-west and 10 km north-south.

Metadata and data held by CoRIS

Click on the following URL to locate metadata and data on NWHI deeper submerged banks in the CoRIS holdings . When the query screen comes up, enter "Pioneer Bank" or "Raita Bank" or "St. Rogatien" or "Brooks Bank" in the window and then click on <u>Search</u>.

Links to fishes observed at various seamounts

The following two URLs provide a list of fishes observed at various seamounts. Search specifically for the bank of interest.

Rainer Froese (eibniz-Institut für Meereswissenschaften, IfM-GEOMAR, Düsternbrooker Weg 20, 24105 Kiel, Germany) and Arlene Sampang (WorldFish Center, College, Los Baños, Laguna, Philippines) April 2004.

http://www.seaaroundus.org/report/seamounts/ _08_RFroese/RF_Appendix2.pdf

Details of all sampling events from which species have been recorded at that seamount. Returned will be details about when, where, and how each sample was taken, and what taxonomic groups it covers.

http://seamounts.sdsc.edu/

Reference: Parrish, F.A., and R. C. Boland. 2004. Habitat and reef-fish

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assemblages of banks in the Northwestern Hawaiian Islands. Marine Biology. 144:1065-1073

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Status and Health of the Coral Reef Ecosystems of the NWHI

The coral reef ecosystems of the Northwestern Hawaiian islands (NWHI), due mainly to their geographical isolation and economic inattention, represent almost undamaged ecosystems with abundant and large apex predators (predators at the top of their food chain). The reefs possess an extremely high proportion of endemic (native) species, across many taxa, and virtually no impacts from alien (invasive) species. The NWHI are an important breeding and nesting sites for many endangered and threatened species.

The principal stresses to the ecosystems are coral bleaching and effects of marine debris. A multi-agency effort lead by NOAA and its partners has resulted in the removal of almost a half million metric tons of marine debris, primarily derelict fishing gear, from the reefs and beaches since 1996. In recent years, increased federal funding and expanded partnerships among federal and state agencies, academia, and non-governmental organizations have enhanced monitoring, mapping, and research efforts. These efforts have lead to a greater understanding of the spatial and temporal dynamics of the NWHI ecosystems. In turn, management decisions have increased the protection of these areas. The reefs and islands were designated as a Reserve in 2000. Reef fishing is strictly controlled, lobster fishing is prohibited, and all activities require permission from management authorities.

The NWHI can serve as a laboratory of island ecology where scientists and managers can learn to manage and care for healthy and pristine coral reef ecosystems and apply these lessons back to the Main Hawaiian Islands. It also provides a basis for comparison of the health of coral reefs elsewhere (<u>Ref. 3</u>)

Scientists predict that while over the next decade the NWHI coral reefs will remain healthy with the strong collaboration and cooperation among management authorities, but monitoring and surveillance will continue to be necessary over these remote reefs. Predictions of serious climate change and threats of increased coral bleaching remain the major potential cause for reef damage.

Source: Friedlander, A, G. Aeby, R. Brainard, A.Clark, E. DeMartini, S. Godwin, J. Kenyon, R. Kosaki, J. Maragosand P.Vroom. 2005. The State of Coral Reef Ecosystems of the Northwestern Hawaiian Islands. Pp.270-311. In: Waddell, J.E., (ed.), 2005. The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2005. NOAA Technical

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Memorandum NOS NCCOS 11. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 522pp

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and natural Resources, Honolulu, Hawai'i. 46 pp.



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Navassa Island

Introduction

Navassa is a small (5.2 km²; 1,344 acres), uninhabited, and isolated oceanic island located in the Windward Passage approximately 55 km west of the southwestern tip of Haiti (18⁰ 25' N; 75⁰ 02' W). The United States claims the island as an unincorporated unorganized territory that is administered by the U.S. Fish and Wildlife Service as a U.S. National Wildlife Refuge. The refuge includes a 12 mile radius of marine habitat around the island. Navassa is also claimed by Haiti and by a private U.S. citizen. Because of its remote location



Location of Navassa Island in the Caribbean Sea.

and uninhabited status, the surrounding marine ecosystem is relatively healthy. Although there are no permanent residents on Navassa, transient Haitian subsistence fishers regularly visit the island. While quantitative catch data are not available, they seem to have had some effect on the size structure of fish populations. Miller et al. (2003) suggested that the community composition had changed from observations made during a 2000 cruise because of serial overfishing, i.e., a progression of depletion in which the largest and most vulnerable species are removed first, followed by a series of shifts to smaller, less-desirable targets as each is depleted. History

Geography

Field Work

Terrestrial Biota of Navassa Island

Marine Ecosystems

Marine Biota

Status and health of the coral reef ecosystem of Navassa Island

References and Information Sources Wildfires have destroyed some habitats for nesting seabirds and migratory song birds. These fires, in part, may have been caused by squatters seeking to clear land in order to plant food crops. Because of the island's remoteness, existing protective regulations are not enforced. Navassa lacks beaches and mangrove forests. The island rises abruptly from deep water as a raised dolomite plateau (maximum elevation 77 meters) ringed by tall (9-15 meters) vertical cliffs. The depth at the shoreline is about 24 meters and then gradually slopes downward. Coral cover is most extensive in shallow waters (about 30 meters) in limited areas around the northwestern part of the island and in Lulu Bay. The benthic habitats comprise large areas of live bottom (soft and hard corals, sponges and algae), huge boulders which have broken away from the limestone cliffs, rubble, corals growing on cliff walls, scattered patch reefs and hard bottom areas.

The surface of Navassa is forested with brush undergrowth, scattered cacti, and with some grassy areas. About 120 plant species occur, dominated by four species of tropical-subtropical trees. An abandoned 162-foot lighthouse and cistern are located midway along the western shore. Prominent land animals are large colonies of seabirds, migrating songbirds, snails, four endemic species of lizard, 650 species of invertebrates, including over 500 new insect species, 30 percent of which may be endemic. Over 100 non-insect arthropods, mostly spiders, make up the rest. The only mammals on the island are introduced rats, dogs, cats, and goats.

Special thanks to Gregory Andrew Piniak, Ph.D.(NOAA Center for Coastal Fisheries and Habitat Research) and Andrew Gude (U.S. Fish and Wildlife Service) for reviewing and offering expert advice on the original essay manuscript, and to Margaret W. Miller, Ph.D. (NOAA Southeast Fisheries Science Center) and Keith Pamper (Shedd Aquarium, Chicago) for providing photographs used to illustrate the essay.

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U.S. Department of Commerce http://coris.noaa.gov/about/eco_essays/navassa/welcome.html


The abandoned 162 foot-high

appear in the background (Photo: Keith Pamper/Shedd

Aquarium)

lighthouse on Navassa Island. The lightkeeper's quarters

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History

"No hay agua fresca" There's no fresh water on this island! The Spaniards and Indians, under oar and sail, left their discovery of a tiny, waterless island in the West Indies and set their course toward Hispaniola. It was the year 1504 that Admiral Christopher Columbus, shipwrecked and stranded on the island of Jamaica, sent some soldiers and a few Indians in two canoes to Hispaniola for assistance. After two days, they discovered Navassa Island, which they called Navaza, but finding no potable water they continued on their way. Some believe that some of the men died and were buried there. Although claimed by Haiti, Navassa was essentially ignored, except for offering safe haven for pirates in the 1600's, for the next 350 years.

In 1857, an American sailing ship landed on Navassa and the captain claimed the island for the United States under the Guano Act.

The Guano act, passed by Congress in 1856, allowed the U.S. to take possession of islands containing guano deposits. The islands could be located anywhere, so long as they were not occupied and not within the jurisdiction of other governments. It also empowered the U.S. President to use military force to protect such interests. Haiti protested the annexation and claimed Navassa, but the United States rejected the claim.

Guano is the dried excrement of sea birds and bats. It is found principally on the coastal islands of Peru, Chile, Africa, and the West Indies. Guano contains about six percent phosphorus, nine percent nitrogen, and two percent potassium. In the early 19th century, bird guano from Navassa was highly prized as an agricultural fertilizer. It was mined by an American company, the Navassa Phosphate Company, located in Baltimore, Maryland, and was heavily traded by European and American traders. As the 19th century came to an end, guano became less important and became obsolete as artificial fertilizers were developed, at least in U.S. markets. The Spanish-American War of 1898 influenced the mining company to evacuate Navassa and guano mining for agricultural phosphate came to an end. By the end of the century, the guano mining company was defunct and the island deserted.

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The island became a hazard for navigation with the increased shipping traffic between Haiti and Cuba when the Panama Canal opened in 1914. The U.S. Lighthouse Service built a 162 foot-high lighthouse on the southern side of the island in 1917. A lighthouse keeper and two assistants lived there until an automatic beacon was installed in 1929. In 1996, the U.S. Coast Guard dismantled the light as Global Positioning Satellites made the light unnecessary to guide ships around Navassa. An inter-agency task force headed by the U.S. Department of State transferred the island to the U.S. Department of the Interior. By Secretary's Order No. 3205 of January 16, 1997, the Department of Interior assumed control of Navassa and placed it under its Office of Insular Affairs. On April 22, 1999, the U.S. Fish and Wildlife Service assumed administrative responsibility for Navassa Island which



Scientists hiking toward the abandoned lighthouse on Navassa Island_(Photo: Keith Pamper/Shedd Aquarium)

became the Nation's 517th National Wildlife Refuge (NWR).



Subsistence fishers from Haiti travel about five to six hours in the open ocean to reach Navassa Island (Photo: Keith Pamper/Shedd Aquarium)



Haitian subsistence fishers in Lulu Bay, Navassa island (Photo: Keith Pamper/Shedd Aquarium)

Access to Navassa is hazardous and visitors need permission from the U.S. Fish and Wildlife Service office in Puerto Rico in order to enter its territorial waters or land.

Despite its remote location and status as a National Wildlife Refuge, subsistence fishers from Haiti travel about 60 miles (a 5-6 hour trip) in small open boats to fish, and often land on the island for short periods of time, where they may have been responsible for wildfires destructive to the forest habitat of migratory songbirds and nesting seabirds. After about a week, the transient Haitians carry their catches back to their villages in Haiti. This subsistence fishing by traps and hand line so far has had uncertain impact on the reef community structure, but qualitative observations suggest that the rapid depletion of fishery resources is underway (Miller et al., 2005). This represents the greatest management challenge for conserving Navassa's coral reef resources.

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Geography

Navassa is a small, isolated, tear-shaped oceanic island covering an area of approximately 5.2 km2 (2 mi2)or 1,344 acres, surrounded by nearly 570 square miles (364,800 acres) of submerged coral reef ecosystem waters. It lies at 180 25' N, 750 02' W in the Windward Passage, a channel between eastern Cuba and western Haiti that connects the Atlantic Ocean with the Caribbean Sea. Navassa is approximately 35 miles (50 km) southwest of the Tiburon Peninsula of Haiti, 137 miles (220 km) northeast of Morant Point, Jamaica, and about 100 miles (161 km) south from the U.S. Naval Base at Guantanamo, Cuba. The Refuge includes a 12 mile radius of marine habitat around the island.



Map of Navassa Island (courtesy of the Perry-Castañeda Library Map Collection)



Navassa Island - NASA NLT Landsat 7 (Visible Color) Satellite Image (Image: NASA)

Navassa may have formed as a small coral atoll. About 5 million years ago, these reefs began to emerge with an alteration of calcium carbonate sediments (aragonite) to calcium-magnesium carbonate rock (dolomite). Dolomite is a mineral which consists of calcium magnesium carbonate (CaMg(CO3)2) found in extensive beds as a compact limestone. Navassa is comprised of a raised dolomite plateau, surrounded by vertical cliffs nine to 15 meters high which extend downward 23-30 meters in depth to a gradually sloping submarine terrace. There are some shallower areas at the northwestern tip of the island (Collette et al., 2003), but most bottom depths adjacent to shore begin at 20 meters with a gradual depth increase to 40 meters. Depth increases are more pronounced beyond 40 meters, with depths up to 500 meters within 0.8 nautical miles of the north shore (Grace et al., 2001). Much of the nearshore substrate is coarse sand with broad areas of live bottom (corals, sponges, and algae), limestone rock,

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and rubble. The substrate on the eastern side of the island has a lot of cobble and hard bottom/pavement. In some areas, the cliffs are eroded to the point where large chunks, called "calves," have fallen off and rest on the terrace as large boulders.



The imposing cliffs of Navassa Island do not allow easy access to the Island (Photo: Keith Pamper/Shedd Aquarium)



The dock at Lulu Bay (Photo: U.S. Geological Survey)

The surface of Navassa is unsuitable for agricultural use. The land is mostly forested with exposed coral and limestone. There are patches of poisonwood trees and scattered cactus. About 10 percent of the island is covered with grasses. Mangroves and sandy beach habitats are completely lacking. Seagrass beds are extremely limited. There are no natural ports and landing is difficult and hazardous. The most common landing spot is Lulu Bay, a small cove on the southern side of the island.

More photos



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Navassa Island: Natural History Field Work

Until 1998, very little work had been done on the natural history and biodiversity of the biota of Navassa Island. In the late 18th century, a Swedish botanist sailed past Navassa and recorded two cliff-dwelling plant species. In 1928, a second Swedish botanist, spent some time on the island and identified 102 plant species, 44 of which he believed to be endemic. A short time later, in 1929-30, Harvard University scientists collected about two dozen plants and some fishes. In 1956, a botanist with the Institute of Jamaica, documented 38 species of plants (Swearingen, 1999).

In 1998, the Center for Marine Conservation (now called the "Ocean Conservancy") in Washington, D.C., organized a 12 day survey of the terrestrial and marine resources of Navassa. The survey party consisted of teams of individuals from the Center for Marine Conservation, National Park Service, Smithsonian Institution, New York Botanical Garden, U.S. Geological Survey, U.S. Fish and Wildlife Service, Avila College, Center for the Conservation and Ecodevelopment of Samaná Bay and Its Surroundings (CEBSE) and National Museum of Natural History (Dominican Republic), and Deep Ocean Exploration and Research (CA). Scientists from the NOAA Fisheries Systematics Laboratory, Smithsonian Institution, Los Angeles County Museum of Natural History, and Center for Applied



NOAA scientists preparing to land on Navassa (Photo: NOAA)

Biodiversity Science, Conservation International, also conducted an ichthyological survey in 1999.



NOAA's National marine Fisheries Service (NMFS) sponsored an expedition to Navassa Island from October 28 – November 12, 2002 that provided a baseline assessment of the composition and condition of the fishes and benthic organisms (Miller, 2003). The goals of these surveys were to inventory, as much as possible in the allotted time, the plants, terrestrial invertebrates, reptiles, birds, mammals, fishes, corals, and other History

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The Fantail of the NOAA research vessel Nancy Foster on a scientific expedition to Navassa Island (photo: NOAA) marine invertebrates. Rock samples, soils, and other materials were collected to determine the age and geological composition and history of the island. Before these surveys, only one invertebrate (a

spider) was known for the island and no published records of any insects existed (although two beetle specimens were located in the Harvard University Museum of Comparative Zoology).

Benthic and habitat data were also collected on a NMFS 2004 cruise to Navassa. Parameters included benthic cover, prevalence of coral diseases, location of fishing gear, coral density and sizes. Data were collected *in situ* by divers, some using digital cameras. Fishing gear locations were determined visually from boat transects.

In April, 2006, NOAA's Center for Coastal Fisheries and Habitat Research (CCFHR, Beaufort, N.C.) organized a research cruise (NF-06-05) which characterized the benthic and fish communities on the deep (28-34 meters) nearshore shelf of Navassa. Scientists also conducted high-resolution multibeam surveys for which the resulting bathymetry and back-scatter maps provided appropriate context for habitat assessment, and assessed the effects of the transient artisanal fishing on the fish and conch populations. The efforts of this cruise also included food web studies by stable isotope analyses of biological samples, installation of a temperature sensor network around the island to evaluate the potential for thermal coral bleaching events, and provide ground-truth sea surface temperature (SST) data for satellite-sensed SST's, and collection of georeferenced still and video photographs.

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NOAA CoRIS - Navassa Island: Terrestrial Biota



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Terrestrial Biota

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Plants

Approximately 120 terrestrial plant species are known to occur on Navassa (Swearingen, 1999), dominated by four species of tropical and subtropical trees: the mastic (*Sideroxylon foetidissima*), the short leaf fig (*Ficus populnea var. brevifolia* - may be a synonym of *Ficus citrifolia*), the pigeon plum (*Coccoloba diversifolia*), and the highly toxic poisonwood, *Metopium brownei*. Two endemic palm trees occur on the island, one found commonly, and the other, *Pseudopheonix sargentti saonae* var. *navassana* remains as the single living specimen. A number of exotic plants occur on Navassa, including the introduced popular ornamental Madagascar periwinkle, (*Catharanthus roseus*).

Approximately 200 acres of forest were burned by Haitians in 2000. The Haitians also planted a few acres of crops such as watermelon, corn, and squash.

The New York Botanical Society maintains a <u>Virtual Herbarium Web Site</u> which provides an annotated checklist of vascular plants of Navassa Island.

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The last Pseudopheonix sargentti saonae on Navassa (Photo: U.S. Geological Survey)



The highly toxic poisonwood, Metopium brownei, found in the vicinity of the lighthouse (photo: New York Botanical Society)



Invertebrates

Early survey collections documented 650 species of invertebrates, including over 500 new insects, 30 percent of which may be endemic. Over 100 noninsect arthropods, mostly spiders, make up the rest. Arachnologists cataloged 40 new species of spider.



A naturalist collecting insects on Navassa island (Photo: U.S. Geological Survey)



Entomologists use pitfall traps and other techniques to collect insects and other terrestrial invertebrates on Navassa (Photo: Jil M. Swearingen)

Vertebrates

Vertebrate surveys confirmed the existence and abundance of four endemic lizards: the Navassa Island galliwasp (*Celestus badius*), the Navassa anole (*Anolis longiceps*), Cochran's croaking gecko (*Aristelliger cochranae*), and the Navassa dwarf gecko (*Sphaerodactylus becki*), all previously reported for the island. Four other known species of reptiles, including a large

endemic iguana (*Leiocephalus eremitus*) that may now be extinct, and a small boa (*Tropidophis bucculentus*), could not be relocated (Powell, 2005).

Dr Robert Powell (Avila University) maintains a web site on <u>the herpetology</u> <u>of Navassa</u>. This web site contains photographs of reptiles found on Navassa, a list of reptile species reported, museum collections with herpelogical collections, and a bibliography of the island.



An adult Cochran's Croaking Gecko, Aristelliger cochranae (Photo: S. Blair Hedges)



The endemic dwarf gecko Sphaerodactylus becki (Photo: Robert Powell, Ph.D)

More photos



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Navassa Island: Marine Ecosystems

The most up-to-date description of the overall health and condition of the shallow and deeper coral reefs of Navassa is given in Miller et al. (2005). Generally, the coral reefs are in good, healthy condition, although artisanal fishing pressure from Haiti is a growing threat. Except for a few transient Haitian fishers that periodically spend some time on the island as squatters, Navassa is uninhabited. Since mining activity for guano and other phosphorus-rich deposits ended at the beginning of the 20th century, there have been no anthropogenic disturbances to the marine habitats, except for a relatively small amount of marine debris leftover from earlier industrial activities and from recent fishing at Lulu bay. The effects of "ghost fishing" by lost and broken fish traps and nets are not yet known.



A reef wall (Photo: SEFSC/NOAA)



A Navassa seascape (Photo: NOAA)

Many of the habitats with high coral cover are in deep water (>20 meters) and are exposed to strong ocean currents and surge. This feature may provide some protection from coral bleaching from elevated water temperatures. Corals in the shallower habitats (<20 meters) appear to be free from disease, but a white plague-appearing disease is found on some brain corals at some deeper sites. To date, Navassa has not been threatened by the aquarium trade in corals, live rock, or living reef organisms. Aquatic invasive species are not known to occur.

Artisanal fishing at Navassa is unmanaged and NWR regulations are not enforced.

Within the last few years, the Haitian wooden fishing boats have been powered by small outboard engines, and the fishing techniques have been upgraded from hook-and-line and simple fish traps to include net fishing. Finfish catch appears non-selective and includes predominantly small History

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common reef fishes.

Quantitative data are not available for these fishing efforts. Net fishing has added new species to the fishing catch such as the queen conch (*Strombus gigas*) and hawksbill sea turtle (*Eretmochelys imbricata*). The extent to which larger commercial fishing vessels from other Caribbean nations operate in Navassa waters is unknown.



