Chapter 10

Hanau ka ʻUku-koʻakoʻa, hanu kana, he ʻAkoʻakoʻa, puka:

"Born was the coral polyp, born was the coral, came forth"

Reefs and Overfishing

Rainforest of the Sea

Aptly named the rainforest of the sea, reefs are rocky marine structures (made of a combination of coral and a hard form of algae[1]) that support one of Earth's most biologically diverse ecosystems. Although a large and inter-dependent life force relies on reefs for survival, they occupy a mere 0.2% of the world's oceans.[2] Not only are these underwater habitats crucial to supporting the ocean's biodiversity, they are home to 25% of all marine species.[3] But reefs also support the economy for those of us on *terra firma*. Within the United States, the ocean economy is generally proportionate to the size of each state's economy, yet Hawaiʻi defies this trend and is America's largest ocean economy, with 18% of state revenue coming from ocean-related commerce.[4] Hawaii's ocean economy generates $4.8 billion per year, approximately 68%

of the total state gross product in 2004.[5] Coral reefs alone are valued at $10 billion, and their direct economic contributions are valued at $364 million annually.[6] Moreover, coral reefs are the foundation for recreational and social activities statewide, and they are as critical today culturally and for subsistence as they were to ancient Native Hawaiians.[7] The islands isolation in the middle of the North Pacific has produced one of the highest rates of marine endemism in the world. Hawai‘i is a global biodiversity hotspot. Home to 86 endemic reef fishes and over 1,250 unique marine species that are found nowhere else in the world, over 410,000 acres of coral reef habitat are found in the Hawaiian Islands, larger than the landmass of Oahu.

Unfortunately, the world’s reefs are under attack and Hawaii’s reefs can be considered among them. In a review paper published in the prestigious journal Science, a consortium of researchers reviewed the state of reefs throughout the world and concluded that the diversity, frequency, and scale of human impacts on coral reefs is increasing to the extent that reefs are threatened globally.[8] Increases in carbon dioxide and global warming projected to occur over the next 50 years exceed the natural conditions under which coral reefs have flourished for the past half-million years. The authors of the report predict that reefs will change rather than disappear as their living communities adapt to these stresses. Some species have already displayed greater tolerance to climate change and coral bleaching than others.

Locally, Hawaiian waters show a trend of increasing sea surface temperature in recent decades of about 0.8^{o}C. These rising water temperatures are expected to increase the frequency and severity of bleaching events threatening our reefs[9]. Coral bleaching occurs when corals expel their symbiotic algae during periods of stress induced by high water temperatures or other environmental stressors. Bleaching is a sign of poor health, and may eventually lead to death of the coral. However to date there have only been three documented coral bleaching events among Hawai’i reefs: 1996, 2002, and 2004. The 1996 event was associated with annual late summer heating, low winds, and high sea surface temperatures that developed in waters around the Hawaiian archipelago. Areas of restricted circulation such as Kaneohe Bay got hit the hardest by inshore water temperatures that were elevated as much as 1-2^{o}C above normal levels. The other two events occurred among the reefs of the Northwest Hawaiian Islands and corals appeared to have since recovered.[10] Bleaching has hit other areas of the Indo-Pacific and Caribbean regions with much greater intensity than here in Hawai’i.

Amongst the Hawaiian Islands, managers of our reefs must not only deal with negative impacts from global phenomena, but also manage the effect of polluted run-off, coral disease, water shed development (and increased freshwater run-off), overfishing, alien species, storm impacts, commercial trade of reef species, ship groundings, marine debris, and siltation. For instance, researchers have reported that in the Northwestern Hawaiian Islands there is 6.7 times more fish biomass on average than in comparable habitats in the main islands. These data indicate that humans have reduced fish stocks in the main Hawaiian Islands to about 15% of what they once were[11]. Scientists estimate that more the 340 non-native marine and brackish-water species live in Hawaiian habitats where they often out-compete Hawaii’s unique native species and disrupt native ecosystems. This challenge is immense, especially given that reef mangers tend to have little authority in managing the same uplands which pose threats to the reef community. The good news for Hawai‘i however, is that our reefs are generally in good shape[12] and that a widespread awareness of their importance and the need for their protection is foremost in the minds of Hawai‘i residents and visitors alike.

Ocean Travelers

Although corals have a wide distribution in the world's oceans, the varieties that form reefs are typically restricted to relatively shallow, warm, tropical and subtropical waters between latitudes 30° north of the equator and 30° south. In most cases clean, clear water is essential to coral health, although prolific reefs can be found growing where rivers empty into the sea and waters often turn turbid. For example, healthy coral communities grow near the mouth of the Hanalei River on Kaua'i and in Kāne'ohe Bay, both of which experience periodic muddy run-off during rainfall. However, landward proximities where corals are exposed to chronic mud build-up and/or freshwater influx during spawning season are unlikely to host healthy communities. Once coral larvae settle on a hard surface and become established, colonies can arise if conditions are suitable. Given enough time, coral colonies become thickets, and thickets build upward on the skeletal remains of older colonies, establishing a reef. Today, coral reefs are found in the low latitudes along continental coastlines, on the margins of volcanic islands, and as isolated coral atolls.

The waters of the United States and its territories play host to extensive reefs in the Atlantic Ocean, Gulf of Mexico, Caribbean Sea, and the Pacific Ocean. The extended Hawaiian Island chain holds over 10% of the nation's shallow coral reef habitat and much of that is included in the Papahānaumokuākea Marine National Monument, the largest nature preserve in the U.S.[13]

Like all Hawaiian life forms, ancestors of the organisms that build our reef communities traveled across the vast Pacific to arrive on our shores.[14] Roughly half of native Hawaiian marine species are indigenous to the waters of Indonesia, the Philippines, and other islands of the Indo-West Pacific region. Another 10 to 15% are shared with the west coast of the Americas, about 13% are ubiquitous tropical marine species found across the oceans, and 20 to 25% are endemic to Hawai'i alone.[15]

These organisms were dispersed to Hawai'i as floaters, swimmers, and hitch-hikers on the system of currents that circulate across the North Pacific. The *Kuroshio Current* from the Philippines and southern Japanese islands carries into the *North Pacific Current* that spans the mid-latitude waters to our north. Both currents spin off periodic eddies that are probably responsible for the delivery of much marine biota to our island chain. Some attached to debris and grew to maturity on the journey. Others traveled in larval stage gambling to hit shore before reaching adulthood.[16]

Although some species endured sustained journeys, most probably took advantage of short-cuts using fortuitous "stepping stone" islands harboring abundant reef communities at intermediate positions across the ocean.[17] The trip is arduous and only the hardiest individuals of the most appropriately adapted species survived. Eastern Pacific reef communities (including Hawai'i) are notable for their low species count in comparison to those of the west Pacific.[18] The number of marine types steadily decreases along an eastwardly extending line. This *biotic attenuation* is a natural filter ensuring that those arriving and thriving in Hawaiian waters are survivors of a lottery in which there are not many winners.

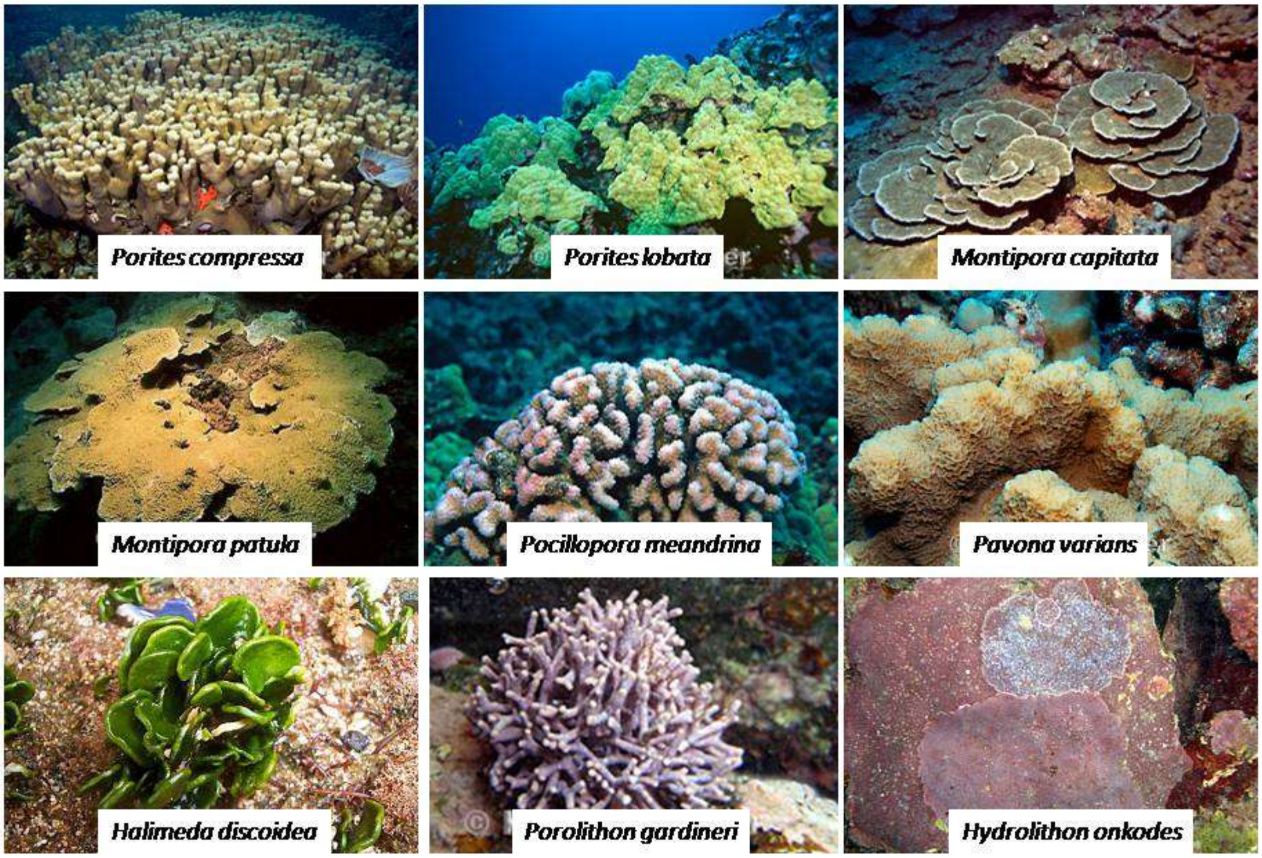
The Bone Yard

The planet's first reefs were built by photosynthesizing bacteria, among Earth's earliest life forms, about 3.5 billion years ago. From fossils it is known that a variety of organisms have constructed reefs across geologic time. Clams, oysters, bryozoans, and sponges are all reef-builders. The oldest corals date to about 500 million years ago, but these were solitary souls that did not build the vast colonies typical of modern reefs.[19] Corals similar to modern varieties have constructed reefs only during the past sixty million years making the northernmost seamounts of the Hawaiian-Emperor Chain, perhaps the first place on Earth to host these special organisms.[20]