Fish trap used by Haitian fishers (photo: Keith Pamper/Shedd Aquarium)



The most common fish trap used by the Haitian fishers is the Antillean "Z" trap. It takes the form of a double chevron or "Z" with two down-curving "horseneck" entrance funnels. Typically, these measure between 180 and 230 cm in length and are 60 cm high. (Illustration: FAO Document repository: Fishing with traps and pots. FAO 2001).

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Marine Biota

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Algae

Macroalgae (seaweeds) appear to be the dominant benthic groups of the shallow and deeper locations. Prominent genera are the brown algae, *Lobophora, Sargassum, Dictyota,* and *Stypopodium,* and the green alga, *Halimeda. Lobophora variegata* is of pharmaceutical interest because it produces a potent antifungal compound used as a natural antibiotic to defend itself against infection. Some coralline algae and Foraminifera are found at depths much greater than expected, indicating very clear water around Navassa.



Lobophora variegata, a dominant macroalgal species (photo: US. Geological survey)



Prominent brown alga, Dictyota sp, is found in the shallow and deeper marine habitats of Navassa Island. (Photo: U.S. Geological Survey)

Sponges

Large, brightly colored sponges in the genus *Agelas* cover 10-20 percent of the reef area at most locations sampled (Miller, et al., 2005). Species of barrel sponge (*Xestospongia*) and other Demospongiae (Grace, et al.

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2000) are also found in these reef habitats. The dominant sponge across all habitats was the touch-me-not sponge, *Neofibularia nolitangere*.



The touch-me-not sponge, Fibularia nolitangere. (Photo: NOAA/Frank and Joyce Burek)



A Coral and two sponges (Photo: NOAA)

Corals

Within the benthic communities, live coral cover ranges from three percent on the northern shelf hard bottom communities to over 40 percent on some deep patch reefs. Shallow shelf and spur and groove habitats average almost 20 percent live coral cover (Miller, 2003). The dominant hard corals deeper than 25 meters are species of star corals (*Montastraea* sp), lettuce corals (*Agaricia* sp), and finger corals (*Porites porites*). Other corals deeper than 25 meters are the mustard hill coral (*Porites astreoides*), brain coral (*Diploria* sp), pencil coral (*Madracis* sp), fire coral (*Millepora* sp), smooth flower coral (*Eusmilia fastigiata*), boulder brain coral (*Colpophyllia natans*), cactus coral (*Mycetophyllia danae*), maze coral (*Meandrina meandites*), and the massive starlet coral (*Siderastrea siderea*). Lettuce coral (*Agaricia* sp) is the dominant coral in the shallower sites (Miller et al., 2005).

Miller (2003, 2005) reports that the elkhorn coral (*Acropora palmata*) is increasing in abundance, compared to earlier observations in 2002. Staghorn coral (*Acropora cervicornis*), however, remains rare and in poor condition.

Threats to the live coral are few, but include the short coral snail, *Coralliophila abbreviata*, a voracious predator on corals, invasion by bio-eroding sponges, *Cliona* sp, and a disease of unknown origin, but similar to white plague, in deeper habitats that affects the brain corals, *Diploria* spp and



The marine snail, Coralliophila abbreviate, feeding on living coral polyps (Photo: Andrew Bruckner/NOAA)

Colpophyllia natans (Miller 2003, 2005). In general, the overall condition of corals in shallow habitats is good with little incidence of disease.



The star coral (Montastraea cavernosa) from Navassa Island (Photo: USGS)



The black sea fan (Iciligorgia schrammi) (Photo: Geoff Schultz)

Twenty-one species of gorgonians (sea fans) typical of Caribbean shallow water gorgonians, are found at habitats from 15 to 20 meters. The population densities of gorgonians are relatively low at the shallow depths, but may be greater at other habitats. The dominant species in the northwest is the purple sea fan, *Gorgonia ventalina*. The black sea fan, *Iciligorgia schrammi*, is usually found along vertical walls or slope breaks in deeper waters with very clear water and high currents. It has not been observed in the shallow waters of Lulu Bay or in the northwestern sector of the island. Other gorgonians observed at study sites are the forked or bipinnate sea feather, *Pseudopterogorgia bipinnata*, the bottle-brush coral, *Muriceopsis flavida*, the shelf knob sea rod, *Eunicea succinea*, the tan bushy soft coral, *Plexaura flexosa*, the common bushy soft coral, *Plexaura homomalla*, the purple sea plume, *Pseudopterogorgia acerosa*, and the spiny sea fan, *Muricea muricata*.



Maze coral (Meandrina meandites) (Photo:CCMA/NOAA)



The black sea fan (Iciligorgia schrammi) (Photo: Geoff Schultz)

Mollusks and Other Invertebrates

Conch surveys in 2006 indicated low abundances of mostly adult queen conchs (*Strombus gigas*) (Piniak et al., 2006)

A partial list of mollusks, other invertebrates, and algae observed at Navassa Island appears in <u>Grace et al, 2000</u>.

Fishes

Numerically, approximately 71 percent of the fishes of Navassa Island are plankton-feeding species. Herbivores constitute about 18 percent of the remaining fish assemblages and the remainder is composed of fish-eating and invertebrate-eating species. Large individuals of all species were notably absent (Miller, 2003, Collette et al., 2003). In the spring of 1999, Collette et al. (2003) collected or recorded 224 species of fishes from 66 families, making a total of 237 species known from Navassa. <u>Miller (2003)</u> added an additional 35 species, making a total of 272 species. Most of the Navassa fishes are reef species that are widely-distributed throughout the Caribbean sea (Collette et al., 2003).



The princess parrotfish, Scarus taeniopterus (Photo: gmc travel)



The red band parrotfish Sparisoma aurofrenatum (Photo: Dr. John E. Randall)

Navassa lacks families associated with the continental shelf or seagrass meadows. Forage fishes such as herrings and anchovies are also absent. Most medium to large sized fishes such as grunts (*Haemulidae*), groupers (*Serranidae*), snappers (*Lutjanidae*), and parrotfishes (*Scaridae*) were rare or absent from the shallower and accessible areas at the northwestern end of the island. There were more large fishes in the deeper and less accessible southern end of the island. This marked difference may be the result of the heavy fishing pressure by the Haitian fishers. Piniak et al. (2006) surveyed the fish communities along the deep shelf (28-34 meters) and observed numerous squirrelfishes, triggerfishes, and parrotfishes. Groupers and snappers were also present, but no small individuals were observed. The three most common families of fishes were parrotfishes (Scaridae), triggerfishes (Balistidae), and surgeonfishes (Acanthuridae).

Miller (2003) reported that the most abundant species, comprising nearly 60 percent of the total number, are the blue chromis (*Chromis cyanea*), creole wrasse (*Clepticus parrae*), bluehead wrasse (*Thalassoma bifasciatum*) and bicolor damselfish (*Stegastes partitus*). Species with the highest frequency of occurrence from all of the samples were the blue tang (*Acanthurus coeruleus*), followed by the princess parrotfish (*Scarus taeniopteru*), redband parrotfish (*Sparisoma aurofrenatum*), bluehead wrasse, bicolor damselfish, and black durgon (*Melichthys niger*).



The bicolor damselfish (Stegastes partitus) (Photo: Dr John E. Randall)



The scalloped hammerhead shark (Sphyrna lewini) (Photo: Dr John E. Randall)

Collette et al. (2003) published an annotated and illustrated list of shore fishes of Navassa Island. A list of fish species with collection and observational methods is given in <u>Grace et al., 2000</u>.

Captures by bottom longline include the bull shark (*Carcharhinus leucas*), smooth dogfish (*Mustelus canis*), scalloped hammerhead (*Sphyrna lewini*), great barracuda (*Sphyraena barracuda*), silk snapper (*Lutjanus vivanus*), and misty grouper (*Epinephelus mystacinus*).

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More photos



A diver collecting data at the edge of a reef



Lobophora Variegata, a dominant macroalgal species



The touch-me-not sponge, *Fibularia nolitangere*



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The marine snail, *Coralliophila abbreviate*, feeding on living coral polyps

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Status and Health of the Coral Reef Ecosystem

Given the remoteness of Navassa Island and its lack of permanent habitation, development, and tourism activities, its marine habitats are mostly undisturbed by human activities. Some apply the term "pristine" to describe these habitats that are free from anthropogenic land-based pollution and recreational activities.

In general, the hard or stony corals (*Scleractinia*) are relatively healthy, although there has been some disease reported on brain corals in deeper sites. The most common condition affecting coral tissues is overgrowth by macroalgae. A small percentage (just over 4 percent) of coral colonies showed evidences of predation by snails, fire worms or fishes (Miller et al., 2005).

Although Navassa Island is a National Wildlife refuge, regulations are not enforced. The major threat to Navassa Island's coral reef communities is the ongoing fishing



The purple sea fan, Gorgonia, is a dominant sea fan in the northwestern part of Navassa Island (Photo: NOAA/Larry Zettwoch)

pressure on reef fishes, queen conch, spiny lobster, and marine turtles by transient Haitian fishers. These substantial fishing activities are unmanaged and quantitative data on catch statistics and other fishing activities are lacking. Qualitative observations by scientists (Collette et al. 2003; Miller and Gerstner, 2002) suggest that large fishes had already been greatly reduced and the fishing intensity and impact would increase. Commercial fishing operations from neighbouring copuntries within the Reserve boundaries may also reduce the pelagic fish populations. Threats to the terrestrial ecology include the burning of forested areas by Haitian squatters and the introduction of invasive species such as rats, dogs, cats, and goats.

Link to metadata and data held by CoRIS

Click on the following URL to locate metadata and data in the CoRIS holdings on Navassa Island. When the query screen comes up, enter Navassa in the window, and then click on <u>Search</u>.

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Interesting Web Sites

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U. S. Virgin Islands

The biologically rich coral reef ecosystems in the U.S. Virgin Islands (USVI) consist of a mosaic of benthic habitats, principally hard coral and other hard bottom areas, seagrass meadows, and mangrove forests that are home to a great diversity of organisms. These coral reef ecosystems provide, inter alia, shoreline protection and support valuable socio-economic activities. The USVI consists of three large main islands, east of Puerto Rico and several smaller islands. St. Croix is the largest island, St. Thomas is the second largest, and St. John is the third largest. Coral reefs in the USVI and reefs elsewhere in the Caribbean face similar environmental stresses which include climate change, diseases, storms, coastal development and runoff, coastal pollution, tourism and recreation, fishing, and vessel groundings.

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Introduction

If you leave Playa de Fajardo, on the east coast of Puerto Rico, sail into the Caribbean Sea on a heading of 89 degrees and travel for approximately 40 nautical miles along this heading, you will enter an archipelago of small, mountainous islands. These are the islands which Christopher Columbus discovered on his second voyage (*ca.* 1493) and named "Los Once Mil Virgenes" (the Eleven Thousand Virgins, in honor of the feast day of St. Ursula and 11,000 virgins, who were said to have been martyred with her) or, in modern usage, the U.S. Virgin Islands. The United States purchased what is now the United States Virgin Islands (USVI) from Denmark in 1917. The non-U.S. Virgin Islands are British.



The U.S. Virgin Islands are to the left of the dotted line.



Map of the Caribbean showing the location of the U.S. Virgin Islands.

The principal islands of the U. S. Virgin Islands are St. Croix, St. John, and St. Thomas. There are, in addition, a number of small islands and cays, 82

of which are named (some with colorful names such as Cockroach Island, Cow Rock, Watermelon Cay, and Whistling Cay). Water Island (considered the fourth major island by some geographers) lies in the Charlotte Amalie Harbor (St. Thomas) and for historic ecological reasons, is one of the more interesting of the smaller islands. The name "Water Island" is based on the historic occurrence of many fresh-water ponds on the island. These ponds were so numerous that seafarers used them to replenish their supplies of fresh water. Unfortunately the kinds of fresh-water plants and animals which might have lived in this unique environment appear to be unknown. The ponds were ultimately lost to cattle grazing and the development of cotton plantations.

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History

The Virgin Islands were believed to be uninhabited until the Ciboney Indians arrived from South America about 1600 or 1700 years ago. The pre-Columbian Ciboneys were displaced by the Arawaks who were ultimately displaced by the war-like (and presumably cannibalistic) Caribs. During the early 1700s, Europeans began to arrive in sufficient numbers to displace the last of the Caribs and begin the slow process of transforming the pristine woodlands of the islands into a quiltwork pattern of agricultural fields, open areas for cattle grazing, and small villages. These have now largely been replaced by wastelands, large cities, and much larger villages, all of which are interconnected by a network of paved and unpaved roads. The pristine forests, first seen by the Ciboneys, have since been transformed into second-growth woodlands containing a great variety of introduced non-native species.

The Virgin Islands were originally Spanish possessions, but several other European countries (Holland, France, England, and Denmark) attempted to establish colonies there. As a consequence, a number of battles were fought which ultimately left the British in the northern Islands and Denmark on St. Thomas, St. John, and St. Croix. During the First World War the United States considered the possibility of an invasion of Denmark by Germany – a circumstance which could have resulted in the development of German military bases in the Virgin Islands. The United States consequently purchased the Danish West Indies from Denmark. The Virgin Island archipelago now consists of the British Virgin Islands(BVI) and The United States Virgin Islands (USVI).

Geological history

The geological history of the Virgin Islands dates back at least 100 million years to the Late Cretaceous and involves a complex history of undersea mountain building, periods of extreme volcanism, centuries of coral reef deposition, and several major changes in sea level. The Virgin Islands are located on an active plate boundary between the North American and Caribbean tectonic plates. The Virgin Islands Trough (deepest point over 4000 m) separates the island of St. Croix from the remainder of the Virgin Islands to the north. The islands north of the trough, St Thomas and St John, are of volcanic origin and formed by the subduction of one tectonic plate beneath another. The formation of St Croix is geologically associated to the islands of the Greater Antilles whereas St Thomas and St John are geologically associated with the Lesser Antilles.

Because of their position between two geologically active tectonic plates, the Virgin Islands are subject to sometimes severe earthquakes. Such an earthquake occurred off the Virgin Islands on 18 November 1867 resulting in a tsunami on St. Croix which produced waves presumably ranging in height from nine to twelve meters (Zahibo, et al., 2003) NOAA CoRIS - Ecosystem Essays:U.S. Virgin Islands

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Coral reef ecosystems of the U.S. Virgin Islands

Coral reefs

Coral reefs are a major and conspicuous component of the shelf regions of the U.S. Virgin Islands. Four other ecologically distinct marine habitats (seagrass beds, algal plains, mangrove forests and salt ponds) interact in various ways with the coral reefs and are considered to be part of the coral reef ecosystem. Other habitats such as octocoral hardbottom, sand communities, shallow mud, and fine sediment habitats also interact with the coral reefs.

Extensive coral reefs lie in deeper water along the shelf edge in depths from approximately 37 to 61 meters. These deeper reefs are dominated by plating forms of the *Agaricia* spp. and *Montastraea* spp. complexes, while corals in shallower water vary from columnar forms of *Montastraea* spp. to *Acropora* spp. to gorgonian dominated habitats. Maps of USVI benthic habitats (to 30 meters) show that 61 percent of the 485 km2 area is coral reefs and corals on hard bottom; 33 percent is predominantly seagrass beds, and 4 percent is sediment or rocky bottom.

Fringing and patch reefs, along with spur and groove formations, are typical of St. John and St. Thomas. St Croix, on the other hand, has several large barrier reefs, some of which are associated with welldeveloped lagoons. Several threatened and endangered species, in addition to elkhorn and staghorn corals, feed, reproduce, nest, rest, or calve in the waters of the USVI. Vertebrates, such as humpback whales, pilot whales, four species of dolphins, several sea birds, and marine turtles all use portions of these waters. The reefs of the USVI also provide habitats for many species of reef fishes, invertebrates, and plants.

Seagrass beds

The highly productive seagrass beds provide food and shelter for a great variety of marine vertebrates and invertebrates. Seagrasses also act as sediment filters and consequently improve the water clarity over coral reefs. Four major sea grasses occur in the U. S. Virgin Islands: shoal grass, *Halodule wrighti*), turtle grass (*Thalassia testudinum*), manatee grass (Syringodium filiformis, and small turtle grass (*Halophila*



A coral reef at St. Croix. The

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baillonis). All four of these species have been recorded in St. Croix (probably because of well-protected lagoons). Shoal grass, turtle grass, and manatee grass are reported from St. John, while only turtle grass and manatee grass are known to occur in St. Thomas. In the U. S. Virgin Islands (as elsewhere) seagrass beds are typically limited to shallow, clear-water areas which have good water circulation.

Algal plains

Algal plains occur over coral rubble and coarse sand. They are best developed at depths of approximately 18 meters. Various species of green, brown, and red algae, and the spermatophyte *Halophila baillonis* (Florida Keys seagrass) are the dominant plants. Associated biota includes sponges, tunicates, bryozoans, mollusks, polychaete worms, and gorgonians. Fifty-two species of algae and 43 species of fishes have been recorded from a typical algal plain off St. Thomas.



A turtle grass meadow at St Croix (Photo: NOAA CCMA Biogeography Team)

Mangrove forests

Mangrove forests help stabilize shorelines and protect low-lying lands by buffering them against severe tropical storms, winds, and waves. Mangrove prop roots and leaf litter provide excellent habitat for a large number of invertebrate species as well as nursery areas for coral reef fishes (Boulon, 1992). They also provide nesting areas for birds. Mangrove root systems trap and cycle nutrients and organic materials. Mangrove forests are poorly developed in the U. S. Virgin Islands, accounting for only three percent of the total land area. Based on a survey undertaken by the U. S. Geological Survey (USGS, 1994) there were 960 acres of mangrove/salt pond habitat on St. Croix, 424 acres on St. John, and 320 acres on St. Thomas. Red mangrove (*Rhizopora mangle*), black mangrove (*Avicennia germinans*) and white mangrove (*Laguncularia racemosa*) are the dominant trees in the mangrove forests.

Salt ponds

Salt ponds are tidal flats or basins which are at least partially separated from the sea by beach berms. They are a dominant feature of the wetlands of the U. S. Virgin Islands (more than eighty have been counted on the three main islands). Salinities vary from 10 to 100 parts per thousand (ppt). Salt ponds also trap sediments before the sediments reach the nearshore reefs.

Protected and managed areas

Both the federal government and USVI environmental agencies share responsibility for protecting the coral reef ecosysems in the U.S. Virgin Islands. These include the Virgin Islands National Park (St. John), The Buck Island National Monument (St. Croix), the Virgin Islands National Monument (St. John), Marine Conservation Districts, the East End Marine Park (St. Croix), and marine sanctuaries.

The monument south of St. John contains predominantly deep algal plains with communities of mostly red and calcareous algae. Scattered areas of

raised hard bottom are colonized with hard corals, sponges, gorgonians, and other invertebrates. They provide shelter for spiny lobsters, sea basses, and snappers, as well as spawning sites for some reef fish species. These algal plains and raised hard bottom areas link the shallow water reef, sea grass, and mangrove communities with the deep water shelf and shelf edge communities of fishes and invertebrates.

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NOAA CoRIS - U.S. Virgin Islands: Coral Reef Ecosystem Stressors



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Coral reef ecosystem stressors in the U.S. Virgin Islands

Coral reefs are among the World's most delicate and vulnerable ecosystems. A number of events and circumstances can effect them drastically resulting in degradation and even death. Scientists who study coral reefs have coined the term "stressors" to describe these events and circumstances. Some of these stressors are thought to be anthropologic in origin (pollution, ship damage, over-fishing, etc), while others are regarded as natural (earthquakes, tropical storms, disease, *etc*). The number of stressors effecting coral reefs varies, but the following have been clearly identified in the U.S. Virgin Islands:

Climate change and coral bleaching

Over the last few decades there has been a conspicuous increase in average air temperature throughout the World, which, in great measure is probably attributable to the accumulation of "greenhouse" gases resulting from human activities. As a consequence of these changes, sea water surface temperatures (SSTs) are also rising. Coral reefs in the USVI and other parts of the Caribbean experienced extensive and widespread bleaching during 2005, with more than 90 percent of coral cover bleached in some areas. On average, water



Coral bleaching in St Croix (Photo: NOAA)

temperatures surrounding the reefs were much higher than any time during the previous 14 years. Corals are symbiotically associated with various species of autotrophic dinoflagellate algae called zooxanthellae, which live in the coral tissues and provide the corals with pigmentation, and through photosynthesis, energy-rich carbon compounds needed for the corals' metabolic processes. As water temperatures rise, the zooxanthellae, which provide most of the corals' energy requirements, disintegrate or are expelled from the corals. Consequently, the white limestone skeleton of the unpigmented coral is visible, resulting in a bleached (whitened) appearance. Death of the coral may or may not occur, depending on the duration and severity of the temperature increase, any subsequent diseases, and the corals' resiliency. Major coral reef framework building species, for example, elkhorn coral, have nearly disappeared from some sites. Climate change may also be involved with some of the other stressors discussed below. History

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Diseases

Corals are susceptible to a number of different diseases. Four kinds of coral diseases have so far been recognized in the USVI: black band, yellow-blotch, white plague, and dark spot (Nemeth, et al., 2003). Very little is known about the causative agents of these diseases, but microbial pathogens have been identified in at least five cases. As with coral bleaching, the recent increases in severity of coral diseases may be a consequence of global warming.

After the dramatic 2005 bleaching event in the Caribbean, corals also suffered significant losses due to a post-bleaching disease outbreak. There was a greater than 2,000 percent increase in disease lesions and nearly 800% increase in denuded skeleton caused by disease over pre-bleaching levels. Mortality was primarily from white plague and resulted in the loss of 52 percent live coral cover from more than 30 acres of coral reef (Rothenberger et al., 2008).

Tropical storms

Severe storms can directly affect the coral reef environment by reducing living stands of live coral to coral rubble and by causing major shifts in the topography of reef areas (for example, moving the location of reef crests). The effects of storm-caused degradation on reefs in the Virgin Islands was clearly demonstrated following Hurricane Hugo in 1989. Fifteen years after the storm, reefs in Lameshur Bay, St. John, had shown no significant increase in live coral cover (Jeffrey, *et al.*, 2005)

Coastal development and runoff

Coastal sedimentation resulting from heavy rainfall and excessive runoff has been a natural occurrence in the Virgin Islands since the Holocene sea level rise. However, the causes of coastal sedimentation have clearly shifted from natural to anthropogenic origin. In the U.S. Virgin Islands this increase in runoff and the resulting increased sedimentation can be attributed to increased population with the resulting need for more housing, roads, and other development. This is particularly true in St. John and St. Thomas where steep mountain slopes allow rapid runoff (Brooks, et al., 2007). Nemeth and Nowlis (2001) have pointed out a direct relationship between shoreline development in St. Thomas and increased sedimentation in Caret Bay during periods of heavy rainfall.

Coastal pollution

As in other Caribbean islands, coastal pollution has long been a major problem in the U.S. Virgin Islands. Both biological and chemical (industrial) pollution are evident. Bacterial contamination of coastal waters is a primary problem caused by numerous point and nonpoint sources. Heavy rainfall sometimes overloads existing sewage systems resulting in severe pollution of coastal waters. In 2003 there were eighty days in which beaches were closed because of biological contamination. In St. Croix, a rum factory discharges waste water directly into the sea forming a plume which can be traced for about 10 km from its point of origin (Jeffrey, et al., 2005)

Tourism and recreation

The transition from an agricultural/fisheries economy to an economy based primarily on tourism has been strikingly evident during the last few decades and has resulted in an ever increasing demand for land-based accommodations (houses, resorts, recreational facilities, new roads). As forests and top soils are removed, rain water runoff increases, resulting in increased siltation of the coral reefs. Direct recreational use of coral reefs can be especially damaging. For example, with an annual visitor population of about 170,000, a "snorkeling trail" in the Virgin Islands exhibited major deterioration over the first twenty-five year period following its establishment in the 1960s (Bruckner, et al., 2005).

Fishing

As in most other Caribbean Islands, overfishing, habitat degradation, more efficient fishing gear and techniques, and less than rigorous enforcement of fishing regulations have all contributed to major losses in fishery resources in the USVI. Many species of reef fishes have declined remarkably in the last several decades. This is especially true of a number of species of snappers and groupers. Both the lobster and conch fisheries are under ever increasing pressure regardless of the numerous regulations aimed at protecting them (Jeffrey, et al., 2005).

Live trade and Souvenir collecting

In spite of strong regulations prohibiting the taking of both living and dead biological material from the coral reefs of the Virgin Islands, U. S. Customs Agents confiscate large amounts of such material at all of the major airports in the Virgin Islands as well as at points of entry in the continental United States. Fortunately there is no aquarium trade in the Virgin Islands, and the few permits which have been issued for collecting coral reef plants and animals have been issued only for the purposes of research and education.

Vessels and related problems

Vessel impacts such as groundings, anchor damage and waste discharges affect coral reef ecosystems in the USVI. Accidental groundings can cause serious structural damage to the coral reef environment. The anchoring of boats and the dragging of anchor chains over coral reefs and sea grass beds are also major boat-related threats. Recreational vessels, the numbers of which are increasing rapidly in the USVI, can also cause environmental degradation through the release of sewage and fuel-related hydrocarbons.

Marine debris

Plastic bags, glass and plastic bottles, plastic lids, cans, plates, utensils and discarded fishing line are among an array of items which are washed directly into the sea from beach activities and from several landfills in the Virgin Islands. During the 2006 Ocean Conservancy's annual International Coastal Cleanup, volunteers removed nearly 20,000 pounds of trash and debris from about 50 miles of shoreline. Underwater cleanups removed about 500 pounds of marine debris. Over 90 percent of the marine debris had its origin in the USVI; only a very small percentage washed in from offshore sources.

Introduced and invasive species

Invasive species can rapidly and seriously degrade endemic or established island populations by altering natural processes and reducing biodiversity. Native to South America, the red imported fire ant (*Solenopsis invicta*) has been introduced into parts of some Caribbean islands, notably Puerto Rico and the Virgin Islands. The small Asian mongoose was deliberately introduced into many Caribbean Islands, including the Virgin Islands, as a biological control agent against rats in sugar cane fields. However, the

mongoose became a serious pest that wreaked havoc with local biodiversity. Non-native rats and feral pigs also interfere with natural ecosystem dynamics. Buffelgrass (*PennisTum ciliare var ciliare*) is a nonnative pasture grass that can form thickets that displace native species. However, aquatic invasive species have not been recognized as a major threat in the USVI.

Saharan dust

The Sahara is the major source on Earth of mineral dust (60-200 millions of tons per year), which are eroded mineral soils from the Sahara Desert and the transition zone (sahel) between the Sahara Desert and tropical forests to the south. This mineral or Saharan dust is lifted by convection to high altitudes where is transported by trade winds across the Atlantic Ocean to the Americas and the Caribbean. Besides depositing nutrients utilized by Atlantic phytoplankton and other organisms, the dust also contains harmful contaminants which may play a role in the degradation of the Caribbean coral reefs. Found in the dust are viable pathogenic microorganisms, metals, heavy metals, pesticides, polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons. A known coral pathogen, the fungus *Aspergillus sydowil*, which produces the disease aspergillosis in sea fans, is also transported by Saharan dust.

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NOAA CoRIS - U.S. Virgin Islands: Threatened and endangered species in the US Virgin Islands



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Threatened and endangered species in the US Virgin Islands

Several terrestrial and marine species of plants and animals in the USVI are threatened or endangered. The list includes a number of plants, staghorn and elkhorn corals, black coral, the green sea turtle, hawksbill sea turtle, Kemp's ridley sea turtle, the leatherback turtle, and the loggerhead sea turtle, St. Croix ground lizard, the Virgin Islands Boa, the brown pelican, the peregrine falcon, many other species of nesting birds, the slipperyback skink, the Atlantic goliath grouper, and three species of bat. Other threatened, endangered or vulnerable species in Virgin Island waters include the West Indian manatee, several species of dolphins and whales (blue whale, finback whale, humpback whale, sei whale, and sperm whale). Fishes and coral species of concern include the ivory bush coral, dusky shark, mangrove rivulus, night shark, sand tiger shark, speckled hind, striped croaker, Warsaw grouper and white marlin.

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Status of the coral reefs and adjacent environments of the U.S. Virgin Islands

The U.S. Coral Reef task force calls for local action strategies to reduce key threats to U.S. coral reef ecosystems. The USVI locally driven initiative was designed to identify and implement priority actions to reduce key threats to coral reefs through partnerships and collaborative actions among federal, state, territorial, and non-governmental partners. The U.S. Virgin Islands directed all LAS activities towards the newly formed St. Croix East End Marine Park (STXEEMP). The LAS focused on four areas: (1) Lack of awareness (Goal - Build awareness of the importance of coral reefs and teach and encourage positive behaviors that will protect and nurture them; (2) Recreational use (Goal - Reduce impacts of recreational use to coral reef systems within the STXEEMP); (3) Fishing (Goal - To provide resource managers with sufficient baseline information to assess the current status of coral reef ecosystems within the STXEEMP, to assess existing harvest patterns of fisheries resources from the STXEEMP, and to determine the relative impact of fishing within the STXEEMP; and (4) Land Based Sources of pollution (Goal - Reduce non-point source pollutants in watersheds contributing to the East End Marine Park).



The St. Croix East End Marine park (STXEEMP)

Results from water quality monitoring programs in the USVI show that water quality, while generally good, continues to decline, in large measure due to point and nonpoint sources of pollution. According to the 2008 State of the Coral Reef Ecosystems of the U.S. Virgin Islands report

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(Rothenberger, 2008), surface waters in the USVI continue to be adversely affected by increasing sources of pollutants, ranging from runoff from construction sites and unpaved roads, failure of best management practices on construction sites, failure of onsite disposal systems, failing sewage systems and the direct discharge of waste overboard from vessels. The major problems affecting nearshore waters are sedimentation and bacterial contamination. Regulation of such activities is difficult and largely voluntary. Sewage bypasses from the municipal sewage system and wastewater effluent from both permitted and illegal discharges continue as well. Efforts are underway to remedy these problems or mitigate their effects.

The USVI did not escape from the effects of the Caribbean mass bleaching event of 2005.

In some areas, more than 90 percent of the coral cover bleached during the 2005 bleaching event. In addition to mortality associated with bleaching, bleached corals also suffered significant losses due to disease. The overwhelming mortality documented was attributed to white plague disease, caused by the bacterial pathogen, *Auratimonas coralicida*. White plague disease is characterized by an abrupt line or band of white, exposed coral skeleton that separates living tissue from algal-colonized skeleton, and often a narrow band of bleached tissue may be visible adjacent to exposed skeleton. Usually beginning at the base of a colony, it spreads quickly upward and outward.

Coral recovery from the bleaching was variable. Some corals showed significant recovery followed by disease impacts, while others appeared to die as a result of the bleaching event itself.

The overall consensus of experts is that coral reef ecosystems in the USVI are in decline and continue to be threatened by a number of natural and anthropogenic stressors. The long-term impacts of significant loss of live coral cover may not be known for years or decades. Changes to coral reef architecture may have significant effects on the populations of fishes and invertebrates which depend upon the corals. Baseline information is needed on coral diseases and coral resiliency. Much more research is needed to understand the synergistic (cumulative) effects of stressors. Inadequate information is available on reef fisheries for commercially and recreationally important fishes and invertebrates, such as the mutton snapper, some groupers, and queen conch.

Scientists recommend that management and enforcement capacity of regulations be heightened. These include increased collaboration between federal and territorial



Smooth brain coral, Diploria strigosa with white plague that is spreading upwards from the colony base. (Photo: Dr Andrew bruckner/NOAA)

agencies working on coral reef issues in the USVI, improving enforcement of existing regulations, expanding management capacity, and increasing awareness of coral reef ecosystems among residents and visitors. Progress has been made in many of these areas, but additional efforts are warranted.

Thousands of Americans participate yearly in snorkeling and scuba-diving

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activities in the Caribbean, with many tourists traveling to the U.S. Virgin Islands. However, as coral reef quality and habitat declines, tourists may go elsewhere, with a resulting loss of millions of dollars to the USVI economy.

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The Republic of Palau (Belau)

Introduction

Palau (or Belau), part of the Caroline Islands group, is the westernmost archipelago in Oceania. It is located 460 miles (741 km) east of Mindanao in the southern Philippines and about 808 miles (1,300 km) southwest of Guam. Palau is composed of nine or more inhabited islands and greater than 700 islets. The archipelago also has six isolated islands, which lie approximately 211-372 miles (339-559 km) to the southwest. Numerous volcanic islands, atolls, raised limestone islands, and low coral islands comprise Palau. A barrier reef surrounds much of the main island cluster, merging into a fringing reef in the south. Palau has the most diverse coral fauna of Micronesia and the highest density of tropical marine habitats of comparable geographic areas around the world. In addition to coral reefs, mangrove forests, and seagrass meadows, Palau has deep algal beds, mud basins, current-swept lagoon bottoms, rich tidal channels, and anoxic basins within the Rock Islands.

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The Republic of Palau (Belau)

Geography

The Republic of Palau, also called Belau, located between 5° 53' and 8° 12' north and 134° 07' and 134° 39' east, is part of the Caroline Islands group. It is the westernmost archipelago in Oceania, lying at the far western end of Micronesia in the Philippine Sea. Palau is located approximately 460 miles (741 km) east of the island of Mindanao in the southern Philippines and about 808 miles (1,300 km) southwest of Guam. The archipelago extends over I50 miles (241 km) and has about 177 square miles (458 km²) of dry land and approximately 203 square miles (525 km²) of coral reef habitat. Numerous volcanic islands, atolls, raised limestone islands, and low coral islands comprise Palau. Tropical forests cover much of the islands with ironwood, banyan, breadfruit, coconut, and pandanus making up the bulk of the greenery. Mangrove forests and grassy savannas are also present. Palau's highest point, Mt. Ngerchelchuus on Babeldaob Island, is 715 feet (215 m) above sea level.

Palau is composed of approximately nine inhabited islands and more than 700 islets stretching 435 miles (700 km) from Ngeruangel Atoll in the Kayangel Islands in the north to Helen Reef in the south. The archipelago consists of a clustered island group of four high islands (Babeldaob, Koror, Peleiu, and Angaur), two low coral atolls (Kayangel and Ngeruangel), and the famous karst-weathered, forested limestone Rock Islands. Six isolated Southwest Islands (Helen Reef, Tobi, Merir, Pulo Anna, Sonsorol, and Fana) lie approximately 211-372 miles (339-599 km) to the southwest. Babeldaob is the largest island in the Palauan chain and the second largest island in Micronesia; only Guam is larger. Babeldaob and its reefs are separated from Koror and the southern islands of the group by Toachel El Mid, a deep east-west pass. All the islands are enclosed within a 104 km-long reef, except for Angaur in the south and several small atolls in the north.

The Rock Islands are a small collection of relic coral reefs. They surfaced in Palau's Southern Lagoon to form approximately 250 islands, most of which are uninhabited, small, mushroom-shaped, and topped with vegetation, although some are large enough to have beaches. Tourists are attracted to the Rock Islands for their white sandy beaches, blue lagoons, and marine lakes, which invite snorkeling, scuba diving, fishing, and kayaking. A portion of the Rock Islands, known as Seventy Islands, has been set aside as a marine turtle conservation area. Turtle hatchlings are taken to a mariculture center, where they are raised to nearly six inches and are then released into Palauan waters.

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Map of the Republic of Palau courtesy of Waddell, J.E. and A.M. Clarke (eds.), 2008. The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. 569pp. (Click on the image for large view)



Palau is home to about 70 marine lakes, which are connected to the ocean through fissures in the islands' porous limestone. One of the most famous marine lakes, Jellyfish Lake, is found among the Rock Islands. It provides habitat for millions of "stingless" jellyfish, which snorkelers can swim among without fear of being stung. Before the recent introduction of a predator anemone into Jellyfish Lake, the two species of jellyfish that live there had had no predators and had, over time, lost the potency of their principal defensive and prey-catching weapons (stinging cells). These jellyfish became completely "stingless". As with their coral relatives, they host symbiotic, photosynthesizing algae in their tissues which provide food energy. The greatest number of jellyfish ever recorded in the lake was 31 million $(accuracy \pm 8 million)$ in January 2005.

The Southwest Islands are small oceanic islets that sit atop flat-topped seamounts, except for one islet that sits on a perimeter reef surrounding a lagoon.

Ngeruangel and Velasco Reefs are the northernmost reefs in Palau and share the

IKONOS satellite image of Palau (Click on the image for large view)

same reef formation. Ngeruangel is a small atoll that has only one small coral islet at the southwest side. The reef that forms the barrier of Ngeruangel atoll is nearly

continuous except for some small passes in the west and the north facing Velasco Reef. Velasco Reef is a sunken atoll north of Ngeruangel Reef, rising abruptly from the surrounding deep seafloor.



Surface view of Jellyfish Lake (Photo: Julian Sachs/Sachs Lab/University of Washington)



Jellyfish in Jellyfish Lake have tiny stinging cells that do not affect swimmers, hence the term "'stingless"



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The Republic of Palau (Belau)

Climate

Palau's climate is tropical, with a hot and humid rainy season extending from May through November. The mean annual temperature is 82°F (27°C). Rainfall averages 150 inches (3,800 mm) a year, with June through August being the wettest months. There is a drier period between January and April when the average monthly rainfall is 9 inches (229 mm), although at times it can be as low as 6 inches (147 mm). Additionally, Palau's surface waters average in the low 80°s F (20°s C).

The maximum rainfall is in July. Most rainfall occurs as short heavy showers. Over the land, these showers are most frequent in the afternoon, but over the surrounding ocean area, showers occur most often during the early morning hours. Spells of rainy weather lasting several days occur when typhoon storm centers pass to the north. Typhoons are uncommon in Palau, as the islands lie outside the main typhoon path; nevertheless, during the typhoon season (June through December), it is hit by occasional storms with high winds. Typhoons may occur in any month but are least common from February through April.



A threatening storm (Photo: Julian Sachs/Sachs Lab/University of Washington)



Rain showers in Palau (Photo: Julian Sachs/Sachs Lab/University of Washington)

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The Republic of Palau (Belau)

Geology and Natural Resources

The Palauan islands have a varied and interesting geology, which includes volcanic islands, coral reefs and atolls, low platform islands, and high limestone islands. Babeldaob, Meiuns, Malakal and the western part of Koror are volcanic in origin. Reefs and atoll islands are located north and northeast of Peleliu, and the southwestern islands are a combination of low platform islands and atolls. The central and southern regions of the archipelago feature over 300 limestone islands, the majority being the steep-sloped, mushroom-shaped Rock Islands. Because of physical and chemical differences between volcanic and limestone islands, there are distinct differences in the terrestrial plant communities. There also are a number of outlying atolls, including Kayangel in the North and Helen and Tobi in the South.

Palau is comprised of numerous types of forests (upland, swamp, limestone, atoll, and mangorve); savanna and grasslands (in Babeldaob and Ngarekebesang); freshwater habitats, including rivers, streams, lakes, swamps, and taro patches; brackish water habitats, such as the wetlands and coastal lagoons of Babeldaob, Peleliu, Angaur, and the Southwest Islands; marine lakes (in the Rock Islands); nearshore habitats, including



Rain forest habitat in Palau (Photo: Julian Sachs/Sachs Lab/University of Washington)

mudflats, seagrass beds, and sandy beaches; and barrier, patch, and fringing coral reefs.

Palau's natural resources include one of the largest tropical rainforests in Micronesia, as well as minerals, natural gas deposits, marine products, and deep-seabed minerals. Three major economic industries have been developed in the Republic: phosphate and bauxite mining in Anguar and Babeldaob, respectively, and copra production. Main crops are pineapple, banana, taro, cassava, papaya, breadfruit, mango, betel-nut, and leguminous trees.

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Freshwater is somewhat limited in Palau, although lenses of fresh water can be found on some of the atolls. The only sustained surface water stream flow is found on the large volcanic island of Babeldaob, which supports a complex network of surface streams and rivers with five major watersheds that supply the majority of public drinking water systems. The Ngerikiil watershed in Airai has an area of 13 square miles (33.7 km²) and is the primary source of water for the National water system, which serves 80% of Palau's population. Of Babeldaob's two freshwater lakes, Lake Ngardok, which is the largest freshwater lake in Micronesia, has been named a Wetland of International Significance under the Ramsar Convention. A secondary source of water is ground water, which has not been developed extensively for public use. Instead, many homes incorporate a private rainwater catchment system to obtain drinking water, while other areas rely solely on rainwater.