Our reefs are comprised of two components: biological and geological. The biological realm exists as a living veneer, an organic seafloor community of coral, coralline algae, molluscs, fish, echinoderms, bacteria, plankton, and others that draw nutrients and expel waste among the coastal waters of Hawaiʻi. The skeletal debris produced by this community is composed of calcium carbonate ($CaCO_3$). It accumulates as a geological product: whitish sediments or a rigid framework of rock made of the same secreted chemistry. While the organic community on the seafloor engages in the demands of metabolism, the sediments it produces are skeletal fragments collecting in voids and interstices of the rock framework beneath the seafloor. Like a bone yard of skeletal debris, these fragments consolidate into a mosaic of limestone composed of fossil coral and algae.

Reefs are a collection of fossil skeletal debris composed of calcium carbonate that is secreted by living coral, coralline algae, and other organisms. [need great photo of Hawaiʻi reef that shows more than just the surface]

Over time, the upward accumulation of this skeletal pile kept pace with the sea-level rise that accompanied the end of the last ice age. As the reef matrix accreted upward, the living ecosystem built on the skeletal debris that collected beneath the living community. In shallow water, the living ecosystem must interact with the physical realm of waves and currents. Waves remove and redistribute sediments produced by the reef community but also concussively impact the reef. This inhibits further upward growth and the seafloor takes on a character adapted to withstand the high energy of shallow water. Instead of growing in relatively fragile branching forms, coral in shallow water grows as a thin layer that encrusts the seafloor. Importantly, hard algae known as *coralline algae* also accumulate that can withstand the hammering of waves. Shallow reef communities must withstand periodic inundation by flooding streams, intense sunlight, seasonal evaporation, and a mixture of land and marine-derived pollutants. Offshore, however, on the front of the reef below the waves, the action of accretion and reef-building continues in deeper, cleaner, quieter waters.



Some of the major coral and algal species that build Hawai'i reefs. [full page – permission needed from http://www.marinelifephotography.com/default.htm]

Birth of a Reef

Freckle-sized animals, known as *coral polyps*, a relation of the jellyfish, are the masons behind the intricate structure and chemistry of a coral reef. Corals begin their life as free-floating larvae, traveling ocean currents until they're able to adhere to a hard surface such as a cooled lava flow or ancient fossilized reef. Once grounded, larvae rapidly develop into polyps equipped with small tentacles and a tube-like body with a mouth at one end.

Coral polyps remove calcium from the surrounding seawater and excrete it as a *calyx*, or shell, that armors the polyp when it's lying dormant or being threatened. To feed or expel wastes, the polyp extends its tentacles into the water column. One coral is bordered by several, which in turn are bordered by dozens, a radiating condominium on the seafloor made of millions of individuals. Over centuries these continue to secrete their *exoskeleton* of $CaCO_3$, some species forming annual growth rings like a deciduous tree. Growing upwards, laterally, and even downwards, corals grow within the governing authority of sunlight, wave energy, community competition, nourishment, and water quality.

Plants and Animals

Two organisms serve as principal architects of Hawaiian reefs: scleractinian (stony or hard) corals, and coralline and calcareous algae. Corals are animals. Most of them host microscopic single-celled plants, known as *zooxanthellae*, within their digestive system. This is a long-standing and successful partnership that gives corals their rainbow of colors and provides them with an additional food source through photosynthesis. These symbiotic algae are the reason most corals need sunlight, thus limiting stony coral development to shallow waters. In turn, the coral provides protection and access to light for the zooxanthellae.

Calcareous green algae (Halimeda kanaloana) and red encrusting coralline algae (Hydrolithon onkodes) dominate the habitat on many shallow reefs. Some scientists suggest that these reefs be called "algal reefs" rather than the more common term "coral reefs" because of the dominant role of algae in their construction.

There are over fifty species of coral found in the Hawaiian Islands but only a few are common[21]. These grow in a range of forms designed to generally maximize the collection of sunlight and food, and minimize their exposure to stresses made by large waves. *Stout branching*, *delicate branching*, *platy*, *encrusting*, *doming*, *mounding*, these and other terms describe the numerous growth forms assumed by coral colonizers as they make the most of their environment. The more abundant Hawaiian genera include rice corals (*Montipora* species), lobe and finger corals (*Porites* species), cauliflower or moosehorn corals (*Pocillopora* species), and false brain corals (*Pavona* species).

Coralline algae and *calcareous algae* are members of a marine plant group on the reef that deposits calcium carbonate in its tissue. When the algae dies, it leaves a fossil skeleton behind that is hard, whitish, and essentially the same chemistry as the coral. These plants do not have real skeletons in the sense that animals do but the limestone deposits they produce make it appear so. A few species of algae, such as the *Halimeda*, are not completely calcified. Their body segments alternate between calcified and non-calcified. The main segment, looking like a flat leaf, becomes firm with calcium carbonate while the joints between these segments remain flexible. Hard plant debris builds up as piles of sediment in reef environments and are important sources of beach sand, making up over half the grains on many Hawaiian beaches. The coralline algae look like coral and grow in a binding and encrusting form on the reef, competing for space with corals. Most coralline algae are red, but there are some exceptions. A visit to any intertidal rocky coast in Hawaii will reveal the encrusting coralline community coloring the rocks a brilliant hue in between the rise and fall of the waves.

Geologic History

O‘ahu has the best studied of our reef systems but what has been learned about the geologic history of O‘ahu reefs should only be extended to the neighbor islands with care – largely because of vastly differing environmental histories among the shores of the various islands. Ranging in age from decades to a few hundreds of thousands of years old, O‘ahu’s reefs remain relatively youthful compared to the million year-long history of the main shield volcanoes.

Contrary to popular belief, the seafloor around the main Hawaiian Islands is not replete with rich stands of fragile coral and thriving reef ecosystems. Strap on a scuba tank and jump into our waters anywhere around O‘ahu, Kaua‘i, or Maui and chances are slim that you would encounter the idealized coral reef painted by the media and in tourism brochures. Instead, you would likely settle to the seafloor on a smooth limestone pavement, which at first glance you might take to be a submarine desert. This is the *insular shelf*, and it is a long dead graveyard of fossilized coral and their algal partners.

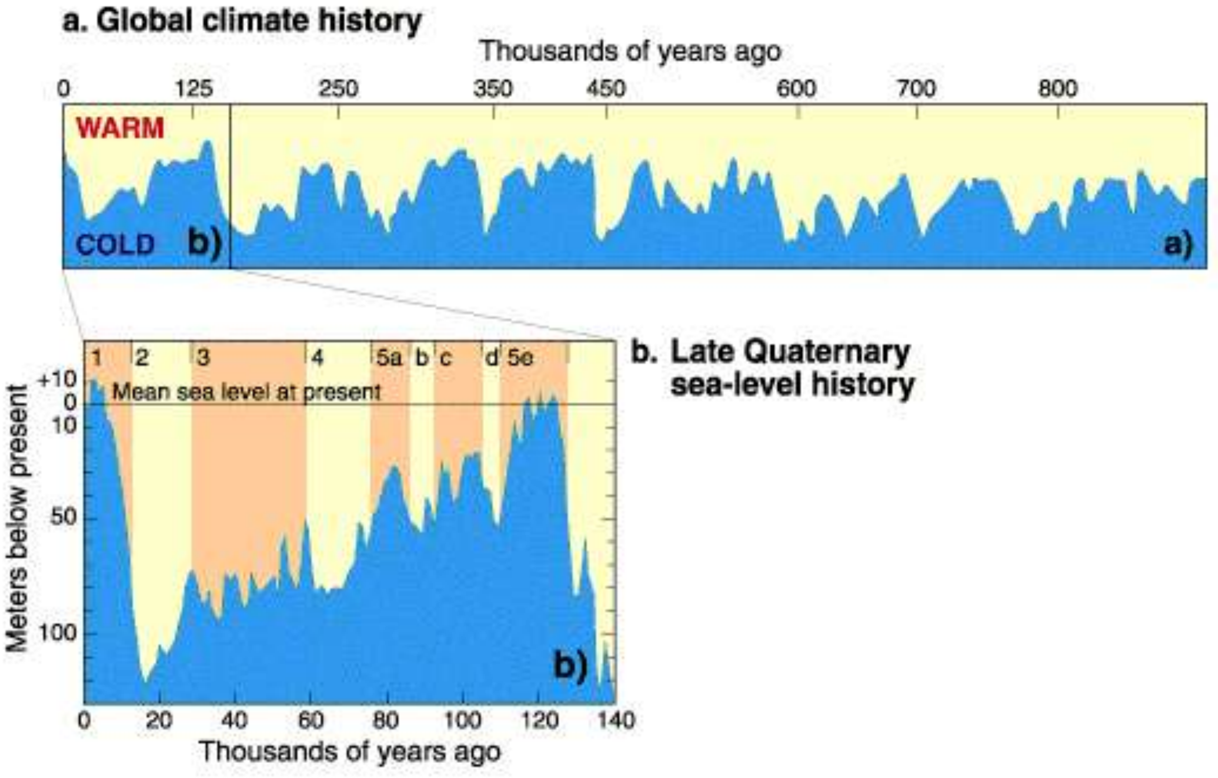
Most of the insular shelf around O’ahu is a fossil reef that was last active 200,000 years ago.[22] Since then there have been two ice ages! In shallow water on the windward side of O‘ahu north of Kāne‘ohe Bay, the reef was last alive about 5,000 years ago, about the time researchers think that extraordinary large swell associated with strong El Nino years began hitting the Hawaiian Islands. Although these huge wave events only occur every few decades (the last was in 1998), because they spell bone-jarring concussion and stress for the reef surface, they shut down any hope of widespread coral growth on those exposed shores.[23] The same is likely true for all Hawaiian shores that experience north swell. South of Kaneohe Bay in Kailua and Waimānalo and in other protected locales such as west Maui, south Molokai, and east Lanai, the reef is largely protected from the most massive northerly large swell. These sites plays host to a diverse community of coral and algae in waters not stressed by trade wind waves or land-based pollutants. But in shallow waters, trade wind waves, swell, heavy rainfall, and occasional storminess limit widespread coral growth.

Much of the seafloor around O'ahu and other Hawaiian shorelines exposed to high waves and storms is characterized not by lush coral thickets but by fossil reefs that grew many thousands to tens of thousands of years ago. At this location on Molokai, living coral consisting of robust branching Pocillopora meandrina, doming Porites lobata, and encrusting Porites lobata cover approximately 30 to 40% of the seafloor. Notice that most of these colonies are approximately the same size – meaning that they are about the same age. These grow on a fossil reef that is over 5000 years old. Every few years a large wave event comes along and wipes out these corals, resetting the age of the seafloor back to 5000 years ago. As long as there continue to be large waves in Hawai'i, reefs exposed to them are not likely to experience net expansion. The age of these corals probably dates back to the last huge wave event, 1998, when their predecessors were wiped out. These corals are likely to live only until the large swell arrives.[24]

On the majority of the O'ahu shelf, a diver might find the occasional growth of coral sparsely distributed across the field of view, and there are plenty of nooks and crannies along the coast where coral can take root. But on the open shelf, most of the living community is a short grassy-looking "turf algae", rock-burrowing invertebrates such as various crabs, urchins, snails and others, and scatterings of sand with stands of *Halimeda* and other alga. Clearly any coral growing on this ancient surface has as much chance of a long life as a mouse in a closet full of cats. Hurricanes, tsunamis, and heavy concussive swell generated by distant storms in the Southern Ocean and the North Pacific have all taken their turn at stopping any permanent reef accumulation for millennia. To understand this history, we need to understand the ultimate agent controlling reef growth: the position of sea level.

Sea-Level History and Reef Accommodation Space

You learned in earlier chapters that the blue skin of the sea is never still. In addition to tides, waves, and storms, the ocean level is perpetually changing as global climate warms and cools, glaciers wax and wane, and volcanic islands erupt and subside. Today the climate is turning warmer and so the seas are rising. But in the past, Earth has been plunged into arctic conditions leading to the growth of one to two mile thick continental-scale glaciers that grew at the expense of the oceans. Water that evaporated from glacial epoch seas fed expanding ice sheets on all the world's continents and thus the sea level fell.



The past one million years of Earth history has been characterized by predictable climate changes caused by regular oscillations in Earth's orbit around the Sun (called "Milankovitch Cycles"[25]*). Ice ages (periods of low sea level) and interglacials (periods of high sea level) occur approximately every 100,000 years. Higher frequency changes in sea level also occur related to shorter swings in climate.*[26]

The last ice age peaked about 20,000 years ago and the natural manufacture of all that ice lowered global sea level by approximately 400 feet.[27] Ancient humans walked from Siberia to Alaska and from Asia to Indonesia across the exposed lands. Had the Hawaiian Islands been peopled, they might have walked from Maui to Lanaʻi, and over to Molokaʻi. Reefs at the time were abandoned hundreds of feet in the air where their ecosystems died, partially dissolved, and recrystallized in lightly acidic groundwater and rainfall. Approaching the islands of Polynesia by boat, a voyager would have been greeted by forbidding white cliffs on most shores, not welcoming soft sand.

But the last ice age was not the first time this had happened; detailed histories of global climate written in fossil plankton on the seafloor and buried layers of ice at the south pole record that these ice ages have come and gone for a million years approximately every 100,000 years. In unpeopled Hawaiʻi, past ice ages were followed by a warm period with high seas, subtropical conditions, and renewed opportunity for reefs to grow along our shores – if there was room. Fossil reefs fill available *accommodation space* where a new reef would prefer to grow. If budding coral polyps are squeezed out between the ancient seafloor and modern wave scour, a new reef cannot form. Try as it might, a new reef community cannot get a foothold and build anew on the rooftop of its predecessor unless sea level goes unusually high and/or the regular occurrence of high waves, hurricanes, and tsunamis is somehow halted.

This does not mean that luxuriant coral growth is absent from our islands. Witness the protected and isolated corners of the coastline such as Hanauma Bay, the south shore of Molokaʻi, the south shore of Lanaʻi, the west coast of Hawaiʻi, and other sheltered shores and embayments throughout the islands. In these sites, hidden from high waves, you will discover an undersea paradise of coral growth, reef accretion, and abundant marine diversity.

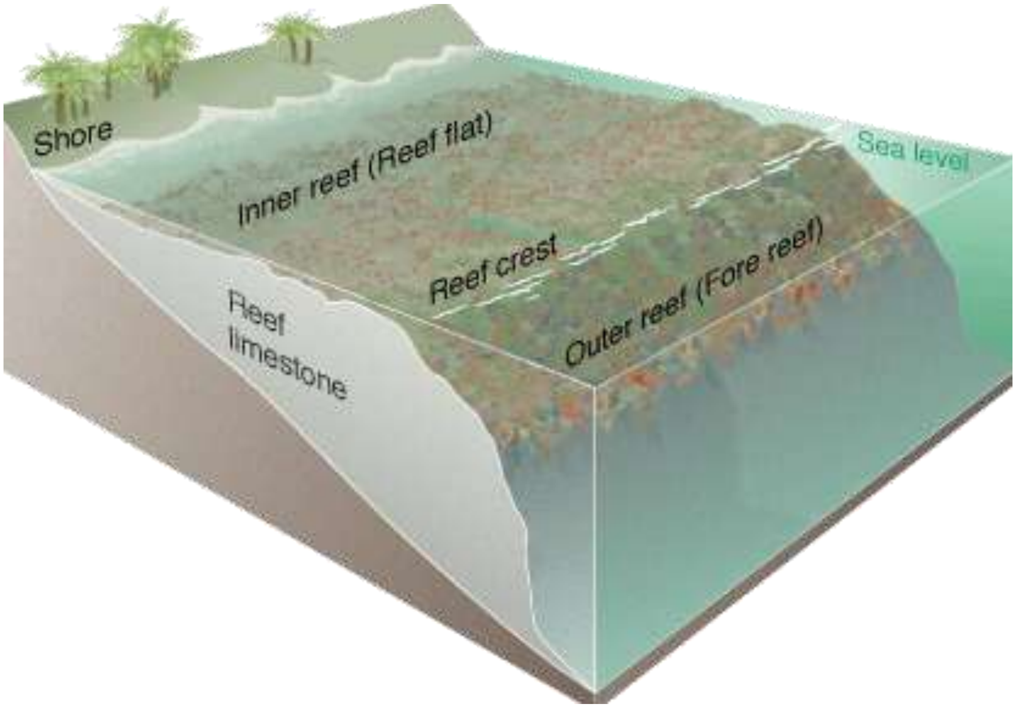
Reef Organization

Scientists have discovered that corals grow from 0.4 to 4 inches per year.[28] This range depends on the level of disturbance experienced by a coral as well as the available light, food, and water temperature. Because of Hawaiʻi's location in the middle of the North Pacific, our reefs are pounded by rough swells arriving from the north and south and the buffeting effect of waves kicked up by the trade winds. This persistent wave environment influences the structure of coral reef outcroppings.

Reefs at greater depths receive less impact from nature's roughhousing than those in shallow waters – but they in turn are limited by the sunlight they receive. *Coral reef zones* define the depth and types of species inhabiting each level. Every marine scientist has his favorite scheme for classifying reef zones, but a simple one includes: the *shore zone*, inner reef or *reef flat*, *reef crest* and, outer reef or *fore reef*.

In the shore zone, the closest reef habitat to shore, hardly any coral develops due to breaking waves and large amounts of fresh water and silty mud flowing into the ocean. The seafloor tends to be fossil reef limestone covered in a sedimentary blanket of both marine and terrestrial minerals. Still, a medley of fish, seaweeds, and invertebrates can be found swimming in these shallow, warmer waters.