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The Republic of Palau (Belau)

Habitat Types

Palau's remarkable diversity of plant and animal species is due not only to its geographic location in relationship to southeastern Asia and the Philippines, but also its wide diversity of terrestrial and aquatic habitats. For example, coral reef habitats include barrier reefs, channels through barrier reefs, lagoon patch reefs, outer fringing reefs, island fringing reefs, fringing reefs, sunken barrier reefs, offshore banks and reefs, and atolls. Other habitats include shallow-water and deep-water seagrass beds; beaches and rocky shores; estuaries; stratified and vertically-mixed marine lakes; shallow and deep lagoon



Palau has a wide diversity of terrestrial and aquatic habitats

areas, *Halimeda* meadows; sediment-laden bottoms; coastal, riverine, and marine lake mangrove forests; forest and grassland vegetation, including volcanic soil forest, riverine forest, swamp forest, atoll forest, rock island forest, limestone forest, strand vegetation, and savanna grasslands; and freshwater streams, lakes, and marshes. There are also reproductive, nesting, feeding, and other aggregation sites, such as fish spawning aggregation sites for transient and resident fishes, turtle nesting beaches and cays, green turtle feeding areas, hawksbill turtles feeding areas, dugong concentration areas, crocodile nesting areas and corridors, Micronesian megapode nesting areas, fruit bat roosting areas, and nesting cliffs and caves for birds.

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The Republic of Palau (Belau)

People

The original settlers of Palau are believed to have arrived from Indonesia as early as 2,500 B.C. The islands' proximity to Southeast Asia and exposure to Oceania contributed to a population mixture of southeastern Asian, Melanesian, Filipino, and Polynesian ancestry. In 2008, the population of Palau was approximately 21,000, of whom 70% were native Palauans. Two-thirds of Palau's population is located on Koror, even though the new capitol city, Melekeok, is on the large island of Babeldaob. Palau's most populated islands are Babeldaob, Kokor, Peleliu, and Angaur, which lies several miles to the south.



A traditional meeting house (bai) in Palau. (Photo: Jane Thomas, IAN Image Library)



Skulls of small-bodied humans from Palau (Photo: Institute for Human Origins and the Bernard Price Institute for Palaeontology/University of the

Scientists from the South African University of the Witwatersrand have found evidence of a population of small-bodied humans that lived in Palau at least 3,000 years ago. Thousands of bones between 1,400 and 3,000 years old were discovered in seawashed caves indicating that the population probably died out about 1,400 years ago. The inhabitants were of particularly small size - around 3-4 feet (94-120 cm) tall and weighed between 70 and 90 pounds (32 and 41 kilograms). Scientists have debated whether the bones in the caves came from a species of miniature humans, as their discoverers argue, or just modern humans with unusually small bodies, possibly malformed by genetic or pathological disorders. Populations of modern humans on isolated islands with limited resources often evolve short statures.

The Palauan social structure is now a complex blend of old traditions and western

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Witwatersrand, Johannesburg, South Africa)

concepts. Before European influence, Palau had already developed a sophisticated and highly organized matrilineal social system

based on clans and chiefdoms. Villages were organized by clanships through the female line and subdivided into two political statuses. A Council of chiefs, comprised of a member of each of the ten ranking clans of a community, governed the village. Women had an important advisory role and were particularly influential in the control of land and money.

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The Republic of Palau (Belau)

History

The Palau Islands were discovered in 1543 by the Spanish explorer, Ruiz Lopez de Villalobos, and rediscovered in 1710 by the Spaniard, Francisco de Padilla. In 1783, a schooner belonging to the British East India Company was shipwrecked on the reef off Aulong Island. Great Britain claimed the islands and dominated trade in the area until about 1885. Spain then claimed control of Palau until 1899. In 1899, following its defeat in the Spanish-American War, Spain sold Palau, along with the rest of the Caroline and Northern Mariana Islands, to Germany. During the German administration



Laborers from Palau and Yap working in the phosphate minds on Angaur, Palau (Photo: Georg Fritz Collection)

from 1899 to 1914, coconut agriculture and phosphate mining were introduced.



An old photograph of a typical Palauan home (Photo: Belau National Museum)

Japanese forces occupied Palau during World War I and received a mandate over Palau, the Northern Mariana Islands, the Marshall Islands, Yap, Chuuk, Pohnpei and Kosrae from the League of Nations in 1920. The Japanese increased efforts in mining, agriculture, and commercial fishing. Fighting between Japanese and Allied forces during World War II occurred throughout much of Palau, and in 1947, the United Nations created the Trust Territory of the Pacific Islands (TTPI). The United States was named as the TTPI's administering authority. The TTPI comprise four island jurisdictions: the Commonwealth of the Northern Mariana Islands and the three freely associated states (the Federated States of Micronesia, Republic of the Marshall Islands, and Republic of Palau).

The Trust Territory jurisdictions formed a single federated Micronesian state in 1979, but this eventually dissolved. Palau approved a new constitution in 1981, subsequently signing a Compact of Free Association with the United States in 1982. The Compact

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went into effect on October 1, 1994, marking Palau's emergence from trusteeship to independence. Under the Compact, the U.S. remains responsible for Palau's defense for 50 years.

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The Republic of Palau (Belau)

Tourism and Recreation

Eco-tourism activities include scuba diving and snorkeling in the islands' diverse and pristine marine environments. An increasing number of tourists are also drawn to Palau's natural island beauty and challenges and its World War II battlefields, war memorials, and shrines. This increase in tourist activity could add stress on the marine environments and coral reefs; therefore, Palauans have taken steps to prevent or reduce reef damage.



Tourists kayaking on the beautiful waters of Palau (Photo: Wayfaring Travel Guide)



Beautiful resorts attract tourists from all over the world (Photo: Wayfaring Travel Guide)

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Terrestrial Ecosystems of Palau

Originally, Palau was almost completely forested. Currently, forest cover is only 75% of its historic numbers, as forests have been cleared and replaced by savanna and grassland. Non-forested land in Palau is comprised of savannah, marsh, secondary vegetation, cropland, strand (shoreline) vegetation, and urban development. However, tropical broadleaf forests do still cover much of the volcanic and all of the limestone islands. In addition, tropical moist forests, including littoral forest, upland forest (on the high volcanic islands),



A forested Rock Island (Photo: Aiken/Widom Family Travel List and Photos)

swamp forest, mangrove forest, atoll forest, casuarina forest, limestone forest (with a subtype in the Rock Islands), plantation forest, and palm forest can be found throughout the entire archipelago.

The interior upland forests of Palau contain several endemic species of broadleaf trees found on flat or gently sloping sites as well as river and stream banks. There are six native palm species generally found in the understory or middle canopy layers of the forest. *Campnosperma brevipetiolata* is a conspicuous component of the upland forests throughout the Carolines and is generally found at lower elevations on flat or gently sloping sites, close to streams. Other major upland species include *Maranthes corymbosa* (kayu batu), *Alphitonia carolinensis* (Etabob), *Rhus taitensis* (island sumac), *Elaeocarpus carolinensis* (elaeocarpus), *Serianthes kanehirae*, *Semecarpus venenosus*, *Calophyllum inophyllum*, *Gmelina palawensis*, and *Pterocarpus indicus*. Common understory species include *Pandanus aimiriikensis*, *Ixora casei*, *Eugenia cuminii*, *Osmoxylon oliveri*, *Manilkara udoido*, *Symplocos racemosa*, and *Cyathea lunulata*.



A waterfall in a Babeldoab forest

Swamp forests are the most limited forest type in terms of area, making up only 2% of the forest and 1% of Palau's land area. Swamp forests are found in low-lying areas, often just inland of mangroves, where the soils are inundated with fresh or slightly brackish water and above tidal influence. Swamp forests are particularly vulnerable to siltation resulting from road building activities and clearing for taro patches, which causes coastal swamp forests, in particular, to degrade and become

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inundated with *Hibiscus tiliaceus*. In the few areas of swamp forest remaining, including Peleliu, common tree species include *Barringtonia racemosa* and *Terminalia catappa*. *Derris trifoliata* is a common climbing vine found on trees in the swamp forest.

Mangrove forests, which border all but 20 miles (32 km) of coastline, are found along the lower portions of rivers, on coastal mudflats, and on some offshore islets. Mangroves are ecologically important because they help stabilize coastal areas by trapping and holding sediments washed down from inland areas and local watersheds. The most extensive areas of mangrove forests occur along the west coast of Babeldaob, covering approximately 80% of the shoreline. The dominant species in Palau's mangrove forests belong to the



Palauan forest at higher elevations (Photo: Pacific Worlds & Associates)

genus *Rhizophora*. Well-developed mature stands can grow to 49-66 feet (15-20 m). On the seaward side, *Rhizophora stylosa* and *Sonneratia alba* dominate; at larger river mouths or bay indentations, *Rhizophora apiculata* and *R. stylosa* can become pure stands or occur with *Sonneratia alba* and *Bruguiera gymnorrhiza*; landward, *Heritiera littoralis, Lumnitzera littorea* and *Xylocarpus granatum* are included in the mix; and where the estuary becomes river-like, *Bruguiera, Lumnitzera, Sonneratia* and *Xylocarpus* species are common, wherease *Rhizophora* spp. becomes uncommon.

The palm *Nypa fruticans* is fairly common along the lower portions and mouths of rivers. Other woody species include *Avicennia marina*, *Ceriops tagal* and *Scyphiphora hydrophyllacea*.

Because of agroforestry, little remains of the native atoll forests, except on uninhabited atolls. Atoll forests are found toward the interior of the larger, wetter uninhabited atolls and along coasts of the high islands. They are generally located behind the strand zone but may be mixed with strand vegetation. They usually have an outer shrubby fringe of *Scaevola taccada*. In addition, small *Pemphis acidula* are common on rocky coasts, and tall *Casuarina litorea* trees are often found on leeward coasts.

Only some *Casuarina* species form forest communities. Many are too short or sparse to be classified as forest. Because their roots can produce nitrogen through nodules containing special nitrogen-fixing bacteria, *Casuarinas* can grow on nutrient-poor soils and other marginal environments such as granite outcrops or sandy soils. *Casuarina* spp. Are evergreen shrubs and trees growing as tall as 115 feet (35 m). They are sometimes called she-oaks, ironwood, or beefwood.

Limestone forest is found on the coral islands of Peleliu, Angaur, and the Rock Islands and is composed of sharply eroded limestone with little soil cover.Although the limestone forests of Palau were heavily disturbed during World War II, they are still fairly common in patches throughout the islands. Species composition varies from island to island, and an assortment of endemic species are present; however, the habitat is similar among islands. Humus from decomposing vegetation provides a sustained cycle of nutrients. Woody species include *Aidia racemosa, Badusa palauensis, Cycas circinalis, Cyrtandra todaiensis, Eugenia reinwardtiana, Flacourtia rukam var. micronesica, Garcinia matudai, G. rumiyo var. calcicola, Geniostoma sessile, Guettarda speciosa, Gulubia palauensis, Intsia bijuga, Ixora casei, Meryta senfftiana, Morinda latibracteata, Polyscias grandifolia, Premna serratifolia, Psychotria hombroniana, Rinorea* *bengalensis and Tarenna sambucina.* The endemic *Gulubia palauensis* palm, now found only in Chelbacheb, was once common in the limestone forest but was decimated by introduced cockatoos.

The Rock Island forest is a subtype of limestone forest that is extremely diverse in species composition. Common species in this forest include endemic palms, such as *Gulubia palauensis* and *Ptychosperma palauensis*, and forest trees such as *Semecarpus venenosus*, *Premna obtusifolia*, *Cordia* spp., and *Bikkia palauensis*. *Pandanus* spp. and *Dracaena multiflora* are common understory plants.

Plantation forests are stands of trees created by regular placement of seeds or seedlings. Plantation forests can be composed of either native or exotic species but are often part of a diverse landscape of remnant native forests. Mahogany plantations were established during the 1930's, but most of the older plantations have been harvested completely. However, stemming from a tree planting program established in 1970, the Forestry Department of Palau is currently planting about 10,000 mahogany seedlings and 5,000 seedlings of other species each year.

Terrestrial Biodiversity

Palau's flora is far richer than the rest of the Caroline Islands, with the exception of the island of Yap. Together, Yap and Palau form a distinct phytogeographic unit with the easternmost extension of several species of Indo-Malesian flora. The Palauan archipelago lies in an area influenced by the North Equatorial Counter Current (NECC) and the Mindanao Eddy. Both the NECC and the Mindanao Eddy affect overall island biodiversity by carrying coral and fish larvae, which originate in the Philippines, New Guinea, and Indonesia, to Palau. Terrestrial flora and fauna reach Palau via wind, rafting, or drifting with the NECC.



A coconut crab (Photo: Julian Sachs/Sachs Lab/University of Washington)



The crab-eating macaque was introduced into Palau by the Germans (Photo: Sakurai Midori)

Due to its proximity to the NECC, Palau supports the highest level of terrestrial diversity in all of Micronesia and maintains a high level (25%) of species endemism among terrestrial biota. Elevated endemism is a direct result of the isolation of the islands, both from one another and from the rest of the world. There are approximately 1,260 species of plants in Palau, of which 830 species are native and minimally 194 species are endemics (although endemic plants are typically found only in Babeldaob). In addition, more than 428 invasive plant species have been documented.

Palau's terrestrial fauna include approximately 5,000 species of insects; 141 species of birds, of which 11 species and nine subspecies are endemic; at least 40 species of freshwater fishes, of which 4 are endemic; 46 species of terrestrial reptiles and amphibians; and three species of bat, of which one species and one subspecies are endemic.

Palau has 50 species of resident birds, many

of which are protected by local laws. The national bird is the Palauan Fruit Dove or Biib. Ten bird species, including two doves, an owl, a swiftlet, and six passerines, are restricted to the islands; however, none are threatened. In total, 16 restricted-range species are found in Palau, and one of these, the Micronesian scrubfowl (*Megapodius laperouse*), is considered endangered. The endangered Japanese night-heron (*Gorsachius goisagi*) is also present. Because of development, habitat loss is affecting some birds on Koror and Babeldoab.



The Palau Conservation Society logo is of a biib – the endemic Palau fruit dove

Terrestrial mammals are restricted to two extant bat species: the common Palau flying-fox (*Pteropus pelewensis*) and the less common insectivorous sheath-tailed bat (*Emballonura semicaudata palauensis*). The sheathtail bat is considered endangered while another species,the large Palau flyingfox (*Pteropus pilosus*), is presumed to be extinct. The island of Angaur is the only place in Micronesia that has feral monkeys, descended, reportedly, from a pair of pet macaques brought to the island in the early 1900's by German miners to monitor air quality in the island's phosphate mines. The crab- and bird-eating macaque monkey (*Macaca fascicularis*) is a pest that destroys farm crops and gardens in Angaur. Other introduced mammals include rats, mice, and the Asiatic musk shrew, *Suncus murinus*.

Palauan amphibians are an introduced marine toad (Bufo marinus) and an endemic frog, Platymantis pelewensis. The most diverse group of Palauan reptiles is the lizards with 30 species, including at least nine endemics (six gekkos and three skinks). The saltwater crocodile (Crocodylus *porosus*) is at the edge of its range in Palau and is under threat from habitat destruction and hunting. The elusive mangrove monitor lizard, Varanus indicus, lives near river banks, mangrove forests, and in coastal forests. There are also seven species of non-venemous snake, which include the endemic Palauan blind snake and the bevelnosed boa. Sea snakes in the waters



The Palau flying fox

around Palau, however, are highly venomous and include the banded sea krait (*Laticauda colubrina*) and the yellow-bellied sea snake (*Pelamis platurus*). Sea kraits are oviparous and must come ashore to lay eggs. The yellow-bellied sea snake, which is less common, births its young at sea. Four species of sea turtles have been documented in Palau, although only two species, the hawksbill (*Eretmochelys imbricata*) and green (*Chelonia mydas*) turtles, maintain resident and nesting populations. The leatherback (*Dermochelys coriacea*) and olive Ridley turtles (*Lepidochelys olivacea*) occur in the islands but are much less common.

Terrestrial invertebrates are poorly known. Over 300 of the 1,200 known species of Palauan insects are endemics. In addition to insects, there are at least 11 families of Arachnida, which include spiders, scorpions, harvestmen, mites, and ticks. Unusual among Palau's insects are the marine y al

> The banded sea krait is amphibious and is found in shallow Indo-Pacific tropical marine environments, coral reefs, and mangrove swamps. On land, the krait inhabits sandy beaches, coral islands, and occasionally low-hanging trees. (Photo: Jan Messersmith/Madang-Ples Belong Mi)

insects that inhabit coastal and offshore waters. Included are two genera and many species of sea skaters – a type of marine insect found only in the Indian Ocean and western Pacific Ocean. The reef midge, *Pontomyia oceana*, is found only in the coral reefs off Palau and Queensland, Australia.

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NOAA CoRIS - Ecosystem Essays: The Republic of Palau (Belau) - Marine Environment



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Marine Environment and Coral Reefs

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Palau has an abundance of coral reef habitat types, as well as complex marine habitats associated with coral reefs, including mangroves, seagrass beds, deep algal beds, mud basins, current swept lagoon bottoms, and rich tidal channels. According to Yukihira *et al.* (2007), the total area of coral reefs in Palau is approximately 203 square miles (525 km²) and includes barrier reefs (102 square miles or 265 km²), fringing reefs (75 square miles or 195 km²), and atoll habitats (25 square miles or 65 km²) with 1,457 patch reefs scattered throughout the lagoons. An effort to map Palau's benthic habitats using high resolution satellite imagery was completed by NOAA's Center for Coastal Monitoring and Assessment's Biogeography Branch in 2007. The project classified marine habitats for 571 square miles (1,478 km²) and estimated that coral reef and hard bottom areas cover 344 square miles (892 km²).

Palau's marine habitats stretch from Ngaruangel Atoll in the north to Helen Reef Atoll in the south. A barrier reef surrounds much of the main island cluster from the northern tip of the island of Babeldaob down to the southern lagoon, merging into the fringing reef with the island of Peleliu in the south. The barrier reef is well-developed on the west coast of the main archipelago – extending for 89.5 miles (144 km) – and less developed and discontinuous on the east. There are also fringing reefs along several island coastlines and numerous patch reefs scattered throughout the archipelago. There are 14 Marine protected Areas (MPAs) with coral reefs, which comprise 40% of the coastal zone area. A national monitoring program annually monitors 22 coral reef sites.

There are more than 70 marine lakes in Palau, each with its own unique physical, chemical and biological characteristics. The lakes were formed both by rising sea level inundation of the land and by erosion of the limestone islands, which created depressions, cracks, and crevices into which marine water seeped over time. Palau's marine lakes are their own individualized ecosystems, containing atypically small and isolated

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populations of unrelated marine organisms that have inhabited and independently evolved for many thousands of years. These heterogeneous environments are natural laboratories for adaptive evolution and speciation.

Some lakes in Palau are comprised of a mixture of fresh rainwater and marine water. Others are vertically stratified and less dense, with lighter rainwater resting on top of denser salt water to form two distinct layers. Some lakes have an anoxic, noxious layer at deeper depths. In addition, certain lakes have completely lost their connection to a lagoon, while others show a continuum from completely isolated to almost lagoon-like. The largest lake in Palau is called the Metukercheuas Uet Lake. This oxygen-rich lake measures over 1.5 miles (2.4 km) long and 200 feet (60.96 m) deep.

Kayangel Atoll

The Kayangel Atoll consists of four low coral islets with only one inhabited island. The lagoon measures 1.4 miles (2.3 km) east to west and 3.1 miles (5.0 km) along the north-south axis. Seagrass beds are found on the lagoon shorelines of Kayangel and Ngeriungs (a small island in the southeast of the atoll), and small patch reefs are found in the other islets of the atoll chain. The lagoon of Kayangel Atoll generally has low coral cover and diversity, although 126 coral species belonging to 47 genera have been reported there. In addition, 147 species of other marine invertebrates have been accounted for.

Ngaruangel (Ngaruangl) Reef is an incipient atoll northwest of Kayangel, which is separated from it by the Ngaruangl Passage. Ngaruangel Reef is protected by the Ngaruangel Reserve. The lagoon floor is covered with thick sand deposits and thickets of staghorn coral.

Velasco Reef, in the northernmost reef area of Palau, is a sunken atoll north of Ngaruangl Reef, rising steeply from the surrounding seafloor. It is not clearly separated from Ngaruangl Reef and appears as its large but submerged northern



Kayangel Atoll

extension. Heavy wave exposure limits coral diversity and cover on Velasco Reef. The lagoon is 131-164 feet (40-50 m) deep with scattered patch reefs. Beds of the seagrass, *Thalassodendron ciliatum*, uncommon in the rest of Palau, are found in the western rim and northern tip of the lagoon.

One hundred forty-five coral species belonging to 52 genera have been reported for Ngeruangel and Velasco Reefs.

Northern Barrier Reef and Lagoon

The Northern Barrier Reef and Lagoon lies south of Kayangel Atoll and north of Babeldaob. It encompasses an area of approximately 200 km² of enclosed reefs and lagoons and is a complex system of rich marine biodiversity and fish spawning aggregations. The Northern Lagoon, which is home to only two high islands – Ngerkeklau and Ngerechur, contains numerous patch reefs, pinnacles, and reef holes. More than 107 species of macroinvertebrates have been reported from within this complex.