The inner reef is anywhere from three to fifteen feet below the ocean surface, depending on the locality and the level of tide. This zone is known for its accumulation of carbonate sand, the growth of coral heads usually of the genus *Porites*, numerous invertebrates, fish, and alga species. Fish here are primarily *herbivores* and nibble on algae growing on dead coral and seaweeds. As gill netting and other types of uncontrolled fishing decimate the herbivorous fish population, their role in limiting fleshy algae growth is diminished.[29] Over-fishing results in coral death because alien algae can out-compete coral for space on the seafloor, often smothering coral beds under thick layers of fleshy tissue. Smaller *honu* (green sea turtle) are also commonly seen in the inner reef, nestled under hanging ledges and feeding on algae.



The simple zones of a fringing reef include the shore zone, inner reef (or reef flat), the reef crest, and the outer reef (or fore reef). On some Hawaiian coasts a reef crest may be absent.[30]

Beyond the inner reef, the reef crest marks the shallowest zone. Waves break directly on sturdy encrusting corals. Thick crusts of coralline algae that resist exposure to the air during low tide may also characterize the crest. Some locations, such as Kailua Bay on windward Oahu, do not have a distinct reef crest, instead the reef flat grades directly into the fore reef, which drops off steeply to a depth of eighty to 100 feet onto a sand-covered terrace.

The fore reef zone is steep and most notable for its coverage of finger coral and other more delicate growth forms. Here may be found the highest density of coral coverage in the reef community. In the deep fore reef, most ocean waves have minimal effect on the slow-growing community. This protection enables the system of stony corals to accrete atop one another and lay down a calcium carbonate base in its most optimal conditions. Below about eighty to 100 feet is a rubble zone defined primarily by coral blocks, rock, and sand that are swept by storm waves off the reef above. These provide a habitat for lobe and finger corals, an assortment of fish, as well as the sluggish sea cucumber, lobsters, and the more adventurous open ocean carnivores willing to wander into shallower waters.

Hawai‘i’s Reefs

In the broadest sense, reefs grow in one of four types: *barrier reefs*, *atolls*, *fringing reefs*, and *patch reefs*.[31] Hawai‘i has no true barrier reefs, atolls populate the northwest Hawaiian islands, fringing reefs are found attached to the shore among the main eight Hawaiian islands, and patch reefs (smaller in scale than the other reef types) are well-developed in Kaneohe Bay, and occasionally elsewhere.

Thought by many to be a Hawaiian-style barrier reef, the ridge forming the seaward boundary of Kāne‘ohe Bay is actually an old hardened sand dune formed during lower sea levels approximately 80,000 to 110,000 years ago.[32] This was a time when the eastern shelf of O‘ahu (and perhaps other islands) was covered in a broad field of forested sand dunes. Flooded today by high seas, opportunistic polyps and other reef denizens colonized the sandstone and have grown a thin coral-algal veneer upon its surface. Proof of this is found in the sandstone displaying dipping beds (former dune faces) composing Kapapa Island, Kekepa Island, and Laie Peninsula and its system of small islets.

Seaward of the Na Pali coast on Kaua‘i is a fossil coral plain sixty feet deep that could be taken to be an old barrier reef. It ramps gently up from deeper water forming the insular shelf. At its landward edge, it ends abruptly in a steep landward facing wall that reveals its internal construction of fossil *Porites compressa* columns as long and thick as your forearm. This wall has retreated seaward under the relentless pounding from huge north swells. But with no offshore-facing reef front this feature is no barrier reef. It is merely a former fringing reef being pounded out of existence today by huge waves. The fringing reef grew between 8,000 and 5,000 years ago prior to the era of huge waves that mark more recent millennia.[33] Under incessant seasonal hammering, the seafloor is being lowered by the destruction of fragile fossilized corals to reach a depth that is more in equilibrium with the high energy.

The vast majority of Hawai‘i’s reefs are of the *fringing* variety. Fringing reefs attached to island shores are forced to undergo the same evolutionary changes endured by the mass of the shield volcanoes. When an island is young and still under Pele’s influence, lava entering the ocean prevents reef accretion. Although young coral colonies do grow, they are too often wiped out by lava flows to have accumulated the mass of a true reef. But moving up the west side of the Big Island where the seafloor is not swept by high swell, the beginnings of fringing reefs attached to the land can be seen.

North of the Big Island on the Kihei coast of Maui and extending out from the north Maui shoreline are broad fringing reefs, demonstrating that reef development has a firm foothold on these stabilized volcanic coasts. Fringing reefs generally grow in size and become commonplace among the islands north of the Big Island, but among the northwest Hawaiian Islands their shape fundamentally changes. Fringing reefs give way to submerged pinnacles, drowned platforms, and atolls as the volcanic shield structure subsides beneath the waves and the fringing reefs struggle to stay near the surface.

Human Impacts

Because natural geological limitations to reefs (such as powerful waves from every direction, and watersheds associated with prolific rainfall) are the rule on many Hawaiian shores, those locations where modern reef growth is successful become precious treasures worthy of special protection. Yet even the fossil limestone surfaces that mark most of our shallow seafloor and are largely devoid of stands of living coral provide important habitat for thousands of other species. The lack of high coral cover does not negate their value as sensitive environments in their own right and deserving of careful management.

The most significant human threats to Hawai‘i's coral reefs are overfishing, land-based pollution, invasive algae, recreational overuse, and increases in ocean acidity and surface temperature associated with carbon dioxide build-up in the atmosphere[34].

In 1900, Hawai‘i fishermen sold 3.5 million pounds a year of reef fish, but by 1950 the catch had dropped to less than one million pounds a year.[35] The yield of reef fish has been sinking ever since. One reason for the decline is that humans tend to target the biggest fish. The largest fish are also the most fecund members of a community. As the most successful individuals are depleted, the community becomes skewed to small, immature, and less prodigious reproducers. With the selective removal of adults that are proven successful breeders, the productivity of the entire population has declined.

Another problem is land-based stressors such as polluted run-off, soil eroded from open agricultural fields and construction sites, and the excessive freshwater related to our urbanized watersheds.[36] Run-off in our rainfall-intense climate can introduce silt into coastal waters within hours, and throughout winter rainy months reefs that are unlucky enough to be located near fallow fields of open dirt may be physically buried by the red mud. Well known to inter-island travelers are the long sections of Moloka‘i, Maui, and Lana‘i coasts that turn from aqua-blue to muddy brown during heavy rains.

Other potential sources of coastal pollution include cess pools, leaks and breaks in sewage delivery pipes buried below ground, sewage injection wells in the coastal zone, and accidental discharges of untreated sewage from wastewater plants during heavy rainfall events[37]. Each of these presents some cause for concern as their potential impacts are poorly understood. Hawaii has an estimated 100,000 cess pools, more than any other state, but new cess pool construction is now banned on Oahu and Kauai, and heavily restricted on Maui, Molokai, and Hawaii. Leaky sewage delivery pipes are a focus of intense repair and reconstruction programs. Although this is an expensive and time-consuming effort, it is high on the list of “to do” projects among politicians. The impact of sewage injection wells on reefs is also not well understood. A 2007 study by the U.S. Geological Survey on a single well indicates that a plume of sewage does move toward the coast and may discharge to the ocean fairly close to shore and in water less than 100 ft deep. However, while this wastewater is not stripped of all nutrients and pathogens, it is treated to the secondary level and is presumably filtered somewhat in the groundwater environment. According to an email broadcast by the Maui Surfrider Foundation Nov. 6, 2008 “Although the county incorporated biological nutrient removal systems that reduced nitrogen discharges by 60%, sewage wastewater continues to contribute to the harmful algal and bacteria blooms that smother our coral reefs, adversely affecting marine life.” The basis for this statement is unknown. At sewage treatment plants, accidental discharges continue to be worrisome, especially during periods of intense rainfall. But upgrading in-ground pipes and expansion of key treatment plants together should offer some mitigation of this problem.

Seven major ocean outfalls discharge treated sewage into coastal waters. Five of these, Sand Island, Honouliuli, Waianae, Kailua, and Hilo expel their fluids into waters that lie deeper than 130 ft and thus are likely to have little impact among our reefs[38]. Two other outfalls, belonging to East Honolulu and Ft. Kamehameha, discharge in shallower waters but the waste is treated to the secondary level and at East Honolulu studies show there is no impact to coral communities.

Just offshore of the Waikīkī Aquarium (among other places) grows an invasive alga nicknamed “gorilla ogo.” This aggressor has pushed aside native *limu* and altered the ecology of the coral reef in the Waikīkī Marine Life Conservation District.[39] Although a dozen volunteer cleanups have hauled out tons of the plant, marine botanists predict that stronger methods are needed to control the species. It was only a few decades ago that the reef had sixty-five to eighty species of native algae. Now the rampant ogo blankets the environment from the reef crest to the shoreline. Similar invasions of algae have occurred along other Hawaiian shores and the question of whether human sources of nutrients are feeding this problem remains unanswered. One study of a small region in west Maui found that over 90% of the nitrogen delivery came from human sources. However, since that study (1997), nearly all sugarcane and pineapple farming in the region has stopped and current levels of nutrient loading to coastal waters remain unmeasured[40].

As locals and visitors alike increase their desire to experience first-hand the beauty of our reefs, they threaten to love it to death. All the attention paid to corals has the potential to damage them. Oils from human hands can be harmful, heavy footsteps and fin kicks, anchor damage, and even accidental brushes and bumps, can all add up to a significant impact given the thousands of enthusiasts that seek out the seafloor.

However, despite these sources of human stress, as concluded in the 2008 *The State of Coral Reef Ecosystems of the Main Hawaiian Islands*, “…many of Hawaii’s coral reefs, particularly in remote areas, are still in fair to good condition.”