Deep-water channels situated along Palau's Northern Barrier Reef are spawning areas for groupers and other commercially important fishes. Ebiil Channel, only a few miles north of Ngarchelong, is one of the most important grouper spawning sites in Palau, prompting the community of Ngarchelong to make it a specially managed conservation area.

Western Babeldaob

Western Babeldaob has an extensive fringing reef that extends 118 miles (190 km) from Ngarchelong in the north to the southernmost part of Babeldaob. It is



Northern Barrier Reef of the Republic of Palau

continuous, except where a channel cuts through the entrance to Ngermeduu Bay, and is comprised of numerous partial channels, fingers, and indentations. It provides habitat for more than 200 species of corals and approximately 200 species of macroinvertebrates. Three main passes connect the western barrier reef to the open ocean. These passes are important migratory routes for many fishes and other marine organisms.

Ngermeduu Bay in western Babeldaob is the largest estuary and bay in Micronesia, containing mangroves, seagrass beds, and coral reefs. Several rivers including the Ngermeskang – the longest river in Micronesia, drain into the bay. Ngermeduu Bay is a unique area in terms of overlapping fish communities. One fish community is the rich coral reef assemblage typical of other areas in Palau and Micronesia, and the other fish community is dominated by planktivores, which are typical of islands in Indonesia. These ecosystems support a highly productive fishery for mangrove crabs, sea cucumbers, rabbitfish, snappers, groupers, surgeonfishes, jacks, parrotfishes, and many more.

The Toachel Mlengui channel, north of the Ngermeduu Bay entrance, is the most important pass connecting the open sea with the western and southern lagoon. The next pass, Sengelokl, located 53 miles (85 km) south, only offers subtidal connection between the western ocean and the southern lagoon. During 1992 Ngermeduu Bay Natural Resource Surveys, 200 species of corals, 170 species of other macroinvertebrates, and 277 species of fishes were found.

Eastern Babeldaob

In eastern Babeldaob, the reefs run from Ngos to Airai and end at Toachel El Mid, a deep east-west channel separating Babeldaob from Koror. Fringing reefs cover the entire coastline of eastern Babeldaob, while protective barrier reefs lie toward the southern part of the island. Those areas that have fringing reefs with protective barrier reefs have extensive seagrass beds and mudflats. In areas without protective barrier reefs, the inner fringing reef seagrass beds are not as extensive and sand replaces mudflats. Two hundred species of scleractinian (stony) corals have been reported from eastern Babeldaob and approximately 69 species of noncoral invertebrates. Sea squirts, sponges, sea stars, and sea cucumbers are also common on the reef flats.

Southern Barrier Reef and Lagoon

The Southern Barrier Reef and Lagoon is the largest area in Palau covering 193 square miles (500km²) from Toachel El Mid, through the pass between Babeldaob and Koror, and extending south to the island of Peleliu. It is also home to a 53.4 mile-long (86 km) barrier reef. The Southern Lagoon has a large number of small islands, including the Rock Islands, low coral islands on the barrier reefs, and raised platform islands. Palau's nine unique marine lakes are found in the interior of some Rock Islands. The Southern Lagoon also has more patch reefs than any other region of Palau.



Palau's famed "Rock Islands" are a collection of rounded, foliagecovered isles which seem to float above the surface of the water.

An incomplete channel of the Southern

Barrier Reef, Ngerumekaol is an important fish aggregation site, which has been established as a conservation area by the Palau government. According to a 1991 survey, coral cover at Ngerumekaol was 52% with very high coral diversity (90 coral species). Nearby, at Rebotel, another incomplete channel, coral cover was 50% with diversity as high as 55 species.

On the ocean side of the barrier reef, coralline algae are common with seaweed beds along the outer margins. Sand deposits and coral knolls dominate the lagoon side. The southeastern walls of the Southern Barrier Reef have coral cover around 50% (40 species), whereas ocean slopes off Ngederrak, just south of Koror, have 50% coral cover (45 species).

The isolated island group, known as Ngerukewid or Seventy Islands, in the Southern Lagoon is a protected Wildlife Preserve. These inner reefs are characterized by sand and rubble interspersed with branching *Acropora*, *Porites*, and micro-atolls. Coral cover is variable, ranging from 3–51%.

Peleliu and Angaur

Peleliu supports the largest seagrass beds in Palau. Coral cover and diversity on the reef flat terrace is low, but the reef walls are more diverse with higher coral cover. In Angaur, coral cover ranges from 50-80% along the western coast and 25-40% along the other areas of the island.



Southwest Islands

Prior to the 1998 coral bleaching event, Helen (or Helen Reef), the smallest of the remote Southwest Islands, was home to 248

Seagrass meadow in Peleliu (photo by Brad)

species of coral, making it the most diverse coral reef known to exist in Palau or in the Pacific Islands. Fanna, the third smallest island of the Southwest Islands, has the least amount of reef habitat and fewest coral species at 94.

The coral reefs of Sonsorol, the largest island in the southwest of Palau, showcase about 130 species of corals, while Merir, the second largest island, is home to 132 species. Tobi, the third largest island in the Southwest group, is surrounded by healthy fringing reefs that support 174 coral species.

Marine Biodiversity

Not only is the Palauan archipelago home to the greatest diversity of terrestrial plant and animal species in Micronesia, it also provides habitat for greater than 10,000 marine species. Situated close to the global center of biodiversity, Palau has the highest recorded levels of marine biodiversity in Micronesia, especially among corals. The archipelago is also thought to have the highest density and variety of tropical marine habitats of comparable geographic areas around the world, including the Philippines, Indonesia, and Australia, which has served to attract divers and snorkelers from all parts of the globe. While known



Staghorn coral in Palau (Photo: Jane Thomas, IAN Image Library)

endemism among Palauan marine organisms is low, many groups of organisms are not well documented; therefore, true levels of endemism in the marine environment are difficult to estimate.

Numerous marine ecosystems within Palau, including fringing, patch, and barrier coral reefs, seagrass beds, mangrove forests, and marine lakes, support about 300 species of sponges (Kelly-Borges and Valentine 1995), 185 species of sea slugs, 21 species of sea lilies, more than 100 species of sea squirts, 1,300 species of reef fishes, 350 species of stony coral, and greater than 200 species of soft coral. Palauan waters also provide habitat for endangered and threatened species such as the dugong (a relative of the manatee), saltwater crocodile, hawksbill and green turtles, and giant tridacna clams (which include seven of the world's nine giant clam species). However, of the more than 10,000 species in Palau's marine environment, only two major groups of marine organisms can be considered "well-studied": the scleractinian (stony) corals and coral reef fishes.

Palau contains extensive seagrass beds, which are comprised of 10 species of seagrasses. Seagrass beds are important nursery grounds that provide food and shelter for juvenile fishes, invertebrates, sea turtles, and dugongs. They also assist in sediment accumulation and stabilization. *Thalassia hemprichii* and *Enhalus acroides* are the most abundant and dominant species of seagrasses in Palau. They serve as the main food source for herbivorous fishes, sea turtles, and dugongs and provide habitat for rabbitfish, pipefishes, juvenile wrasses and parrotfish, and various invertebrates.

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and live reef species; ships and boat groundings; marine debris; aquatic invasive species; security training and military base activities; and offshore oil and gas exploration.

Climate Change and Coral Bleaching

Climate change over time can be driven by natural variability and human activities, working individually and in concert. In the 20th century, mean near-surface air temperature over land and mean sea surface temperature (SST) increased $0.6 \pm$ 0.2°C, with the 1990s being the warmest decade in recorded history. Elevated water temperatures cause corals to bleach, a process that is characterized by the loss of photosynthetic zooxanthellae (symbiotic algae) from coral tissues. If prolonged, corals may starve to death. Mass bleaching typically occurs when sea temperatures increase 1 - 2 degree above local seasonal maxima, although many colonies will bleach at lower temperatures. Although some



Small patch of bleached coral at a site monitored by the Palau International Coral Reef Center. (Photo: Jane Thomas, IAN Image Library)

corals may recover from brief episodes of bleaching, if ocean temperatures warm too much or remain high for an extended period, bleached corals often will die.

Prior to the 1997-1998 El Nino and subsequent coral bleaching, Palauan coral communities were in excellent condition with no signs of stress. In 1999, however, surveys found that bleaching was widespread and variable throughout Palau. Bleaching devastated *Acropora* spp., which had the highest mortality compared to other stony corals. In fact, mortality of *Acropora* spp. was virtually 100% at all depths at some locations. Corals in estuaries closer to shore survived better than corals farther from shore. Off-shore reefs saw mass mortalities of faviids, poritids, *Fungia* spp. and *Acropora* spp.

Since the 1997-1998 El Niño, Palau has not experienced any major bleaching events other than some localized bleaching in different parts of the archipelago, which may be related to human impacts. However, coral reefs throughout the archipelago are still displaying signs of stress and bleaching, which demonstrates the destructive effects that one major bleaching event can have on the recovery and resiliency of these marine ecosystems.

Coral Diseases

The increasing global prevalence of coral diseases has become one of the major stressors affecting the health and resiliency of coral reef communities. Since the early 1990s, scientists have documented a rapid emergence of coral diseases with increases in the number of diseases reported, coral species affected, geographic extent, prevalence and incidence, and rates of associated coral mortality. Diseases have played a prominent role in regulating coral population size, diversity, and demographic characteristics. Very little is known about coral diseases in terms of causative agents. Some diseases have already had widespread catastrophic effects. In the Caribbean, for example, two once-dominant *Acropora* spp., the staghorn and elkhorn corals, are now officially listed as endangered.

Little is known about coral diseases in the Indo-Pacific. Baseline information for coral diseases in Palau, first obtained in 2004, suggest that diseases are spreading in Palau. At individual study sites, initial surveys identified between five and nine diseases and syndromes, including black band disease, brown band disease, skeletal eroding band, white syndrome, patchy necrosis, yellow spot disease, other cyanobacteria-causing diseases, and various tumors.

Tropical storms

Cyclonic storms are an important process in the structure and dynamics of coral reef ecosystems. They constitute a powerful mechanism for change and can dramatically disrupt the ecosystem, associated communities, resource availability, and the physical environment. However, coral reefs have shown resilience to storm-caused disturbances. Mechanical disturbances from tropical storms can benefit a reef community by helping to maintain high species diversity, particularly when the reef substratum is scoured by a storm, which creates space for new coral recruits to settle. Massive and robust boulder-shaped corals (e.g., brain corals) are more capable of withstanding powerful wave action than those with more fragile branching structures, such as the *Acropora* spp.

Tropical storms are quite common in Palau. Corals on the outer reef slope are much more susceptible to physical damage and removal from storm surge and large waves. Therefore, many of Palau's forereefs are dominated by encrusting and massive forms of coral species. Data quantifying the effects of storms on Palau's coral reefs are currently not available.

Coastal Development and Runoff

Increased sedimentation associated with runoff from coastal development is a growing threat to coral ecosystems worldwide. In the past few decades, there has been a shift toward greater concentrations of human settlement in the coastal zones of many countries. This trend has increased stress on coral ecosystems, especially in the tropics and subtropics. Runoff from landscape altering activities, including the construction of residential developments, hotels, resorts, golf courses, marinas and other recreational facilities, piers, roads, bridges, and waste or water treatment plants have taken a tremendous toll on some close-to-shore-reef areas. Runoff can carry high levels of nutrients, microorganisms, and pollutants, such as petroleum products or pesticides, which can cause diseases in coral colonies or outright kill them. Increased nutrients and/or pollutants over a reef can enhance growth of



Mining coral rock for construction materials.

certain reef organisms, such as sponges, which can outcompete corals for space. Additionally, outflows from water treatment, waste, and other industrial plants, which can discharge extremely hot water into cooler surrounding coastal waters, may also greatly increase the local water temperature and induce bleaching or death of coral colonies. Sediment runoff from cleared areas can also settle on coral reefs and smother them, resulting in the death of dominant hard coral communities and replacement of these communities with macroalgae. In addition, spikes in sedimentation can cause increased water turbidity. This in turn reduces the amount of sunlight reaching corals and greatly diminishes photosynthetic activity of a coral's zooxanthellae, resulting in bleaching and starvation of the coral.

Recent demographic shifts and changes in permitting, construction, road building, sedimentation, and land use have resulted in increased coastal development in Palau. This has, in-turn, greatly augmented the amount of runoff from the land into the surrounding marine environment. Much of the increased coastal development is a direct result of the construction of a paved, two-lane, 53-mile (85 km) highway ("Compact Road") around Palau's main island, Babeldaob, in 2007. The Compact Road and its associated bridge connect Palau's former national capitol in Koror with its new capitol, Melekeok in Babeldaob.



Forest cleared for the construction of the Compact Road in Babeldaob (Photo: P.L. Collin/CRRF)

Moving the central government from Koror to Babeldaob led to increased mining of corals for use as construction materials, escalated development in and around Babeldaob, and subsequent runoff from the island into local waterways and the marine environment. Additionally, access roads constructed out from the paved Compact Road were unpaved, which led to an upsurge in the amount of sediment washing into surrounding waters. It is expected that as communities, new airports, and resorts spring up around Babeldaob, farming and eventually commercial agricultural production will also increase, which could lead to intensified sedimentation, nutrient runoff, and pollution coming from the island.

Coastal Pollution

It has been estimated that as much as 22% of the world's coral ecosystems are currently threatened by land-based pollution and soil erosion. Pollution affects a coral ecosystem by introducing microorganisms, excess nutrients or sediments, and toxic chemicals into the environment. These can cause either diseases and/or mortality in corals or they can depress the immunity, reproduction, or functionality of the corals, making it susceptible to other stressors such as climate change, disease, and invasive species.

The primary stressors from land-based sources of pollution are documented to be nutrients; chemicals from fertilizers, pesticides, herbicides, and sewage; and increased sedimentation from coastal development and stormwater runoff. Other noxious substances such as heavy metals and petroleum products also add to the pollution load at specific locations.

Sources of pollution may be either point source or non-point source. Point source pollution originates from specific conveyances, such as pipes, tunnels, ditches, channels, wells, and fissures. Examples include sewage outfalls; untreated wastewater from factories and other industrial plants; heated water discharge from power plants; and vessels that discharge wastes in marinas and nearshore areas or accidentally spill petroleum or other noxious chemicals and heavy metals into the water. Non-point source pollution refers to pollutants not introduced from a single, welldefined site. Non-point sources include acid rain; excess fertilizers, herbicides, and insecticides from agricultural lands and residential areas;

oil and toxic chemicals from urban runoff and energy production; sediment from improperly managed construction sites, agricultural lands, and eroding stream banks; salt from irrigation practices; and bacteria and nutrients from livestock, pet wastes, and faulty septic systems.

Major industries in coastal areas of Palau that contribute point source pollution include fishing companies and hotels. Fishing companies discharge brine, oil trash, and sewage from ships moored at their docks. Over time, the cumulated effects of small oil spills and other pollutants from fueling stations may damage nearby coral ecosystems. There are also challenges related to landfill operations, which increase the concentration of nitrates and phosphates in runoff, and a deteriorating public sewer system, in which frequent sewage overflows adversely affects water quality by contaminating the area with bacteria. Improper farming methods and unplanned road construction are also common sources of coastal pollution.

Tourism and Recreation

Healthy coral reefs support thriving tourism and recreation industries. Each year, millions of scuba divers, snorkelers, boaters, shell collectors, and fishermen visit U.S. coral reefs and nearby beaches. Local economies receive billions of dollars from visitors through diving tours, recreational fishing trips, hotels, restaurants, and other businesses based near reef ecosystems. Tourism is particularly significant in many Caribbean and Pacific islands. In the Florida Keys alone, over four million tourists purchase about \$1.2 billion in services annually. Despite their great economic and recreational value, coral reefs are severely threatened by pollution, disease, and habitat destruction. Once coral reefs are damaged, they are less able to support a rich biodiversity, losing value as a tourist destination.



A live aboard scuba diving vessel in Palau

Studies have shown that divers and snorkelers can have a significant impact on coral reefs in terms of physical damage. For example, divers and snorkelers have caused significant damage to corals along underwater "sight-seeing" trails in the U.S. Virgin Islands and other parts of the world by touching the corals, removing chunks of the reef as "souvenirs", and standing on the reefs. Other tourism-related threats that have devastated coral reefs include hotel and resort development, construction of infrastructure to support such resorts,

seafood consumption, beach replenishment activities, airport and marina construction, and cruise ship operations. The negative impacts resulting from these activities include increased sedimentation, nutrient enrichment, pollution, exploitation of endangered species, and increased litter and waste.

Palau is building a self-sustaining national economy consisting primarily of subsistence agriculture, fishing for local consumption and export, construction, and tourism. In fact, the United Nations' 2007 Statistical Yearbook for Asia and the Pacific has placed Palau as the highest tourism earning country in the Asia-Pacific region in terms of contribution to Gross Domestic Product. Currently, the main industry in Palau is tourism. The majority of tourists come to dive, snorkel, and visit the famous Rock Islands. However, a number of people also come to experience Palau's waterfalls, forests, and historical sites. From 1992-1997, the number of visitors to the archipelago doubled from nearly 30,000 to 60,000. In 1997,

however, due to several factors, including a massive El Niño bleaching event, tourism began to decline. As of 2001, though, the number of tourists in Palau has rebounded, and the industry is again booming. For example, many communities in Babeldaob have taken advantage of the opening of "Compact Road" to develop land-based tourism activities; this has substantially enhanced local tourism. In 2007, a river boat tour business also began operating throughout the archipelago opening up areas of Palau that previously were untouched to the ever-expanding tourism industry.

With increasing numbers of visitors annually and complete dependence of the economy on tourism, the potential harm to coral reefs is a major cause for concern. Therefore, many Palauans are taking action to prevent damage to their reefs. For example, locals have placed mooring buoys at known dive sites to minimize anchor and dive boat damage to the coral reefs. In addition, legislation has been enacted by the government to help mitigate harmful impacts at sensitive tourist sites such as Jellyfish Lake. The government also recently enacted legislation outlawing the collection of corals from its reefs. Diving tour operator education is also helping to diminish the negative impacts to corals and reefs from tourism and recreation.

Fishing Pressure

Recreational, subsistence, and commercial fishing on many reefs and coral ecosystems throughout the world play an important social, cultural, and economic role. NOAA's National Marine Fisheries Service (NMFS) estimates that the commercial value alone of U.S. fisheries from coral reefs is more than \$100 million. However, overfishing and destructive fishing practices caused by traps, bottom trawls (which are especially damaging to deep water coral ecosystems), anchor damage, and vessel groundings are threatening to destroy the resources and reef communities that the fishing industry relies on. Overfishing depletes a fishery by catching so many adult and juvenile fishes that not enough remain to breed and replenish the population. In addition to pollution and global climate change, overfishing is now considered one of the greatest global threats to the health and survival of coral reefs.

Approximately one-half of all federally managed fisheries depend on coral reefs and adjacent habitats for a portion of their life cycles. In addition, about 25% of all marine fishes (as well as numerous other marine organisms) are inhabitants of shallow-water coral ecosystems (including coral reefs, adjacent seagrass beds, mangrove forests, and other associated hard and soft bottom habitats) for their entire lives. It is those marine organisms that must rely on reefs and their associated shallow-water ecosystems that are at the greatest risk from exploitation and the negative impacts from overfishing and destructive fishing practices.

Fishing in Palau is a multi-species industry involving subsistence, recreational, and commercial fishers that supply fish to commercial markets, restaurants, and buyers for export. In addition to coral reef fishes and pelagic tuna and mackerels, the mangrove crab (*Scylla serrata*) and the trochus (*Trochus niloticus*) are the top commercial marine animals. Palau established the 1994 Marine Protection Act to better manage local fisheries resources. Specific management tools described in



The trochus or topshell, Trochus niloticus, is a conically-shelled

the Act include: bans on export of certain species; closed harvest seasons for rabbitfishes and groupers;size limits for certain wrasse species, humphead parrotfishes, crabs, and lobsters; mesh size limits for nets; and permit requirements for marine snail that inhabits coral reefs. The inner or nacreous layer of the shell produces valuable mother-of-pearl products, and the large muscular foot is a popular food.

aquaculture and aquarium trade operations. However, overall, there continues to be a noticeable decline in Palau's total maximum yield from several reef areas. This decline has been attributed to several factors, including the presence of large-scale pulse fishing operations, coral bleaching, habitat loss, and sedimentation from land-based activities.