Status of Hawai‘i’s Reefs

As a general rule, Hawaii’s reefs are in good shape. Widespread coral bleaching (when a stressed coral polyp expels its zooxantheallae symbiont) related to high water temperatures that have been seen in the Caribbean and Indian oceans has not been observed in Hawai‘i. Human impacts to reefs operate largely at the localized level, in embayments and small refugia nestled in the nooks and crannies of our shoreline. Given that land-derived stressors are aimed like a gun at the backs of our localized reefs and the offshore open ocean shelf often lacks accommodation space for reef growth due to wave stress, our reefs are squeezed from two sides and need all the help they can get from management authorities to resist the impacts.[41]

Unfortunately, most of the manageable problems threatening Hawaii’s reefs are either a direct or indirect result of human enterprise. While reefs have survived millions of years of Earth’s catastrophes and are indeed highly resilient systems, much of that resilience is in the form of an ability to recover from trauma, not resist it in the first place. Also, many natural traumas are short lived events such as storms, whereas human stressors tend to be persistent and unrelenting over time. Once human abuse is lifted, the reef stands an excellent chance of recovering, but allowing damage on the rationale that future recovery is likely is hardly the basis for an appropriate management system. In any case, scientific understanding of reef ecology is not sufficient to say if total recovery has happened in the past, or if a carpet of recovered living coral masks the permanent loss of other, less visible but still valuable members of the ecology.

Not to be forgotten, as human stressors accumulate on our reefs the very environment they occupy is shifting as well. Ocean acidity and surface water temperature are both on the rise due to the build-up of carbon dioxide in the atmosphere, an alarming trend given the already heavy burden of human impacts laid on the reef systems of the world.[42] Also worrisome is the increased shoreline erosion accompanying accelerated sea-level rise that will release mud and other land-bound pollutants into the reef environment. On the one hand, rising sea level should lift wave base, the depth to which wave scour limits coral development. This will open new ground for reef accretion. On the other hand, sea-level rise will increase erosion patterns along the shore potentially releasing damaging sediment and other buried toxic substances.

Until overfishing is effectively controlled, and land-based stressors to reef communities such as siltation (mud) and polluted runoff are mitigated, Hawai‘i reefs will retain their status as fragile environments worthy of special management status. Especially troubling is the fact that agencies tasked with reef management have no jurisdictional authority among the watersheds that pose such great risks – yet another sign, like the loss of our beaches, that environmental managers have yet to achieve a system of conservation that integrates enough government agencies to be effective.

Disease

Coral disease has only recently received study. Research cruises among the main eight Hawaiian Islands reveal the presence of eight coral diseases afflicting the three major coral genera: *Porites*, *Montipora*, and *Pocillopora*. Generally, disease is widespread but still at a low level with *Porites* trematodiasis and *Porites* growth anomaly being the most often observed (seen at between 60% and 70% of surveyed sites). The cause and carrier of these diseases is not known. Perhaps it is a virus that afflicts the coral polyp, and all researchers can do at this stage is observe disease occurrence and attempt to understand the patterns of behavior.

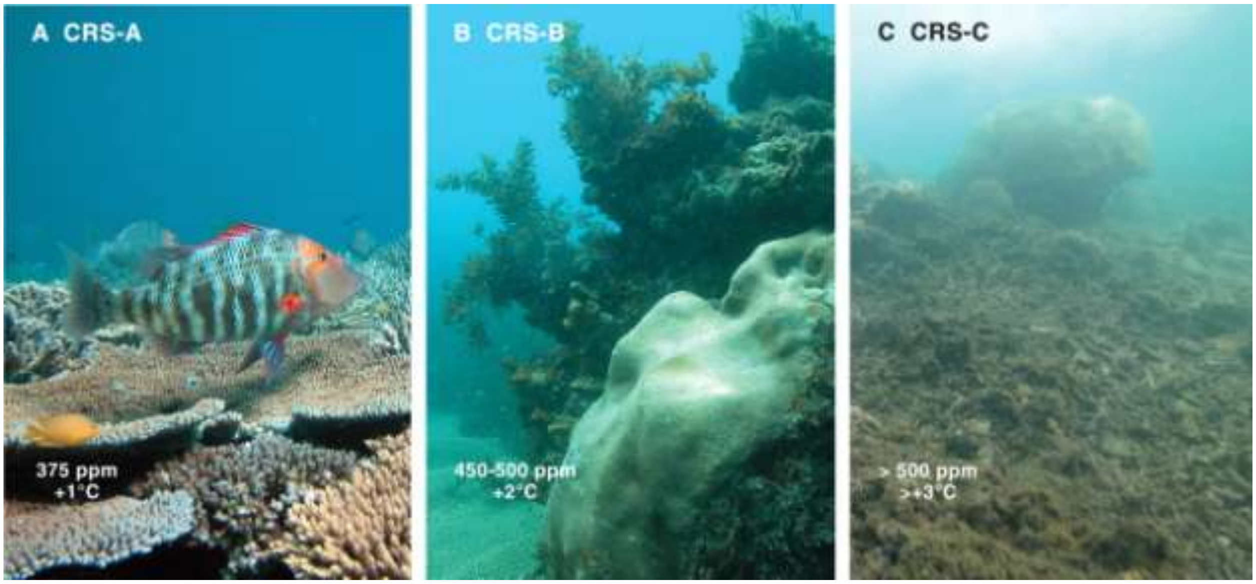
Diseases have also been seen among other reef dwellers. Plants among a patch of *Halimeda kanaloana* were observed to turn yellow and shed their segments off West Maui in the summer of 2006. The green sea turtles of Hawai’i have famously suffered from fibropapillomatosis, a disease that results in the growth of external and internal tumors, perhaps brought on by a version of the herpes virus. Surveys on Molokai suggest the prevalence of this disease has been declining for the past 5-8 years. Skin tumors, parasitic protozoan’s, and other irregularities have been spotted on local reef fish such as endemic butterfly fishes, goat fish, and snappers.[43]

Ocean Acidity and Bleaching

The way reefs see it, increasing the amount of carbon dioxide in the atmosphere is not a good thing. Two problems result: ocean water turns acidic and reduces the rate that a calcium carbonate skeleton can be secreted; and the ocean surface heats up, disturbing the symbiotic algae that corals depend on for food and energy.

As CO_2 increases in the air it mixes with the surface of the ocean. Mix water and carbon dioxide and you get a light acid – carbonic acid ($CO_2 + H_2O = H_2CO_3$). Mix carbonic acid and the calcium carbonate of a coral calyx and you get dissolved calcium ($H_2CO_3 + CaCO_3 = Ca[HCO_3]_2$) – leading to a dissolved coral exoskeleton, or at least difficulty in secreting it in the first place.

Some scientists believe that Hawaii's reefs are more vulnerable to the impacts of ocean acidification since we are located further north in cooler and more isolated waters than tropical counterparts. Cooler water absorbs carbon dioxide in greater quantities than warmer water, potentially causing acidification levels to rise here faster and above the global average. Hawai‘i corals may be exposed to dropping levels of the dissolved carbonate they need to build their exoskeletons. In July, 2008, scientists at the International Coral Reef Symposium in Florida declared acidification the largest and most significant threat faced by oceans today. In the worst case scenario, estimates show that all coral reefs could be gone by the end of the century.



These three images from Australia's Great Barrier Reef illustrate a sequence of degraded states that may result from the combined impact of ocean acidification and increasing sea surface temperatures. In the lower left, each image shows the global atmospheric carbon dioxide concentration and the resulting sea surface temperature increase leading to the degradation.[44]

If ocean water continues to absorb carbon dioxide from the atmosphere at the current rate, researchers expect the acidity of the ocean to increase 200-300% in the next 50-100 years.[45] By watching corals under such conditions in a specially designed aquarium, researchers observed a 50% decrease in skeletal growth at the same time that the photosynthesis of the symbiotic algae within the coral increased, probably because plants absorb, and feed on, carbon dioxide. But the excess growth of zooxantheallae does not help the host coral. The normally mutually beneficial relationship between guest algae and host coral breaks down. A similar breakdown has been widely reported when corals are exposed to elevated nutrient concentrations: the plant benefits and the animal coral suffer. Competition for carbon between the algae and the coral may be the explanation, but this phenomenon is not fully understood.

Bleaching is what happens when zooxanthellae leave the coral, which tends to happen when water temperatures rise past about 90^{o}F. Corals tolerate a narrow temperature range between approximately 77^{o}F and 84^{o}F depending on location. Corals bleach in response to prolonged temperature change and not due to rapidly fluctuating temperatures. They will also bleach in response to other stress events and environmental changes including disease, excess shade, increased levels of ultraviolet radiation, sedimentation, pollution, and salinity changes.

When corals bleach they commonly lose 60-90% of their zooxanthellae and each zooxanthella may lose 50-80% of its photosynthetic pigments.[46] The pale appearance of bleached corals is due to the calcareous skeleton showing through the translucent tissues of the polyp. If the stress-causing bleaching is not too severe and if it decreases in time, the affected corals usually regain their symbiotic algae within several weeks or a few months and the coral recovers. If zooxanthellae loss is prolonged, such as if the stress continues and depleted zooxanthellae populations do not recover, the coral host eventually dies.

Scientists predict global surface temperatures to increase as much as 10^{o}F by the year 2100.[47] Although the effects of climate change on global coral reef ecosystems will vary from one region to another, many species of coral are already in water that is near their thermal threshold. Any additional warming will reduce their growth and affect their health. The combined effect of warming and acidification, in an era of already significant human impacts, threatens reefs and thus constitutes a global problem.