Trade in Coral and Live Reef Species

Many coral reef fishes and invertebrates are collected to supply a domestic and international demand for seafood. In addition, marine organisms are also removed from reefs and coral ecosystems to serve as ornamental aquarium specimens (fishes, corals, other invertebrates, and live rock); construction materials (e.g., coral blocks); jewelry; curios (e.g., mollusk shells, coral skeletons, precious corals, dried starfishes, and lamps made from shells or porcupine fish); pharmaceuticals; traditional medicines; and other products.

Overharvesting of reef species at unsustainable levels leads to unhealthy changes in the population structure and biomass of reef species. In the absence of



A poacher illegally collecting fishes by squirting a sodium cyanide solution into a crevice in the reef.

specific predators, for example, non-target species may undergo a population explosion that alters the dynamics of the entire reef system. In addition, reductions in or the disappearance of certain herbivorous species may result in the replacement of stony coral-dominated reefs by algaldominated reefs, as algae outcompete corals for space.

Additional harm or alteration of reef communities is caused by widespread use of destructive collecting techniques, such as the illegal use of cyanide to capture live reef fish. Cyanide poisoning kills many organisms on a reef, including non-target species, and causes substantial habitat damage. Although cyanide poisoning has not been reported in the U.S., with the possible exception of limited use in some of the Freely Associated States associated with the live reef fish food trade, cyanide use to collect reef species is practiced heavily in many parts of southeastern Asia and the Indo-Pacific.

In the last few years, there has been a significant reduction in the volume of live fish, coral, and other marine organisms exported from Palau for the aquarium trade. This is due in part to the ratification of the *Regulations on the Collection of Marine Resources for Aquaria and Research* in December 2004. These regulations were developed by Palau's Ministry of Resources and Development in response to provisions cited in the 1994 Marine Protection Act, which required the Ministry to develop



A lamp made from a sea urchin

regulations "regarding the taking and export of fish for aquarium purposes". Many Palauans had expressed concerns about the negative impacts associated with an aquarium fishery in the archipelago. For example, the aquarium fishery was viewed

by local fishermen as unnecessary competition from foreigners for food resources, and divers and snorkelers saw it as a destructive practice, which devalued coral reefs and destroyed reef communities needed to support the tourism industry.

Invasive species

The stability of an ecosystem may be threatened by the accidental or purposeful introduction of non-indigenous species, also called "invasive" or "alien" species. An invasive species is a species outside of its native or historical habitat. For various reasons, including the absence of natural enemies, invasive species may grow and reproduce at the expense of native species occupying the same habitat or habitat type. In some cases, the invasive organisms are successful predators which can decimate local or native populations; for example, the brown tree snake in Guam (an accidental introduction) or the mongoose in the islands of the Caribbean (a purposeful introduction). Invasives may outcompete native species occupying the same ecological niche or even worse may cause major changes in the dynamics of an ecosystem, resulting in the extinction of another species.

Invasive organisms can spread rapidly in the open ocean and are very difficult to control or eradicate. Currents may act as dispersal highways between habitats. Many invasive organisms are also carried in the ballast water of vessels or attached to their hulls. Some were aquarium pets which were released into local marine waters or escaped specimens from an aquaculture operation. Quite frequently, scientists are not aware when new invasive species arrive in a new habitat. However, some are visibly noticeable such as the Pacific lionfish *(Pterois volitans)* in warm Atlantic coastal waters.

Invasive species are one of the greatest threats to island biodiversity. In Palau, invasive species of all types threaten local flora and fauna and their associated ecosystems, which in-turn threatens Palau's economy, human health, agriculture, and even the traditional way of life. Terrestrial invasive species, such as macaque monkeys (*Macaca fascicularis*), cause harm as predators on native animals or their eggs, while other invasives, including parrots and



cockatoos, destroy native plant populations.
Certain invasive species such as pigeons,
rats, and mosquitoes carry diseases, while
others are noisy pests, such as the
Caribbean coqui (a tree frog) or parrots and their relatives.The invasive hydroid species,
Eudendrium carneum.
(University of Sao Paulo)

In some cases, a native species can become invasive when environmental conditions change. An example of this is the vigorous and fast-growing vine known as "kebeas" (*Merremia peltata*). Kebeas naturally grows in forest clearings and was not a problem prior to substantial increases in development, road-building, and land-clearing. Currently, there are numerous opportunities for kebeas to proliferate and expand, threatening forests and communities all over the islands of Koror and Babeldaob.

In addition to kebeas, terrestrial invasive species of greatest concern include the crab-eating macaque monkey; wild pigs; rats; mice; *Imperata cylindrica* (a species of quite flammable grass); *Chromolaena odorata*, which is a native North American shrub but an invasive weed in Palau and other parts of Asia; the coral bean tree or red sandalwood tree (*Adenanthera pavonina*); the African freshwater cichlid fish; and tilapia (*Oreochromis mossambicus*), which was introduced for aquaculture. The tilapia has escaped captivity and proliferated excessively, becoming an invasive species throughout the archipelago.

Although several marine invasive species have been identified in Palau, according to the 2008 version of *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States*, it appears that these invasives are not having a quantifiable effect on Palauan fisheries or the marine tourism industry; however, they do have the potential to become a serious problem. Most marine invasive species in Palau belong to a small group of invertebrates that were most likely introduced as fouling organisms on ship's hulls or from ballast water pumped out in harbors. These include sea squirts, hydroids and other cnidarians, mollusks, sponges, and bryozoans.

Presently, only one marine invasive species, the hydroid, *Eudendrium carneum*, is threatening to become a "pest" organism in Palau. It is a rapidly growing species and has been found on rocky bottoms, often forming intertwined tangles of branches that trap sediments and interfere with the feeding of grazers, such as parrotfishes and surgeonfishes, which scrape algae from rock surfaces, and the settlement of invertebrate larvae.

Of note, there are three known invasive species in Palau's famous Jellyfish Lake: an anemone in the genus *Aiptasia* (glass anemone); its endosymbiotic strain of dinoflagellate algae (zooxanthellae) belonging to the genus *Symbiodinium*; and a sponge of the genus *Haliclona*. The glass anemone appears to establish itself on any suitable hard substrate, which makes it a formidable competitor for space and a potential threat to benthic biodiversity.

Ships, Boats, and Groundings

Vessel groundings and impacts from boat anchors cause substantial and visible physical damage to coral reefs. More than 2,000 grounding accidents and 400 sunken vessels are reported annually. As recreational and commercial boating traffic increases in and around coral reefs, the grounding and sinking of ships poses great hazards to these ecosystems both immediately and for the long-term.

Even after a vessel is grounded or sunk, it may continue to move because

of currents, wave action, and high winds, causing additional, significant reef damage. Diverse fish assemblages damaged by grounded ships may not recover, especially on a reef that has a spur and groove configuration. Pollutants, such as oil and other chemical contaminants, may be released as a result of the impact from a grounding or sinking. Loose chunks of coral rubble knocked free on impact may threaten adjacent undisturbed coral habitat. In addition, contamination by components of antifouling paints, which are used to reduce the growth of aquatic organisms on ship's hulls, can significantly reduce coral recruitment in the area of the grounding and may hinder recovery of the community.

The dropping and dragging of large anchors, particularly from cruise ships, destroys large areas of reef habitat. Designation of anchorages in less sensitive areas, installation of mooring buoys, and identification of areas sensitive to anchor damage are necessary to reduce the destructive practice of unregulated anchor dropping and dragging.

Four major ship groundings occurred in Palau since 2005. One – a military vessel – caused such severe damage to the affected coral reef that the ecosystem has not shown signs of recovery. Not only was the reef physically damaged by the crushing impact, but thermal discharges from the ship's energy sources (generators, engines) led to bleaching and subsequent death of corals, especially *Acropora* spp., and antifouling paint, scraped from the hull, inhibited growth and reestablishment of many reef organisms.

Marine Debris

Marine debris presents a serious and continuous worldwide threat to the marine environment. Debris adversely impacts marine life through the destruction of essential habitat as well as entanglement of and ingestion by marine organisms and seabirds. The majority of marine debris comes from land-based sources, particularly urban centers, but a significant proportion also comes from ships. Typical debris collected from beaches and other shorelines includes beverage cans and bottles, styrofoam containers, cigarettes, disposable lighters, plastic utensils, food wrappers, and fishing line. The most notable impacts of marine debris on coral ecosystems come from derelict fishing gear such as nets, fishing line, and traps. Netting and fishing line can roll across reef habitats, crushing corals and dislodging sessile organisms. Additionally, fishing gear frequently becomes snagged on corals and continues to trap ("ghost fishing") fishes, seals, and sea turtles, resulting typically in their death.

Marine debris is commonly found in Palau, particularly on beaches around the islands, and fishing lines and nets are sighted frequently in surrounding waters. However, impacts of this debris on nesting bird and turtle populations are not known. Palau recently initiated a marine debris prevention and removal program to reduce and remove debris from the shores and coral reefs. This project is designed to improve the island's marine habitats and associated resources and educate local fisherman about sustainable solutions to pollution and recycling issues. In addition, the Koror State Government has a regular cleanup program around the Rock Islands to collect marine debris, as currents bring debris originating outside of Palau to the atolls of Ngeruangel and Helen Reef.

Security Training Activities

Military bases and associated activities including exercises, training, and operational procedures (i.e., construction, dredging, and sewage

discharge) have the potential for adverse ecological impacts on coral reefs, including excessive noise, explosives and munitions disposal, oil and fuel spillage, wreckage and debris, breakage of reef structure, and invasive species introductions from ship bilge water or aircraft cargo. Currently, there are no security training activities being conducted in Palau; however, the long-reaching activities of U.S. military installations in Hawaii, Johnston Atoll, Wake Atoll, Kwajelein Atoll, Guam, and the Commonwealth of the Northern Mariana Islands have the potential to negatively impact reefs and coral ecosystems of Palau.

Offshore Oil and Gas Exploration

The release of oil and other noxious petroleum products into the marine environment can have serious consequences for reef ecosystems, such as smothering and causing the death of marine fauna or by inhibiting coral growth and recruitment. Cleanup of a coral reef following an oil spill is exceptionally difficult, and certain studies suggest that it may be most productive to let natural processes, including a combination of wind, solar radiation, currents, waves, and degradation by microorganisms, disperse and evaporate the oil. It should be noted, however that recovery of a coral ecosystem from an oil spill can require decades, in which time potentially substantial damage may have been done to the affected reef and surrounding ecosystems for hundreds of miles.

The processes of locating, recovering, transferring, and transporting petroleum resources also have the potential to have serious negative effects on coral ecosystems, especially those that are located in threatened areas. Initially, seismic surveys involving very loud sound (pressure) waves are sent into the sub-bottom rock layers to study their geological structure. Once oil and gas reserves are located, production requires platform installation, dredging, drilling, the discharge of wastes and drill cuttings, and polluted air emissions. These impacts, in addition to the physical effects related to the movement of ships and equipment, can all present significant threats to the organisms and environments where these activities occur.

Although there has not yet been any oil extraction in Palau, there has been interest from the private sector in exploring the northern Velasco Reef, a sunken atoll north of Ngaruangel Reef. Consequently, the Palau government recently passed a resolution that supported an agreement between the Kayangel State and Palau Pacific Energy Inc. (PPE) that gave the oil company exclusive rights to conduct exploration, drilling, and production operations for petroleum during the terms of the exploration license.

Ocean Acidification

Ocean acidification is the term given to the ongoing increase in acidity of the oceans, caused by their uptake of anthropogenic atmospheric carbon dioxide (CO^2). Dissolved CO^2 in seawater increases ocean acidity by elevating the hydrogen ion (H^+) concentration in the ocean. There is a relationship between ocean acidification and corals' ability to build their calcium carbonate ($CaCO^3$) skeletons. As the acidity of the oceans increases, many reef community inhabitants grow at slower rates. This is because higher CO^2 levels in the ocean also reduce carbonate ion availability, which is critical for corals to build their skeletons.

The increase in acidity has numerous negative consequences for other

marine calcifying organisms such as coccolithophores, foraminiferans, echinoderms, crustaceans, and mollusks. These, like corals, use the calcite or aragonite forms of calcium carbonate to construct calcareous coverings and skeletons. Should atmospheric CO² reach levels 25% higher than present day, which certain studies have forecasted, some coral reefs may no longer grow fast enough to keep up with natural forces of erosion and dissolution. Stressed by warming surface temperatures, bleaching, sedimentation, predation, pathogens, pollution, overfishing, etc., the world's coral reefs and coral ecosystems may soon face their ultimate threat in rising ocean acidity.

Currently, no information is available on ocean acidification and Palau's coral reefs.

Other Threats

The Crown-of-Thorns Starfish (*Acanthaster* spp),also known as COTS, is a large voracious predator of coral reefs throughout the Indo-Pacific. It feeds on polyps of several stony coral species. In moderate numbers, COTS plays an important role in maintaining high biodiversity on a reef by keeping fast-growing corals from overwhelming slower growing corals. However, COTS also experiences periodic population explosions and has been blamed for widespread reef destruction, particularly on Australia's Great Barrier Reef.

Damage to coral reefs due to outbreaks of other echinoderms, such as spiny cold water starfishes, which feed on deep-water coral polyps, and sea urchins, also occurs globally. Sea urchins can erode the coral substratum, remove newly settled corals, and intensely feed on the corals (corallivory), greatly diminishing the population.

Other coral reef species such as parrotfish, butterflyfish, blennies, puffers, damselfish, and marine snails (*Drupella*) also feed on corals. Most native coral predators do not pose any major threats to reefs. However,



The Crown-of-thorns starfish is a voracious predator of coral reefs.

explosions of any corallivore population can have disastrous effects on the growth and survival of a reef.

Additional stressors that have been shown to destabilize and disrupt the dynamics of coral ecosystems include cable-laying operations, which scour the sea floor with untethered cables, earthquakes, and volcanic eruptions.

Multiple stressors, acting sequentially and/or synergistically can be extremely harmful to coral reef ecosystems. In many parts of the Caribbean, for example, the effects of several stressors, such as pollution, decline of key herbivores, severe tropical storms, and coral bleaching have likely led to observed shifts in community structure from coral-dominated to macroalgal-dominated reefs. In general, the effects of multiple stressors are poorly understood, making it difficult to discern the cause of local or regional coral decline.

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NOAA CoRIS - Ecosystem Essays: The Republic of Palau (Belau) - Status of Coral Reef Ecosystems



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Status and Health of the Coral Reef Ecosystems of Palau

Overall, especially when compared to other coral reefs of the world, Palau's reefs are in pretty good shape. They showed respectable resiliency and recovery in the aftermath of the significant 1997-1998 bleaching event, whereas in some areas of the world, coral mortality was as high as 90%. Mean live coral cover across 22 monitoring sites in 2004 was 31%. More recent surveys showed continuing recovery and increased coral cover at all sites (Wilkinson 2008). Water quality is also promising in Palau, coral diseases have a low prevalence, and storms and climate change do not appear to be



Sea squirts growing on a healthy coral reef in Palau (Photo: Jane Thomas, IAN Image Library)

great threats. Major areas of concern, however, are coastal development and runoff, pollution, certain agricultural practices, and non-sustainable fishery exploitation.

Positive actions by the Palau government and its conservation partners to protect reef resources by applying ecosystem management approaches that include integrated watershed management have shown great promise for the long-term protection of coral ecosystems and associated habitats. Various governmental and non-governmental organizations (NGOs) have conducted research and monitoring surveys to aid in the management of coral reefs and have put into place a variety of management tools to address issues such as recreational use, fishing pressures, and land-based sources of sedimentation and industrial and domestic pollution. Marine Protected Areas (MPAs) now cover more than 40% of Palau's nearshore marine environments. Community-based ecosystem management holds great promise for resource protection.

In 2006, the leaders of the Micronesian governments of the Republic of Palau, the Federated States of Micronesia, the Republic of the Marshall Islands, Guam, and the Commonwealth of the Northern Mariana Islands launched the Micronesia Challenge, which is a shared commitment to "effectively conserve at least 30 percent of the nearshore marine and 20 percent of the forest resources across Micronesia by 2020."

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Guam (Guahan)

Introduction

Guam, a volcanic island completely surrounded by a coralline limestone plateau, is a U.S. territory located in the southernmost part of the Mariana Archipelago. It is the largest island in Micronesia and lies relatively close to the Indo-Pacific center of coral reefs. A variety of reef types are represented on Guam, including fringing reefs, patch reefs, submerged reefs, offshore banks, and barrier reefs. Fringing reefs are the predominant reef type, extending around much of the island. Guam possesses one of the most species-rich marine ecosystems among U.S. jurisdictions. More than 5,100 marine species have been identified from Guam's coastal waters, including over 1,000 nearshore fish species and 300 species of stony corals.

The health of Guam's coral reefs varies considerably around the island and depends upon a variety of factors including geology, human population density, level of coastal development, level and types of marine resource usage, oceanic circulation patterns, coral predator outbreaks, and natural stressors such as cyclonic storms and earthquakes. Similar to the decline in health of reefs across the Indo-Pacific, the vitality of many of Guam's reefs has declined over the past 40 years. Introduction

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Geography

Location and Physical Geography

The Pacific island of Guam, the southernmost island in the Mariana Archipelago, is a U.S. unincorporated territory located at 13° 28'N, 144° 45'E. It is 1,500 miles (2,414 km) south of Japan, 3,800 miles (6,116 km) west of the main Hawaiian Islands, and 900 miles (1,448 km) north of the Equator. Guam is the largest and most populated island in Micronesia with an estimated population of 173,500 (2007 census). It has a land mass of 216 square miles (560 km^2), excluding coral reef formations, and a maximum elevation of approximately 1,329 feet (405 meters). The island is approximately 30 miles (51 km) long and 9 miles (15 km) wide, narrowing to 4 miles (7 km) at the center. Guam is the westernmost U.S. territory, west of the International Dateline, and is one day ahead of the U.S.

Guam is a volcanic island formed by the

union of two volcanoes. It is the peak of a submerged mountain rising 37,820 feet (11,528 meters) above the floor of the Marianas Trench, which has the greatest ocean depth in the world at 36,201 feet (11,033 meters) or 6.79 miles in the Challenger Deep. The majority of the island is surrounded by a coral table reef with deep water channels. The coral reefs are well developed with reef flats as wide as 1,969 feet (600 meters). Coastline areas are characterized by sandy beaches, rocky cliffs, and mangrove forests.

The northern half of Guam is a relatively flat, uplifted coralline limestone plateau, sloping gently westward, with steep coastal cliffs and narrow coastal plains. It is overgrown with tangan-tangan (*Leucaena leucocephala*), a scrawny tree planted on Guam after World War II to cover the denuded land and prevent erosion of the exposed soil. Northern Guam is the site of the island's principal aquifer. There are low-rising hills in the center and mountains in the south. This topography has numerous watersheds drained by 96 streams.

Southern Guam is made up of rolling volcanic hills and mountains, where

<image><image>

A satellite photograph of Guam

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high waterfalls cut through the landscape. Mount Lam Lam in the south rises to a maximum elevation of 1,334 feet (407 meters) above sea level. Measured from its base at the bottom of the Marianas Trench to its top, it may be the highest mountain on Earth at approximately 37,200 feet (11,339 meters).

Major Features Map of Guam



Map of Guam (Image: NOAA/Ken Buja)



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Climate

The weather on Guam is warm throughout the year with less humidity from November through March. The mean annual air temperature at sea level is about 82° F (27.2° C) with monthly means ranging from 80° F (26.7° C) in January to a little over 82° F (28° C) in June. The temperature rarely exceeds 90° F (32.2° C) during the day or falls below 70° F (21.1° C) at night. Guam's climate is characterized by two distinct seasons: a dry season from January to May and a rainy season from July to November. The mean annual rainfall varies from about 80 (203cm) inches in the central and coastal lowlands to 110 inches (279 cm) on the uplands in southern Guam. However, a wide variation in rainfall can occur from year to year.

The easterly trade winds, usually between 10 and 15 miles per hour (mph), are dominant throughout the year. Winds exceed 24 mph only during major tropical

storms. Small scale storms, or squalls, can occur at any time and with little notice. The likelihood of major tropical storms (typhoons) is greatest during July through September, but they can occur during any month of the year.



The weather on Guam is warm throughout the year. The temperature rarely exceeds 90° F (32.2° C) during the day or falls below 70° F (21.1° C) at night. Introduction

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People of Guam

The original inhabitants of Guam, the Chamorus (or Chamorros), are believed to have been of Indo-Malaya descent and have emigrated from southeastern Asia as early as 2,000 B.C. Through linguistic, archeological, and historical study, researchers have discovered that ancient and present day Chamorus are similar in that they both encompass the languages and cultures of Malaysia, Indonesia, and the Philippines. The present day Chamorus also are a rich mixture of many cultural and ethnic groups originating from Asia, Europe, Pacific Islands, and the Americas, making



Chamorro boys dressed in traditional Cultural wear for a native dance (Photo courtesy of Guampedia)

Guam a cosmopolitan community with many customs and traditions.



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History of Guam

The first known contact between Guam and the Western world occurred on March 6, 1521, when the Portuguese explorer, Ferdinand Magellan, in the employ of Spain, anchored his fleet of three remaining ships in Umatac Bay. Magellan called Guam the "Island of Lateen Sails" because they saw many boats with triangular lateen sails. They renamed it (and the Marianas islands in general), *Islas de los Ladrones* (Island of Thieves) because some of the fleet's small boats were stolen by the Chamorus. Guam and the other Mariana Islands were formally claimed by Miguel Lopez de Legazpi, on behalf of the Spanish crown, in 1565. In 1668, Jesuit missionaries arrived to establish their European civilization, Christianity, and trade. The Spanish taught the Chamorus to cultivate corn and raise cattle. The Catholic Church became the focal point for village activities, and Guam became a regular port-of-call for Spanish vessels crossing the Pacific Ocean between Mexico and the Philippines.

Guam remained under Spanish rule until it was ceded to the United States in 1898 after the Treaty of Paris ended the Spanish -American War. It was formally purchased from Spain for \$20 million in 1899. Guam surrendered to Japanese military forces on December 10, 1941 and was subjected to a brutal occupation administered by the Japanese military until 1944, when it was reclaimed by U.S. forces.

In 1949, U.S. President Harry S. Truman signed the Guam Organic Act of 1950, making Guam an unincorporated territory of the United States with limited self-governing authority and granting American Citizenship to the people. Guam remains a strategic western Pacific outpost for the U.S. military. In 1962, security clearance requirements for travel to Guam that had been in place since World War II were lifted, thereby permitting Guam's economy to flourish and develop a to



The U.S. Military liberated Guam from Japanese occupation in 1944

Guam's economy to flourish and develop a tourist industry that increased U.S. Federal government spending.

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Terrestrial Fauna of Guam

Guam never supported a rich terrestrial vertebrate fauna. Of the limited number of vertebrates which once occurred there, many species were extirpated by the introduction of the invasive brown tree snake (*Boiga irregularis*) shortly after World War II. The brown tree snake was transported to Guam from its native range in Indonesia, Papua New Guinea, Australia, and northwestern Melanesia, probably as a stowaway in ship cargo. The snake, which is a member of the family Colubridae, possesses grooved fangs in the rear portion of its mouth, along which mildly neurotoxic



The brown tree snake is responsible for extensive economic and ecological damage. (Photo: U.S. Fish and Wildlife Service)

venom is directed when the snake bites its prey. It is aggressive if threatened but does not pose a health hazard for adult humans. Infants and small children, however, may experience severe medical consequences if bitten.

Due to an abundance of prey species and lack of major predators, the brown tree snake's population exploded shortly after being introduced to approximate densities of nearly 13,000 per square mile. Not only does the snake inhabit grasslands, heavily forested areas, and sparsely forested areas, caves, and cliffs, but it also has invaded residential areas, resulting in the loss of poultry, pets, and caged birds.



The Micronesian kingfisher

of the island.

Overall, the brown tree snake is responsible for extensive economic and ecological damage in Guam. Of 10 of 12 native bird species, 10 native lizards, and two native bats (flying foxes) now extinct, all but four of the bird species (which vanished due to habitat loss and alteration), were exterminated by the brown tree snake. With the loss of most seed-eating birds on the island, Guam's forest ecology has undergone substantial change. It has been suggested that these changes may ultimately increase the severity of bush fires, already a major problem, and increase run-off from storm-caused erosion, which adversely affects delicate coral ecosystems

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Aside from the brown tree snake, Guam is home to a number of native lizards (skinks, geckos, and monitor lizards) and introduced anoles, skinks, and geckos - all of which are preyed upon by the brown tree snake. (Interestingly, the eggs and young of the monitor lizards are preved upon by the brown tree snake, but the adult monitors prey upon the snakes themselves, though not in high enough numbers to significantly reduce the brown tree snake population.) Additionally, the Spaniards introduced dogs, cats, chickens, pigs, the Philippine deer, and the Asiatic water buffalo (carabao) to the island. Other introduced species include the marine toad (Bufo marinus), the giant African land snail (Achatina sp.), and a species of frog, which not only is a noisy pest, but also is prey for the brown tree snake. A damaging pest of coconut palms, the coconut rhinoceros beetle (Oryctes *rhinoceros*), also was detected on Guam as recently as 2007.



The Guam fruit bat

Guam's forest ecology has also been altered substantially as a result of the damage to the indigenous flora during World War II, subsequent introduction of the tangan tangan tree and other non-native flora, and arson by poachers. Flourishing grasslands and barren areas have also replaced previously forested areas, leading to greater erosion and siltation in coral reef areas. Besides loss of the pollinating and seed-dispersing birds and bats, Guam's forests are also threatened by grazing feral carabao (water buffalo), wild pigs, and Asian deer, all of which cause extensive damage to trees.

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Guam's Coral Reefs

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<u>Coral Reef Area</u> <u>Mangroves</u> <u>Seagrasses</u> <u>Biodiversity</u> <u>Crown-of-thorns Starfish</u> <u>Fisheries</u>

The inshore coastal waters around Guam are characterized by a variety of interrelated habitats including coral reefs, seagrass beds, mangrove forests, and lagoons. Fringing reefs, the predominant type of coral reef, extend around most of the island, but there are also patch reefs, submerged reefs, barrier reefs, and offshore banks. There are two barrier reef lagoons on Guam: Cocos Lagoon on the southern tip and Apra Harbor on the west coast.



Polyps of a soft coral in Apra Harbor (Photo: D. Burdick)

Coral Reef Area

Recent estimates for the combined area of coral reef and lagoon is approximately 42 square miles (108 km^2) in nearshore waters (within three nautical miles from shore) at depths between 0-18 feet (0-5.5 meters) and an additional 42.5 square miles (110 km^2) in federal waters at a distance greater than three nautical miles offshore. NOAA scientists estimate that of the 105 square miles (273 km^2) of potential coral reef habitat up to a depth of 600 feet (183 meters) within the Exclusive Economic Zone (including offshore banks), 78 square miles (203 km^2) of reef are directly associated with the island of Guam. There are also welldeveloped lagoons, the best-known of which are Cocos Island Lagoon, Ipan Beach Lagoon, the Ylig River Estuary, and Tumon Bay (Blue Lagoon).

Mangroves

Mangrove forests are poorly represented on Guam and are now restricted to two coastal areas. Much of the original mangrove forest was destroyed by dredging years ago. Where they do occur, only a few of the typical western Pacific mangrove species are represented. Among these are: Introduction

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Avicennia marina var. alba, Bruguiera gymnorrhiza, Heritiera littoralis, Hibiscus tiliaceus, Lumnitzera littorea, Nypa fruticans, Rhizophora mucronata, and Xylocarpus moluccensis. Apra Harbor has the largest and most developed mangrove forest in Guam, as well as in the entire Mariana Archipelago. Achang Bay is the only sizeable area of mangrove forest in the southern tip of Guam.

Seagrasses

Only three species of seagrasses occur in Guam waters: *Enhalus acoroides*, *Halophila minor*, and *Halodule uninervis*. The largest species, *Enhalus acoroides*, inhabits the sandy-silt areas near the mouths of rivers in the southern half of Guam. *Halodule uninervis* is abundant in Cocos Lagoon; a few patches can also be found on the shallow sandy reef flats near shore in the southern bays. *Halophila minor* can be found in shallow sandy reef flats and deeper lagoon environments.

Biodiversity

Guam is located close to the Indo-Pacific center of coral reef biodiversity and has a species-rich marine ecosystem. Over 5,100 species of marine organisms have been identified from Guam's coastal waters, including more than 1,000 species of fishes and near 500 species of hard corals. Major threats to Guam's biodiversity include illegal fires, harmful water recreation practices, and land-based sources of pollution from adjacent watersheds.

Guam is home to more than 300 species of marine macroalgae, approximately 400 known species of hard corals, 77 species of soft corals, 128 sponges, 295 species of Foraminifera, 53 flatworm species, 1,673 mollusks, 104 marine polychaete worms, 840 arthropods, 194 echinoderms, 117 species of sea squirts (Ascidiacea), three sea turtles, and 13 species of marine mammals. Nearly 100 families of fishes, containing more than 880 species, occur on Guam's coral reefs, half of which are contained within 10 families. These include the gobies (Gobiidae), wrasses (Labridae), damselfish (Pomacentridae), snappers (Lutjanidae), blennies (Blenniidae), cardinalfish (Apogonidae), butterflyfish (Chaetodontidae), surgeonfish (Acanthuridae), moray eels (Muraenidae), and pipefish (Syngnathidae). The species-rich area of the southern Marianas contains more than 1,000 species of epipelagic and demersal fishes to 656 feet (200 meters).

Three of the seven species of the world's marine turtles have been reported from the coral reefs of the Mariana Archipelago: the green turtle (*Chelonia mydas*), hawksbill turtle (*Eretmochelys imbricate*), and leatherback turtle (*Dermochelys coriacea*). Harvesting of sea turtles for food was legal on Guam until 1976, when numbers were so low that the government chose to ban fishing of turtles. Yet, even with a ban in place, poaching remains a significant problem in Guam and continues to contribute to the decline of turtle populations in this region.



The Guam green sea turtle. (Photo: David Burdick)

Crown-of-thorns Starfish

Macroinvertebrate surveys (towed divers' field observations of invertebrates that can be seen without the aid of a microscope) in 2005 and 2007 revealed that macroinvertebrates, with the exception of sea urchins and crown-of-thorns starfishes (COTS), were in relatively low abundance around Guam's coral reefs. The current abundance of COTS (Acanthaster planci) in Guam is a direct result of the outbreak of tens of thousands of COTS in the late 1960s and early 70s. This outbreak devastated corals in the northwest guarter of Guam. Live coral cover in some areas was reduced from 50-60% to less than one percent. Most corals recovered to some degree (>60%) by the early 1980s. However, continued coral resiliency has been affected by ongoing



Raccoon butterflyfish (Chaetodon lunula) at Gun Beach, in the Tumon Bay Marine Preserve, Guam (Photo: David Burdick)

degradation of water quality, low abundance of target fish species, additional COTS outbreaks, and reduced rates of coral recruitment.

Fisheries

Of the fisheries catch in the coastal waters, crustaceans make up a large portion of non-finfish catch. There are several hundred species of crustaceans on Guam's coral reefs, but only about nine species of crab are targeted, including land and marine crabs. *Carpilius maculatus* (the "7-11 crab") and *Etisus splendidus* (the splendid pebble crab) are well fished. Spiny lobsters (*Panulirus pencillatus* and other species) and slipper lobsters (*Scyllarides squamosus* and *Parribacus antarcticus*) catches are also highly prized. Mantis shrimp and freshwater shrimp (*Macrobrachium rosenbergii*) are also harvested.

Echinoderms harvested include two species of sea urchins, the priest-hat urchin or hairy pincushion urchin (*Tripneustes gratilla*) and the Rock boring or math sea urchin (*Echinometra mathaei*), as well as two species of sea cucumbers, the warty Selenka's sea cucumber (*Stichopus horrens*) and the black sea cucumber or lolly fish(*Holothuria atra*). The introduced marine gastropod, Trochus or top shell (*Trochus niloticus*), is one of the larger edible shellfish that can be found on Guam's fringing reefs and reef flats. Species of octopus, including the common reef octopus (*Octopus cyanea*) and the Hawaiian night octopus (*Octopus ornatus*) are also popular mollusk food items.

Shore-based finfish harvesting is by cast nets, surround nets, spearfishing, hook and line, hooks and gaffs, and gill netting. The principal fishes caught by these methods are surgeonfishes, jacks, rabbitfishes, goatfishes, snappers, emperors, and rudderfshes. Boat-based fishing adds barracudas and mackerels to this list.

According to *The State of Coral Reef Ecosystems of Guam* (Burdick *et al.* 2008), fish abundance and diversity is generally low in Guam's inshore waters. Species diversity and abundance are higher around the northern and eastern shores where the reefs are more rugose and live coral cover is greater, providing additional available habitat for colonization by benthic sessile organisms and shelter and foraging area for mobile organisms.

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The splendid pebble crab, Etisus splendidus (Photo: University of Florida)



The 7-11 crab (Carpilius maculatus) possesses a very distinctive color pattern - light brown with a few large red spots. (Photo: Dr. Dwayne Meadows, NOAA/NMFS)

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Marine Protected Areas

Federal Marine Protected Areas

In 1993, the Federal government established the Guam National Wildlife Refuge at the northern tip of the island to help endangered and threatened species populations recover, protect habitat, control non-native species - with emphasis on the brown tree snake, protect cultural resources, and provide recreational and educational opportunities to the public. The Refuge includes the Ritidian Unit in northern Guam and two overlay units: Anderson Air Force Base in northern Guam and the Navy Unit. The refuge is composed of 771 acres, of which approximately 400 are coral reef areas and deep water habitats backed by 321 acres of high limestone cliffs and limestone forests. The refuge at Ritidian Point was one of the last areas on Guam to lose native forest birds to the brown tree snake but has retained nesting green sea turtles and foraging fruit bats.



Ecologically protected areas of Guam (Image: NOAA/Ken Buja) (Click on the map for large view)

The Ritidian Unit includes a densely vegetated coastal plain bounded on one side by limestone cliffs reaching approximately 200 feet (61 meters) above sea level. Native vegetation on the Unit includes coastal strand, backstrand, and limestone forest communities, a sandy beach, and nearshore marine habitats to depths of 98 feet (30 meters). The coastal waters of the Ritidian Unit feature sandy areas, platform reefs, and coral habitats that support a diversity of fishes, invertebrates, and algae. These also provide foraging habitat for the endangered hawksbill and green sea turtles.

Other federally protected areas include the Haputo Ecological Reserve Area on the northwest coast, the Orote Point Ecological Reserve on the southern coast of the Orote Peninsula, the War in the Pacific National Historic Park -Agat Unit on the west coast of Guam (bordering the village of Agat, south of the Orote Peninsula), and the War in the Pacific National Historic Park -Asan Unit on the west coast of Guam (bordering the village of Asan). Broad coral reef formations, up to 1,500 feet (457 meters) wide parallel the shorelines of both units and provide habitat to a wide variety of marine life. Water depths inside the reefs vary from 1-4 feet (0.3-1.2 meters). Introduction

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During low tide, some of the reef is exposed.

Territory Marine Protected Areas

In 1997, Guam's territorial government established five marine preserves to restore Guam's fisheries resources. The function of the preserves was later expanded to include the protection and preservation of aquatic life, habitat, and marine communities and ecosystems. Protection of resources within the preserves was strengthened by making all forms of fishing and the taking or altering of aquatic life or any other resources unlawful unless specifically permitted by the Guam Division of Aquatic and Wildlife Resources (DAWR). Guam DAWR is responsible for management of and enforcement within the preserves.

The preserves vary in size from 1.2-7.7 square miles (3-20 km²) and protect a variety of habitats from 33 feet (10 meters) above mean high tide to the 600 feet (183 meters) depth contour, including a mangrove area in Sasa Bay.

The Achang Reef Flat Marine Preserve is located in the southern tip of the island. It consists of inner and outer reef flats, which are exposed at low tide and are separated by a depressed middle-reef flat and a lowtide moat. Mangroves and seagrass beds are also present on the site.

Pati Point Marine Preserve is located on Anderson Air Force Base (AFB), along the perimeter of the AFB property, in northeastern Guam. It contains a diversity of habitats, with seagrasses and shallow and



Guam's marine preserves: Pati Point (PP); Tumon Bay (T); Piti Bomb Holes (PB); Sasa Bay (S); and Achang Reef Flat (A). (Image courtesy of Guampedia)

deeper water coral ecosystems predominating, and is rich in coastal fish species. The outer reef has a very diverse coral fauna, with more than 45 species living within a 656 feet (200 meters) transect.

Piti Bomb Holes Marine Preserve is located in Piti Bay on the west coast of Guam, just north of Apra Harbor. It is a shallow lagoon complex that resembles a barrier reef system. Fringing reefs surrounding Piti Bay keep the water very calm. The Piti Bay habitat is unique in Guam and one of the most diverse in all of Micronesia. Within the preserve, percolation pits are found at depths of about 25 feet (7.6 meters) where freshwater enters the reef flat. Several underwater canyons, white sand-filled depressions, and healthy hard coral colonies can be seen starting in 6 feet (1.8 meters) of water. There are sea-grass beds in shallow water that provide habitat for juvenile fishes. Colonies of soft corals and sea anemones can be observed at depths as shallow as 3-4 feet (0.9-1.22 meters). Sea turtles and marine mammals are also found within the shallows of the preserve.

Piti Bay is famous for its "bomb-holes", which are sinkholes created by collapsed caves. These holes have filled with seawater and sand over time and have become populated by fishes, corals, and other marine invertebrates. The largest sinkhole, Piti Bomb-Hole, is a very popular dive and snorkeling spot home to about 200 species of fishes and a variety of marine invertebrates.

The Sasa Bay Marine Preserve is located in Piti Bay and contains a mangrove swamp that skirts the coastline in a narrow band. Sasa Bay is a Hawksbill Turtle foraging area and provides habitat for a number of oyster and clam species. Four to five strings of patch reef also can be found within the deeper waters of the embayment.



Jacks in Piti Bay (Photo: Lets Dive Guam.com)

Tumon Bay Marine Preserve is a two-milelong, 1,450 feet-wide (442 meters), arc-

shaped reef platform stretching from Ypao Point in the southwest of Guam to Gun Point in the northeast. Many hotels, restaurants, and bars are situated along Tumon Bay's beach, which is a popular site for swimming, wind-surfing, snorkeling, kayaking, and other water activities.

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NOAA CoRIS - Ecosystem Essays: Guam - Natural and Anthropogenic Stressors on the Coral Reefs of Guam



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Natural and Anthropogenic Stressors on the Coral Reefs of Guam

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Shallow-water coral reef ecosystems are impacted by a wide range of physical, chemical, and biological threats and stressors that stem from both anthropogenic (caused by human activities) and natural causes. Threats are defined as environmental trends with potentially negative impacts. Stressors may be defined as factors or processes that harm ecosystem components, causing lethal or semi-lethal effects. Categories of stressors include chemical (e.g., pollution), physical (e.g., storm or boat damage), and biological (e.g., invasive species).

Human activities are major contributors to the worldwide deterioration and degradation of coral reef ecosystems, with loss of live coral cover, declining biodiversity, and reduced population abundances being potential outcomes. Harmful commercial fishing methods, such as bottom trawling, cause much damage to deep water coral ecosystems. Degradation in the structure and functioning of these fragile ecosystems also results in a concomitant decrease in the intrinsic value of the ecological system. Approximately eight percent of the global population lives within 62 miles (100 kilometers) of a coral reef, and many local communities and national economies are directly dependent upon them for tourism revenue, food, and coastal protection.

The most common stressors on coral reef ecosystems worldwide are: climate change and coral bleaching; predator outbreaks; diseases; tropical cyclonic storms; coastal development and runoff (sedimentation); coastal pollution; tourism and recreation; fishing pressure; trade in coral and live Introduction

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reef species; ship and boat groundings; marine debris; aquatic invasive (alien) species; security training activities (military bases and associated activities); offshore oil and gas exploration; and ocean acidification.

Climate Change and Coral Bleaching

Climate change refers to any change in climate over time, whether due to natural variability or human activities. Over the course of the 20th century, mean near-surface air temperature over land and mean sea surface temperature (SST) increased with the 1990s being the warmest decade in recorded history. Elevated water temperatures caused corals to bleach, a process that is characterized by the loss of the symbiotic photosynthetic algae, zooxanthellae, from coral tissues. If prolonged, bleached corals may starve to death. The first large-scale bleaching event recorded in Guam was in 1994 and again in 1996; however, neither event resulted in significant coral mortality. Bleaching also was observed in 2006 and 2007 during a period of above average sea surface temperatures.

Predator Outbreaks

An outbreak of tens of thousands of crownof-thorns starfish (COTS) in the early 1970s had a devastating effect on corals along 22 miles (35 kilometers) of the northwestern coast. While coral cover did recover substantially by the 1980's, COTS outbreaks continued. Coupled with degrading water quality and reduced rates of coral recruitment, COTS outbreaks continue to serve as an important stressor and threat to coral reefs in Guam.