Local Realities

Coral reefs provided early Hawaiians with their primary source of protein, as well as endless hours of recreation. Not surprisingly, the coral polyp was entwined with their earliest and most basic philosophy of existence. Within the *Kumulipo*, the Hawaiian creation chant, coral polyps were brought forth directly following man and woman.[48] In order to protect this precious resource, a system of kapu similar to the ones imposed on fresh water ensured the reefs' vitality. Stewardship of reef systems has been and continues to be vital for Hawaiian culture, yet over the last century the trend of balanced resource management system has shifted.

Currently, the islands are managed at federal, county, and state levels. Resources, including marine and freshwater resources, ocean water and navigable streams, parks, and coastal lands are all managed separately under a mosaic of government jurisdictions and agencies. Land is managed separately from the ocean, ocean water is managed separately from its inhabitants, and the ocean floor is managed under a different set of rules from all of these. Similarly in piecemeal fashion, agencies often have overlapping jurisdictions, but no governing mandate to integrate their activities. This vision of management once again deviates dramatically from the original, integrated management system of the place-based ahupua'a. As natural resources continue to be impacted by human activity, human population continues to climb, and climate to change, it is critical for resource assessment and monitoring to occur continuously and under the same rubric of governance.

If we, as a community, wish to minimize our impact on the natural world, we must deepen our comprehension of what is needed to preserve coral reefs. Both resource assessment and monitoring are appropriate tools for highlighting the most effective measures of action, though monitoring methods used for one aspect of an ecosystem do not necessarily apply to another. Keeping track of fishing pressure requires a different set of tools than, say, monitoring the discharge of polluted waters from fallow agricultural lands. Therefore, a variety of techniques need to be available and applied, with continued reviews and updates under an integrated set of rules.

Sadly, over the last few years, dramatic modifications in budget priorities at both state and federal levels have left marine community management undermined. Yet, without continual funding enabling scientists to identify threats to the seafloor, outline mitigation actions, fully understand reef natural history, and assist in creating new management efforts where outdated ones have failed, the value and natural beauty of Hawai‘i’s reefs will continue to be vulnerable on populated shorelines. The loss of seafloor communities implies serious environmental, economic, and cultural implications for not only Hawai‘i, but also the rest of the world.

Hawai‘i Reef Programs

In 1994, the *International Coral Reef Initiative* (ICRI) was created at the First Conference of the Parties for the Convention on Biological Diversity.[49] This international agreement emerged out of the recognition that the coral reefs found in tropical and sub-tropical areas are facing alarming degradation around the world, primarily due to human-related pressures. According to *The Status of Coral Reefs of the World: 2004*, approximately 20% of the world's coral reefs are beyond repair and 70% of the world's reefs are threatened or have already been destroyed, up from 59% in 2000.[50]

If the health of the planets coral reefs is not fostered, this decline could lead to the loss of most of the world's reef resources within the present century. Some of the ICRI objectives call for countries to include the protection, restoration, and sustainable use of coral reefs into existing local, regional, and national development plans. ICRI also calls for increased capacity for the creation and execution of policies, management, research, and monitoring of coral reefs in member countries.

This international initiative spawned the *Hawai‘i Coral Reef Initiative Research Program* (HCRI-RP) in 1998.[51] This Initiative is managed in conjunction with the Hawai‘i Department of Land and Natural Resources/Division of Aquatic Resources (DLNR/DAR) and the University of Hawai‘i (UH). By supporting scientific research and monitoring, results provide resource managers with information that helps them prevent and possibly undo the damage that has already been inflicted upon seafloor communities. Also, Hawai‘i’s *Living Reef Program*, a public education campaign to increase awareness about the necessity of healthy reefs, was launched in 2004.[52]

According to the *State of the Coral Reef Ecosystems of the Main Hawaiian Islands 2008*, coral ecosystems in Hawai‘i range from fair to excellent condition, but are “threatened by continued population growth, over-fishing, urbanization, runoff, and development.”[53] The report also states that sources of pollution, coastal developments, and aquatic alien species threaten the health of Hawai‘i’s reefs. In order to maintain Hawai‘i’s high quality of life and dynamic economy, continual, sufficient funding is imperative to hone coral reef management and disseminate educational material that promotes reef conservation.

Overfishing

In 2007, a paper published in the journal *Ecological Applications* reported that total fish biomass in Hanauma Bay and ten other protected areas under state management was 2.7 times greater than the biomass in comparable unprotected areas.[54] The study also reported that in the Northwestern Hawaiian Islands there is 6.7 times more fish biomass on average than in comparable habitats in the main islands. These data indicate that humans have reduced fish stocks in the main Hawaiian Islands to about 15% of what they once were. The study author, Alan Friedlander of the National Oceanographic and Atmospheric Administration, concludes that the eleven state marine protected areas are too few, protecting only 0.3 percent of the Hawai‘i coastline, stating, “If you want to rebuild fish stocks, you need to stop fishing in at least 20% of Hawai‘i’s waters and regulate fishing in the rest.”[55]

Within the sea a complex network of predator-prey relationships exists, so in order to maintain Hawaiian fisheries it is necessary to preserve the biodiversity of the community. For example, with traditional fishing methods the spawning and growth to adulthood of species were attentively guarded and regulated as they related to phases of the moon and the seasons of the year[56]. Only a certain amount of fish were harvested at any given time, with certain times of year, type of fish, gender of fish, and size of fish being carefully restricted. All of these management techniques displayed a deep comprehension of the underwater landscape and its geobiological function.

The late 1800’s witnessed a breakdown of Hawai‘i’s traditional resource management system. By the turn of the century, traditional fisheries management practices were virtually eradicated. As the new cash economy multiplied across the islands, so too did the commercial landing of fish. Over the 20th century, tourism, resident population, and shoreline recreation increased dramatically. The face of Hawai‘i’s fisheries was forever changed. What once served as the source of a subsistence lifestyle became the carrot for recreation and a commercial career. Fishing techniques underwent dramatic changes. The areas that were fished increased outwards from the islands to support the amount of catch occurring annually.

In 1900, the population size of the islands was 150,000 with a fish catch of 6.2 million pounds, valued at $1.1 million.[57] Today the population is almost ten times that amount at 1.2 million, with an annual fish catch of 23.4 million pounds valued at $59 million dollars. While the catch has grown approximately 400%, the value has increased exponentially, depicting one of the primary incentives behind the trend of fishery growth. It is certainly easier today to pull hundreds of pounds of commercial fish out of the ocean than it used to be with an old-school hand net; where once a rod or net was used, motorized vessels now restlessly pace coastal waters scooping up the ocean’s creatures.

A report from the U.N. Food and Agriculture Organization on the state of marine fisheries worldwide says that 52% of the oceans' wild fish stocks are fully exploited.[58] Of the rest, 23% are lightly or moderately exploited and still offer some scope for further fisheries expansion, 16% are overexploited, 7% are depleted, and 1% are recovering from depletion, meaning they have no room for further expansion. These assessments are found in the most recent *Review of the State of World Marine Fishery Resources*.[59]

At the same time, however, not all the catch statistics of Hawai‘i’s fisheries can be considered reliable due to the fact that a large amount of resident catch from recreation and a subsistence lifestyle goes unreported. Additionally, commercial fishers have a habit of under-reporting their catch. According to the Pacific Fisheries Coalition, the nearshore recreational catch is likely equal to or greater than the nearshore commercial fisheries catch, and recreational fishers take more species using a wider range of fishing gear.[60] Unlike most other coastal states, Hawai‘i doesn’t require recreational fishers to have a license. Also, a large percentage of the world's home aquarium collector fish are taken from Hawaiian waters, with no regulations limiting the size, number, and season for most of the desired species.[61]

Bigger fish are in no less trouble. Shark, tuna, marlin, and other top undersea predator populations inhabiting the middle of the ocean, thousands of miles from the nearest land, are being replaced by smaller, less desirable rays and other fish, according to a study published in the journal *Ecology*.[62] Studying an area of more than 6,000 square miles in the middle of the equatorial Pacific Ocean south of Hawai‘i and north of the Fiji Islands, researchers Peter Ward and Ransom Myers from Dalhousie University in Nova Scotia found that sharks, tuna, and other top-of-the-food-web fish are half the size and their populations 80% smaller in numbers than they were fifty years ago.[63]

There are several reasons for fish (both pelagic and nearshore) decline:

1. Wasteful fishing practices
2. Habitat destruction
3. Lack of fisheries knowledge
4. Inadequate enforcement
5. Increased human population and market demand
6. Too few larger fish spawning
7. Improved fishing technology
8. Alien species
9. Lack of detailed scientific data in support of new management efforts

Hawai‘i's Fishery Types

Hawai‘i's marine fisheries are divided into three geographical areas: the eight main Hawaiian Islands, including their surrounding reefs; the Northwestern Hawaiian Islands (NWHI), a 1,200 mile string of mostly uninhabited reefs, shoals, and atolls stretching northwest from the main Hawaiian Islands (now closed to fishing unless it is for subsistence by native Hawaiians meaning that catch are consumed within the monument boundaries); and the mid-north Pacific Ocean, ranging from latitude 40 degrees N to the equator, and from longitude 145 degrees W to longitude 175 degrees E.

Hawai‘i's fishing boats can also be divided into three types.

1. *Large-scale commercial fishing vessels*: Although smaller than most U.S. and foreign fleets, almost all of Hawai‘i's large-scale commercial fishing vessels are less than 100 feet in overall length. These include the older aku boats, which use a pole and line fishing technique, tuna long line wooden-hulled fishing craft, and modern tuna and swordfish long line vessels, distant-water albacore trollers, and multipurpose vessels that catch bottom fish and spiny and slipper lobster. These vessels are allowed to fish up to 1,000 nautical miles off of Hawai‘i's shores, throughout the mid-North Pacific, and some span the South Pacific. However, most of these vessels function within 200 miles of the main or northwest Hawaiian Islands and head out for around two to three weeks at a time.