Coral Diseases

Coral diseases have become one of the major stressors affecting the health and resiliency of coral reef communities worldwide. Since the early 1990s, scientists

Crown-of-thorns seastar (Acanthaster planci) in the Achang Reef Flat Marine Preserve, Guam (Photo: David Burdick)

have documented a rapid emergence of coral diseases with increases in the number of diseases reported, coral species affected, geographic extent, prevalence and incidence, and rates of associated coral mortality. Very little is known about coral diseases in the Indo-Pacific. Diseases and syndromes affecting Guam's coral reefs are very similar to others reported in the Southern Marianas. However, only a few recent baseline surveys for disease have been conducted (2006 and 2007). It appears that coral diseases have not yet become a major problem in Guam, although minor outbreaks of white syndrome, black-band disease, brown-band disease, and ulcerative white spot disease have been reported.

Tropical Storms

Powerful cyclonic storms (typhoons) can dramatically disrupt entire ecosystems. Coral reefs, however, have shown resilience to storm-caused disturbances. In fact, such mechanical disturbances can be beneficial to a reef community by scouring the reefs to expose the substratum, thus providing more surface area for new coral recruits to settle. In Guam, tropical storms usually occur in the humid summer months. In the last half century, Guam has felt the impact of more than 50 major storms. Since 1994, it has been visited by four major storms with winds as high as 150 mph. When severe damage to Guamian reefs occurs, it is usually restricted to reefs that developed on unstable substrata in relatively protected areas of the coastline.

Coastal Pollution

It has been estimated that as much as 22% of the world's coral reef ecosystems are threatened by land-based pollution and soil erosion. Primary stressors are nutrients and other chemicals from fertilizers, pesticides, herbicides, sewage, as well as increased sedimentation from coastal development and stormwater runoff. Other noxious substances, such as heavy metals and petroleum products, also add to the pollution load at specific locations.

Sources of pollution may be either point source or non-point source. Point sources of pollution originate from specific conveyances, such as pipes, tunnels, ditches, channels, wells, and fissures. Non-point source pollution refers to pollutants not introduced from a single, well-defined site. Examples of point source pollution include sewage outfalls, untreated wastewater from factories and other industrial plants, and heated water discharge from power plants. Other point sources include vessels that discharge their wastes in ports, marinas and other nearshore areas, dredging, and accidental spills of petroleum and other noxious chemicals, such as heavy metals.

Most pollutants in the nearshore areas of Guam are microbial pathogens, petroleum hydrocarbons, and sediments. The most obvious point source pollutants are from sewage treatment plant outfall pipes. Nonpoint source pollutants in the area include nutrients from septic tank systems, sewage spills, livestock and agricultural areas, and discharge of chemicals from urban runoff, farms, and illegal dumping.

Coastal Development and Runoff

Increased sedimentation associated with runoff from coastal development and other causes of soil erosion are growing universal threats to coral reefs. In the past several decades, there has been a shift toward greater concentrations of human settlement in the coastal zones of many countries. This trend in the tropics and subtropics has greatly increased the stress on coral reef ecosystems. Freshwater runoff from landscape altering or clearing activities, such as the construction of houses, hotels, resorts, golf courses, marinas, other recreational facilities, piers, roads, bridges, and waste treatment plants has taken a terrible toll on some close-to-shore-reef areas. Sediment runoff settles on coral reefs, smothering them or increasing the



Sediment plumes caused by soil erosion after heavy rainfalls, such as this plume in Guam, lead to serious problems in coral reef ecosystems (Image courtesy of the Guam Forestry and Soil Resources Division, Department of Agriculture)

turbidity of the water, which reduces both the amount of light reaching corals and the level of photosynthetic activity by corals's zooxanthellae. This, in turn, can cause diminished coral productivity and growth, enhanced macroalgal growth, and, ultimately, a communal shift on the reef from corals to macroalgae.

In addition to sediment loading, runoff may also carry high levels of nutrients from agricultural areas or septic systems, as well as petroleum products, pesticides, and other pollutants. Increases in the amount of nutrients on reefs enhance the growth of other organisms, such as sponges or macroalgae, which may outcompete corals for space. Outflows from water treatment plants greatly increase the nutrient levels surrounding their outflow pipes. Large power plants alter water temperatures by discharging extremely hot water into the coastal waters.

The rate of sedimentation of nearshore habitats in Guam has increased dramatically since the mid-seventies, primarily as a result of severe upland erosion, particularly in the southern part of the island. Erosion is caused by road construction and by the creation of "badlands", which are a result of range fires (wildfires) set by poachers that denude the steep-sloping landscape. Another major cause of increased sedimentation on Guamian coral reefs is the construction of infrastructure to support the residential and tourist industries and the expansion of the military.

Tourism and Recreation



Healthy coral reefs support thriving tourism and recreation industries. Millions of scuba divers, snorkelers, boaters, shell collectors, and fishermen visit U.S. coral reefs and nearby beaches annually. Local economies receive billions of dollars from visitors to reefs through diving tours, recreational fishing trips, hotels, restaurants, and other businesses based near reef ecosystems. Tourism is particularly significant in many Caribbean and Pacific islands.

Scuba-diving tourists (Photo: Dr. Anthony R. Picciolo)

Studies have shown that divers and snorkelers can have a significant negative

impact on coral reefs in terms of the physical damage they cause and a concomitant reduction in the aesthetic appeal of the reefs. Other touristrelated threats devastating to coral reefs include construction of hotels, resorts, and associated infrastructure, seafood consumption, beach replenishment, building of airports and marinas, and cruise ship operations. Impacts that can result from these activities include increased sedimentation, nutrient enrichment, pollution, exploitation of endangered species, and increased litter and waste.

Guam's economy depends on tourism, U.S. military installations, and locally owned businesses. However, water sports and activities such as snorkeling, scuba diving, jet skiing, and charter fishing can stress and damage coral reefs, the organisms that live on and associate with the reefs, and adjacent habitats. Residents, military personnel, and occasional tourists add to that reef destruction and stress by "harvesting" stony corals, black corals, sea fans, mollusk shells, etc. for decorations and souvenirs.

Stress to coral reefs from scuba diving and snorkeling activities is not well documented in Guam. The greatest volume of these activities occurs in only about five high-profile reef areas in Guam. Many inexperienced resort and student divers visit the same, easily accessible, shallow, popular dive sites within short periods of time. Reefs suffer when they are touched, scraped, grabbed, or sat and stood upon. Stirred-up sediment from snorkelers and divers increases turbidity. Feeding of reef fishes also alters their natural behavior. Additionally, jet skis utilized at these sites produce loud sounds, leak fuel, and damage corals and seagrass beds.

As a tourist destination, it is very important that the beaches of Guam be clean and stable. Beach restoration after major storm damage and almost daily mechanical beach cleaning occur frequently in Guam but can affect the biological communities in the intertidal areas.

Fishing Pressure

Healthy coral reefs support commercial, recreational, and subsistence fishing. Approximately half of all federally managed fisheries depend on coral reefs and related habitats for a portion of their life cycles. NOAA's National Marine Fisheries Service (NMFS) estimates that the commercial value of U.S. fisheries from coral reefs is more than \$100 million. Approximately 25% of all marine species of fishes are inhabitants of shallow water coral reef ecosystems. Other reef inhabitants, such as marine plants, non-coral invertebrates, and some turtles, are also exploited (and not always in a legal manner) for human use.



Reef fish for market

Guam's coral reef fisheries are very important to the island's economy and native culture. Long before the Chamorus had any contact with Europeans, fishes were the primary source of proteins for the islanders. Even today, fishing remains an important part of their life and culture. However, the outlook for Guam's inshore fisheries is poor. A sizeable number of reef fishes and invertebrates have been targeted for commercial harvesting, resulting in a general decline in catch size and changes in species composition over the past half-century. Data also suggest that reef fisheries have not recovered from a steep decline in the mid-nineteeneighties, the cause of which is still unclear.

Fishing methods used on Guam coral reefs include hook and line, cast nets, spear fishing, gill net, surround net, trolling, drag net, jigging, hooks and gaffs, spin casting, and bottom fishing. The use of scuba and underwater flashlights for spear fishing, as well as monofilament gill nets, has caused concern among Guamians and throughout other peoples in the region. These techniques seemed to have led to visible changes in species composition, including the near disappearance of large groupers and overall decline in a number of other fishes, including wrasses, parrotfishes, snappers, and small groupers. Abandoned gill nets also increase the damage to reefs.

To address the problem of declining fisheries, Guam established a system of five marine preserves in 1997, which vary in size and in permissible fishing activities and methods. Although illegal fishing remains a problem, the preserves appear to have provided some benefit in protecting existing stocks.

Trade in Coral and Live Reef Species



A spiny puffer made into a lamp

Many coral reef fishes and invertebrates are collected to supply a demand for seafood, ornamental aquarium specimens, live food for Asian markets, construction materials (e.g., coral block), jewelry, curios, pharmaceuticals, traditional medicines, and other products. Harvesting of coral reef ecosystem components can occur at unsustainable levels and lead to unhealthy changes in reef species composition, relative abundances, and biomass. Non-target species may undergo population explosions that alter the dynamics of a particular reef system. Reductions or disappearances of some herbivorous species may result in the replacement of stony coraldominated reefs with algal-dominated reefs.

Guam currently does not permit the export of corals or live reef invertebrates and fishes. Corals and live rock (calcareous rock with living organisms attached, such as bacteria, coralline algae, sponges, worms, crustaceans and other invertebrates) for aquarium use are protected under local laws. Additionally, the University of Guam Marine Laboratory is permitted to harvest coral and live rock for research but only in areas not designated as marine preserves.

Invasive Species

The stability of an ecosystem may be threatened by the accidental or purposeful introduction of non-indigenous species (also called "invasive" or "alien" species). An invasive species is an organism outside of its native or historical habitat. For various reasons, including the absence of natural enemies, invasive species may grow and reproduce at the expense of the native species occupying the same habitat or habitat type. In some cases, invasive organisms are successful predators that can decimate local or native populations. In Guam, the brown tree snake (an accidental introduction) is a prime example of an invasive, whereas in the Caribbean islands, the mongoose (a purposeful introduction) has devastated local areas. Invasives may outcompete native species occupying the same ecological niche. In some cases, invasive species have caused major alterations in ecosystems and even the extinction of other species.

Although Guam has spent considerable resources studying terrestrial invasive species, such as the brown tree snake, little work has been done on invasive marine species. The first systematic surveys of non-indigenous marine species in inshore waters were conducted in Apra Harbor, the Orote Penisula Ecological Reserve Area (ERA), and the Haputo ERA. Of the 85 non-indigenous species documented, about half were categorized as introduced and half were of unknown origin. The majority of these were sessile invertebrates that probably arrived in Apra Harbor in vessel hulls. These non-indigenous marine species do not appear to be negatively impacting native species yet, but there is concern that increased shipping activities in Apra Harbor may augment the risk to Guam's coral reef communities.

Ships, Boats, and Groundings

Vessel groundings and the impacts of boats and anchors are probably responsible for the most destructive physical damages caused by humans to coral reefs. Worldwide, more than 2,000 grounding accidents are reported annually, with over 400 vessels sinking each year. As recreational and commercial boating traffic increases in coral reef areas, sunken ships pose great hazards to coral ecosystem habitats for the short-term and the long-term. Damage to reefs from ship groundings may also be prolonged if the basic reef habitat and community structure are altered by the vessel. Other vessel



A ship grounded on a coral reef near Honolulu (photo: Floyd Morris for the Honolulu Star Bulletin)

impacts include accidental or purposeful disposal of sewage, garbage, ballast water, oil, and other hazardous materials; introduction of alien species in ballast water or on hulls; and lost ordinance.

Guam's Apra Harbor contains reefs with some of the highest coral cover on the island. It is also the largest U.S. deepwater port in the Western Pacific and the busiest port in Micronesia. Apra Harbor is shared by the Port Authority of Guam and the U.S. Navy. A large number and variety of commercial and military vessels are serviced annually and this number is likely to increase with a planned military expansion. Some of these reef areas may be dredged in the future to facilitate vessel passage and military operations. The coral reefs are also threatened by ship groundings, anchoring, and discharge of pollutants. Many vessels have run aground on Guam's coral reefs, causing minor to major damages to the reef communities. Navigational buoys dragged across reefs during major storms also cause significant damage to the reef habitats.

Marine Debris

Marine debris presents a serious and continuous worldwide threat to the marine environment. Debris adversely impacts marine life through the destruction of essential habitat as well as entanglement and ingestion by marine organisms and seabirds. The majority of marine debris comes from land-based sources, particularly urban centers, but a significant proportion comes from ships.

Marine debris is not categorized as a major stressor to Guam's coral reefs but the impact is felt nevertheless. Approximately 12 metric tons of mostly locally-generated coastal debris was removed from Guam's beaches in 2007. The most common items collected were beverage containers, cigarette filters, plastic bags and cups, plates, and food wrappers. Car batteries, appliances, tires, auto parts, and abandoned fishing gear were also collected. The



A former coral reef in Guam destroyed by debris. (Photo: D. Burdick/NOAA)

majority of this debris is from land-based activities, such as picnics, sports, and beach visits. Litter washed from streets, parking lots, and storm drains also contributes to the debris found on Guam's shores. The major physical threat to the coral reefs is discarded fishing nets that can be found wrapped around coral colonies.

Security Training Activities

U.S. military installations near coral reefs include operations in Hawaii, Johnston Atoll, Wake Atoll, Kwajelein Atoll, Guam, the Commonwealth of the Northern Mariana Islands, Key West and Panama City, Florida, Puerto Rico, the U.S. Virgin Islands, Cuba, and Diego Garcia in the Indian Ocean. Military bases and associated activities, including exercises, training, and operational procedures such as construction, dredging, and sewage discharge, have the potential for adverse ecological impacts on coral reefs. Impacts include excessive noise, explosives and munitions disposal, oil and fuel spillage, wreckage and debris, breakage



of reef structure, and invasive species introductions from ship bilge water or aircraft cargo.

The Department of Defense conducts training activities in Guam, which include underwater demolition and landing craft exercises, and these have the potential to impact Guam's coastal waters and coral reefs negatively. The frequency of these activities has decreased since 2004, but is expected to increase with a proposed military base expansion that is expected to require some 20,000 construction workers. The expansion proposes to transfer more than 8,000 Marines and 9,000 dependents from Okinawa to Guam. Environmental impact studies are underway. The U.S. Military has a strong presence on Guam (Photo: Kddeitrick)



A B-2 "Spirit" Stealth Bomber at Andersen AFB, Guam (U.S. AF photograph)

Offshore Oil and Gas Exploration

There are currently no oil or gas resources identified near Guam.

Ocean Acidification

Ocean acidification is the term given to the ongoing increase in acidity of the oceans caused by their uptake of anthropogenic atmospheric carbon dioxide (CO_2) .

Dissolved CO₂ in seawater increases ocean

acidity by increasing the hydrogen ion (H^+) concentration in the ocean. There is a relationship between ocean acidification and corals' and other calcifying organisms' ability to build their calcium carbonate $(CaCO_3)$ skeletons. As the acidity of the oceans increases, many reef community inhabitants grow at slower rates. This is because higher CO_2 levels in the ocean also reduce carbonate ion availability, which is critical for corals to build their skeletons.

Stressed by warming surface temperatures and bleaching, sedimentation, predation, pathogens, predators, pollution, overfishing, etc., the world's coral reefs may soon face their ultimate threat in rising ocean acidity.



A free-swimming planktonic mollusk (Limacina helicina), an important part of the food web for pelagic fishes, forms a calcium carbonate shell that is negatively affected by increased ocean acidity (Photo: Russ Hopcroft, UAF/NOAA.)

At this time, however, no information is available on ocean acidification and Guam's coral reefs.

Other Threats

The crown-of-thorns starfish (COTS or *Acanthaster planci*) is a large, voracious predator of coral reefs throughout the Indo-Pacific. It feeds on the polyps of several species of stony corals. In moderate numbers, COTS play an important role in maintaining high biodiversity on coral reefs by keeping fast growing corals from overwhelming slower growing corals. However, periodic population explosions of COTS have been blamed for widespread reef destruction, particularly on Australia's Great Barrier Reef. NOAA CoRIS - Ecosystem Essays: Guam - Natural and Anthropogenic Stressors on the Coral Reefs of Guam



A crown-of-thorns starfish feeding on coral polyps (Photo: Konrad Hughen, Woods Hole Oceanongraphic Institution)

Guam has been affected by widespread outbreaks of COTS since at least 2004. A local COTS population is considered in "active outbreak status" when densities reach or exceed 30 individuals/11,960 square yards (10,000 square meters). Manta tow surveys in some areas revealed COTS densities at greater than 1,000/11,960 square yards (10,000 square meters) with extensive COTS-related coral mortality. Persistent COTS outbreaks have had and will probably continue to have a severe impact on many of Guam's coral reefs.

In addition to COTS-induced damage to coral reefs, some genera of cold water starfishes also pose a threat to deep-water corals by feeding on their polyps. Parrotfish, butterflyfish, blennies, puffers, damselfish, and marine snails (*Drupella*) also feed on corals, although most, as natural inhabitants of coral reefs, do not pose a major threat to reef health and productivity. The short-term and long-term impacts of these threats on Guamian reefs have yet to be studied.

Other major threats to coral reef ecosystems include cable-laying operations, the scouring of sea floor by untethered cables, earthquakes, and volcanic eruptions – all of which have been found to interrupt and destabilize coral ecosystems.

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NOAA CoRIS - Ecosystem Essays: Guam - Overall Assessment of the Condition and Health of Guam's Coral Reefs



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Overall Assessment of the Condition and Health of Guam's Coral Reefs

Scientists' assessment of the health of Guam's coral reef ecosystems has not significantly changed in the years between the 2005 and 2008 The State of Coral Reef Ecosystems of Guam reports (Porter et al. 2005, Burdick et al. 2008). The health of Guam's coral reefs is highly variable across the island. Due to multiple stressors, some reefs show signs of poor health, while others appear to be relatively healthy with thriving reef communities. However, long-term monitoring programs have only recently begun, and baseline data are incomplete, making it difficult to objectively assess the actual health of the reefs. In general, coral reefs in the northern parts of the island that are sufficiently distant from river outflows appear to be in better condition than those in the south, which can be subject to higher nutrient levels because of groundwater discharge. In fact, large sections of coral reefs in the south that are close to river mouths are in fair to poor condition. Several other areas, which were otherwise healthy with high percentages of live coral cover, have been heavily impacted by Crown-of-thorns starfish (COTS) outbreaks.

In recent years, Guam has made a great deal of progress in the protection and conservation of its coral reef ecosystems. The Guam Coral Reef Initiative Coordinating Committee (GCRICC) and a network of cooperating local and federal agencies, nongovernmental organizations, academia, private enterprises, and concerned citizenry have partnered in addressing threats to Guam's coral reefs. Through monitoring and research programs, education and outreach activities, enforcement of existing conservation policies, implementation of new policies, establishment of marine



Green Sea Turtle in the Tumon Bay Marine Preserve, Guam (Photo: David Burdick)

protected reserves, watershed management, and erosion control programs, Guam is working to better the health and productivity of its reef ecosystems. Marine areas that are protected have seen significant increases in fish abundances, especially as the growth of suffocating macroalgae has been well controlled in some locations.

Although significant progress has been made in recent years, many challenges remain. The stressors affecting Guam's coral reef ecosystems are increasing with the likelihood of their continued amplification in the future. The abundance of medium and large reef fishes, especially Introduction

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herbivores, is very low compared with other islands in the Marianas Archipelago. Poor water quality and low coral recruitment may decrease the coral reefs' resiliency to recover from future ecological trauma. Pollution, coral diseases, COTS outbreaks, and factors leading to bleaching are also serious stressors.

A proposed major military build-up in Guam could have very serious consequences for Guam's shallow-water coral reefs. In addition to a new Marine base and airfield, the buildup includes port dredging for a nuclearpowered aircraft carrier, which would impact 71 acres of a coral reef. The military also wants to build a Marine firing range on property that includes one of the last undeveloped beachfront forests on Guam. This military buildup would also overtax Guam's sewage-treatment systems and could result in island-wide water shortages.

Wildland fires started by poachers also pose a continuing threat. Restoration of native vegetation in affected areas needs to be accelerated. The threat posed by global climate change is particularly troubling. The ability of Guam's coral reefs to cope with coral bleaching, ocean acidification, and stronger storms will set the stage for their future health and vitality.

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Content on this page was last updated in 2010. Some of the content may be out of date. For more information: <u>http://coralreef.noaa.gov</u>.

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Introduction

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Marine Protected Areas (MPAs)

Natural and Anthropogenic Stressors on the Coral Reefs

Overall Assessment of the Condition and Health of Guam's Coral Reefs

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