2. *Small-scale commercial fishing vessels*: The boats in this category include trailered and moored boats between twelve and forty-five feet in length. Most of these vessels use trolling and hand line techniques. The target species include tunas, billfish, mahi-mahi, ono, and bottom fish for the trollers and hand liners. These vessels typically stay within 10 miles (single day trips) of the main Hawaiian island shores.
3. *Small-scale recreational, part-time commercial, and subsistence fishing*: This category uses the same types of boats as in the previous category. Charter fishing boats are also included in this category. The target species for this segment of the fishery include a variety of reef species, as well as the more familiar tunas, billfish, mahi-mahi and ono, bottom fish, and crustaceans.

In Hawaiʻi, the list of fishing techniques is long and creative. They include: long line; aku pole-and-line; deep bottom, inshore and tuna hand line; trolling; diving; net; trap; rod and reel; handpick; and a few other miscellaneous techniques.

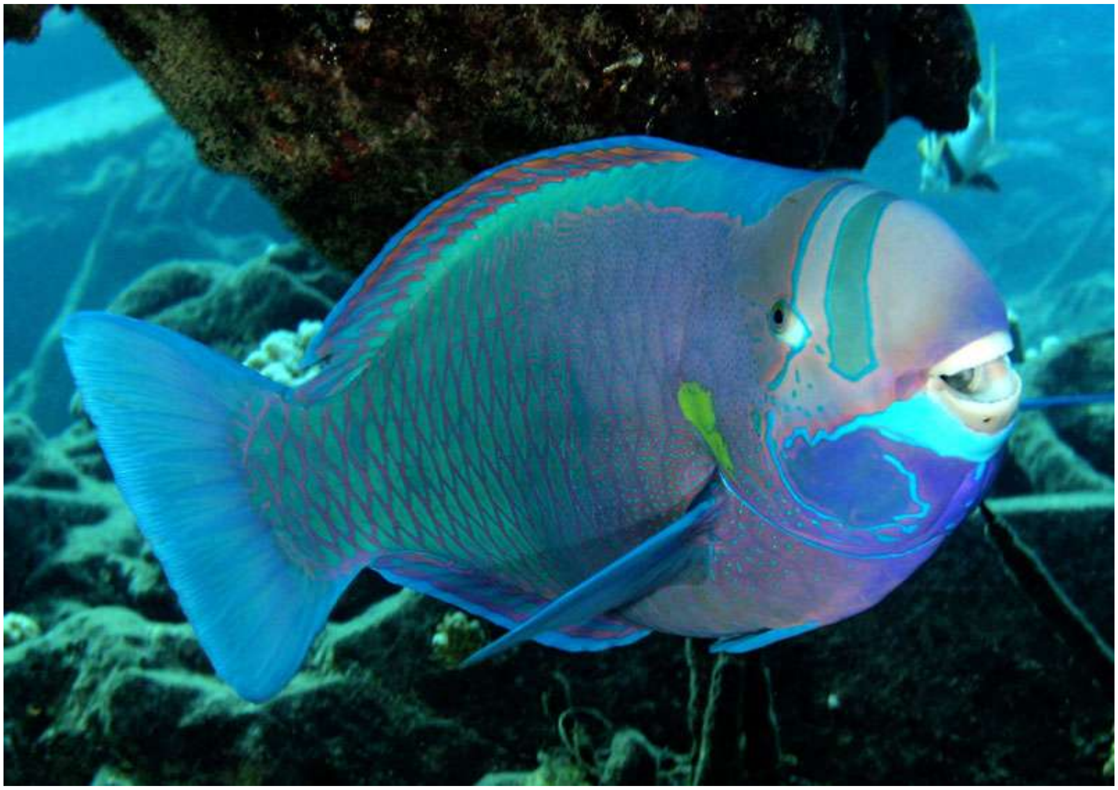
Long line fishing is carried out by using gear that consists of one mainline that extends over a nautical mile in length, and attached to it are a number of secondary lines, hanging with baited hooks. The mainline bobs just below the ocean surface; it is unlawful to engage in long line fishing within state waters, or to sell or offer for sale any marine life taken with long line fishing gear within state waters. Long line fisheries target blue marlin, striped marlin and other bill fishes, mahi-mahi, ono, opah.

The aku pole and line fishery in Hawaiʻi targets primarily skipjack and juvenile yellow fin tuna. This fishery is also called the bait boat fishery because it uses live bait to entice tuna to bite on barbless hooks with feathered skirts. Currently, most Hawaiʻi catch is sold on the fresh fish market.

Two types of pelagic hand line fishing exist. The first, ika shibi, targets squid and small ahi. The hand line fishery is done at night and most fishermen use a parachute anchor to slow the vessel's drift while fishing. Three to four hand lines are set at a time. The other method, called palu-ahi (chum tuna), deploys a weighted "bag" stuffed with chum to attract tuna to baited hooks. The Hawaiʻi offshore hand line fishing grounds are primarily at seamounts and weather buoys 30-200 miles from shore. Bottom fish typically include seven deep-water species: onaga, ehu, kalekale, opakapaka, ukikiki or gindai, hapuʻu, and lehi. Laws governing bottom fishing generally allow use of traditional hand line gear only in order to limit the volume of caught fish.

Trolling is conducted by towing lures or baited hooks from a moving vessel using big-game rods and reels or hydraulic haulers and outriggers. Some troll vessels will also use a hand line especially to target ono and tunas. Commercial troll fisheries target ono, mahi-mahi, and large yellow fin tuna. Trollers fish where water masses converge and where underwater features create dramatic depth changes, and may target fish aggregation devices and foraging seabirds. It is sometimes difficult to differentiate between commercial and recreational troll fishermen because the recreational ones sometimes sell excess catch to cover their expenses. Trolling is the most popular pelagic fishing method in Hawaiʻi. Hawaiʻi is known for its big-game trolling technique such as blue marlin fishing.

Bottom trawling fishing boats drag nets along the ocean bottom in extremely deep water near underwater seamounts. This technique destroys deep-sea habitats containing deep-water corals, sponges, and other fragile organisms in their paths.



Studies[64] show that the uhu, or parrotfish, biomass at heavily fished sites around Oahu is only about 3 percent of that in remote parts of the islands. Parrotfish are herbivores that control algae and maintain the health of reefs.

Sustainable Fisheries: Are They Possible?

There are few sustainable fisheries. In unexploited populations of top predators such as ulua, opakapaka, onaga and ehu, the much greater fecundity of larger individuals determines that a relatively few large individuals can provide a substantial portion of the genetic input to the next generation. However, fishermen tend to target large fish and after awhile only the small individuals remain. In heavily fished populations, nearly all the genetic input is from smaller fish who in turn produce small fish that reproduce early. Once reproduction starts, fish put their energy into producing eggs and sperm and their growth rate slows down.

With continued targeting by fishers, eventually large individuals disappear from the population and the biomass of the entire fishery is reduced. Because of this, fisheries management is evolving into an approach that sets a maximum and a minimum size. The minimum size is that which permits at least one spawning to occur before harvesting is allowed. The maximum size is that which allows the largest females with the most eggs and genetically most robust to survive and reproduce season after season. Fishing gear restrictions protect the pre-reproductive fish; no-take nursery areas protect the largest females. Quotas and bag limits can be used if the intermediate size classes need some protection.

Owing to the poor state of Hawai‘i’s coastal fisheries, the Hawai‘i State Department of Land and Natural Resources Division of Aquatic Resources, has undertaken a number of measures to improve the management of these resources.[65] A few of these measures include changes in minimum size limits for certain resource species, the initiation of marine recreational fisheries surveys, and changes to the rules governing marine protected areas.

Resource management tools include the following:

1. Catch Reporting and Licenses: these involve the commercial fisherman in keeping a log of what they catch each month.
2. Artificial Reefs: these are meant to increase fish populations by increasing habitat.
3. Bag Limits: these should ensure that enough fish are left to reproduce and each fisherman gets a fair number of fish.
4. Closed Seasons: these ensure fish get a break from fishing pressure during their spawning seasons.
5. Education: knowledge of past and current fish abundance and fishing practices, rules, and regulations keep fishers knowledgeable of natural fish abundance and tools used to make and keep fish populations healthy.
6. Community-Based Management: this involves local knowledge, observations, expertise, and work to manage fish resources.
7. Fisheries Management Areas: these are areas closed to certain types of fishing gear or are closed for a certain period of time to allow fish to recover.
8. Gear Restrictions: these limit too efficient, non-selective, or habitat destructive equipment. Lay gillnets kill undersized, out-of-season fish and destroy habitat.
9. Fish Replenishment Areas: these are areas permanently closed to fishing to ensure healthy stocks of fishes of different sizes and species and keep intact whole ecosystems.
10. Minimum Size Limits: these allow a species to reproduce and replace themselves.
11. Stock Enhancement: this activity takes wild fish and breeds them in captivity and then releases them into the wild.

Size limits have limited effectiveness in bottom fish areas because fish often die when caught in deep water and are then brought to the surface. Mortality also results from handling, hooking, and the general trauma of being hauled in. When fishing levels are high, accidental mortality of small fish that are thrown back is enough to dissipate any benefits of a size limit.

Limited entry schemes, which require a data base on users and numbers of fish removed, reduce or restrict the number of participants. Limited entry is not utilized as a management method in bottom fisheries because the government has no statutory authority to limit users and because bottom fish are harvested in Hawaiʻi in small quantities by a large number of local fishers, most of whom are fishing as recreational fishermen.

Hatchery programs and *stock enhancement programs* release young fish into the wild to build up local populations. Hatcheries must incorporate genetic material from wild stocks on a regular basis to avoid problems from interbreeding. Although these programs sound like promising methods for rebuilding fish populations, they are expensive and have not generally proven effective for increasing overall abundance.[66] While stock enhancement is not realistic for bottom fish, opakapaka and ehu may have some aquaculture potential. Hawaiʻi has had some success with seeding certain coastal areas with hatchery-reared moi and mullet.

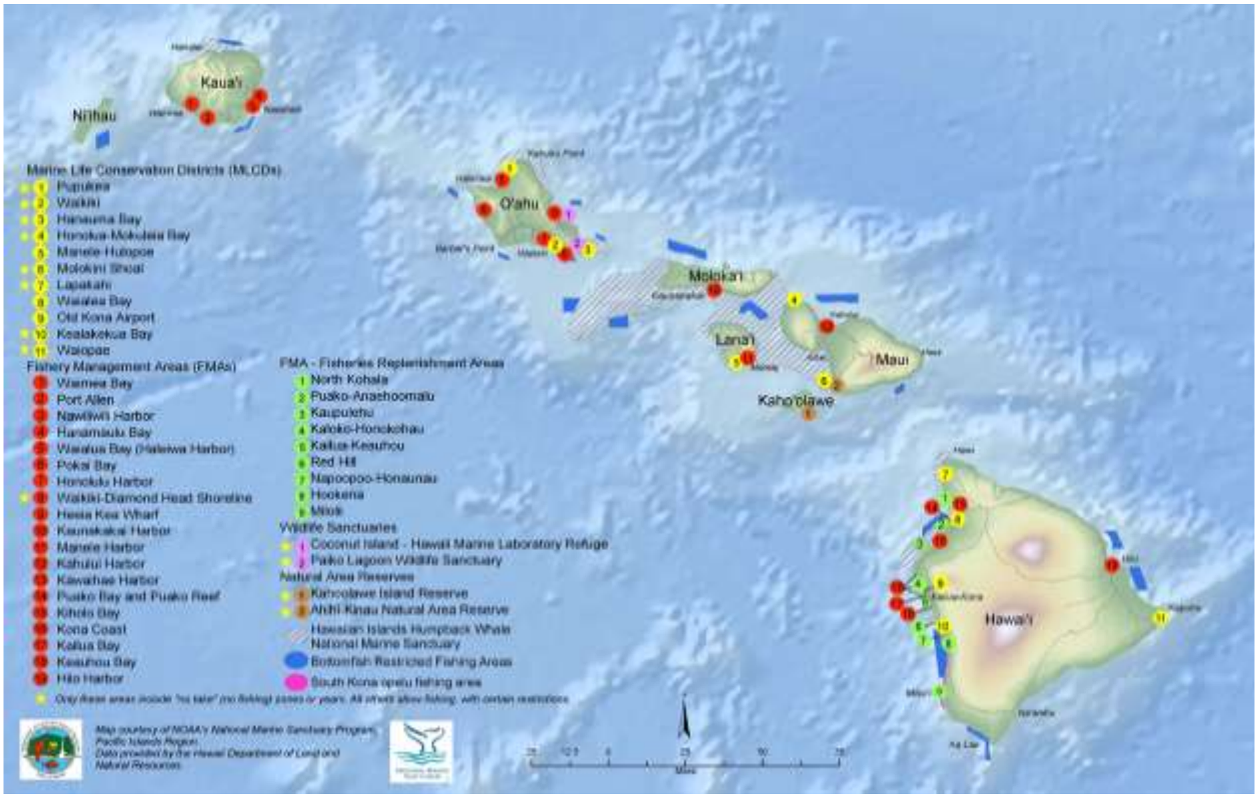
Artificial reefs provide cover from predators and substrate for food and, if properly placed, may increase total biomass. Some critics are concerned that these reefs may be acting like fish aggregation devices drawing both fish and fishers to the same environment. Before placing any artificial reef structures, it is important to examine a prospective area; what may seem like a barren wasteland may in fact be a productive bottom fish nursery. Derelict vessels and concrete fish habitats have been placed at selected locations in Waiʻanae, Maunalua Bay, and Waikīkī reefs on Oʻahu.

A number of communities throughout the state are currently strengthening local influence and accountability for the health and long-term sustainability of their marine resources through revitalization of local traditions and resource knowledge. The State of Hawaiʻi has been encouraging community-based management of subsistence fishing areas since 1994 and a number of these areas are now being established. Other management measures have included the use of stock enhancement for a few highly prized species and artificial reefs to improve the habitat options available to some coastal species in a few select locations. The current challenge is to rebuild sustainable fisheries while conserving marine resources and providing benefits to all of Hawaiʻi's residents.

Perhaps the most important steps yet to be taken are to implement a fishing license program, and vastly increase the coverage of marine life conservation districts in Hawai'i. A licensing program would allow improved collection of scientific data, and offer important restrictions on fishing pressure in nearshore waters. Banning gill nets would also be a strong move as these "walls of death" can be extremely destructive. Gill nets are currently heavily regulated with net openings, restrictive hours of deployment, and the requirement of constant monitoring providing important improvements to the practice of netting. But enforcement is a perpetual problem in Hawai'i and if they were made illegal it would be clear to all persons that when they see a gill net in use, it is an illegal use.

Marine Protected Areas

One of the most widely used tools to control fishing impacts is the *Marine Life Conservation District* (MLCD).[67] These are implemented by government authorities to conserve and replenish marine resources. MLCD's typically allow only limited fishing (or disallow it altogether) and ban or stringently limit other uses that consume reef resources. They provide fish and other aquatic life with a protected area in which to safely grow and reproduce, and are home to a great variety of species. MLCD's are most popular as sites for snorkeling, diving, and underwater photography. Hawaiʻi now has eleven MLCD's and nineteen *Fishery Management Areas* (FMA's).



The first MLCD in Hawai'i was Hanauma Bay, O'ahu, established in the fall of 1967. Fish populations were observed to increase at a phenomenal rate and as a result the bay has become world famous as a premier dive and snorkel site. Source: DLNR [2 page spread]

Marine conservation districts are established by the State of Hawai'i, Department of Land and Natural Resources following suggestions for additions to the system that come from the state legislature or the public. The DLNR's Division of Aquatic Resources conducts surveys of marine ecosystems on a statewide basis and also recommends areas that hold promise of successful restoration for MLCD status.

To commit an area for conservation status, it is evaluated by the DLNR with regard to public accessibility, quality of marine life and future potential value, safety from a public usage standpoint, compatibility with adjoining area usage, and minimal environmental or ecological changes from an undisturbed natural state. The area should have recognizable boundaries so users can easily identify it and so that it can be readily enforced by conservation officers employed by the DLNR. Importantly, the district must be of sufficient size that daily and seasonal fish movement patterns fall reasonably within the protected area ensuring that a population of fish remains protected throughout their normal activities. Movement patterns of many reef fish are not well understood, but research continues to improve our understanding of this aspect of MLCD's.

If an area being considered for protection meets the criteria of a MLCD, state scientists employed by the Division of Aquatic Resources conduct fish surveys, topographic analysis, and establish a baseline of ecologic health for the area. This ensures that future research can determine the performance of the district. Input from public, governmental, and private agencies is considered in making a final determination. Final approval is obtained from the Board of Land and Natural Resources and the Governor.

The most important fishery management objective is to protect the long-term health of fish stocks to ensure that marine ecosystems are not damaged. Many populations of exploited fish are declining in numbers and size despite the best efforts of fishery managers. Sustainable fisheries have become an unreachable goal under current management approaches. Marine protected areas offer a way out of this downward spiral. If some of the larger, more fecund, and genetically more robust fish are fully protected from harvesting, those fish will provide a dependable quantity and quality of offspring.

The actual level of protection within different types of marine protected area's (MPA) in Hawai‘i can vary. The most effective MPA's protect ecosystem structure and function by including a core of no-take reserves in which any extraction of living organisms is prohibited. Because ocean currents transport eggs and larvae over large distances, networks of no-take reserves or *Kapu Zones* are needed to achieve the stock rebuilding objective.

Fishery Management Areas are areas that are closed to certain fishing gears or activities, while remaining open to others, or areas that are closed for a length of time and later reopened to allow fish populations to recover and grow to harvestable size. The Hawai‘i bottom fish plan designates 20% of important bottom fish habitat as no-fishing zones for bottom fish around the main islands. Many wonder when the same level of protection will be levied upon the nearshore, reef-based fishery as called for by researchers.[68]

Marine Life Conservation Districts may permit some extractive activities, including certain kinds of recreational fishing such as pole-and-line, spear fishing without SCUBA, and certain types of nets. Commercial fishing is generally forbidden. There are MLCD's at Hanauma Bay, Pupukea, and Waikīkī on O‘ahu; Lapakahi, Kealakekua Bay, Waialea Bay, and the Old Kona Airport on the Island of Hawai‘i; Molokini Shoal and Honolua-Mokuleia Bay on Maui; and Manele-Hulopoe on Lana‘i. Only two, at Hanauma Bay and Waikīkī, prohibit all harvesting.[69]

Natural Area Reserves, wildlife sanctuaries and other reserves and refuges are closed to all extractive types of fishing and gathering, except perhaps native Hawaiian harvesting. They include Ahihi-Kinau Natural Area Reserve on Maui, Kaho‘olawe Island Reserve, and Coconut Island – Hawai‘i Marine Laboratory Refuge on O‘ahu. Marine Sanctuaries such as the Hawaiian Islands Humpback Whale National Marine Sanctuary usually allow commercial and recreational fishing, although some parts of a sanctuary may be set aside as no-take reserves.

The Spill-over Effect

Reserves serve as natural hatcheries, replenishing fish populations regionally through egg and larval spillover beyond reserve boundaries. The dispersal of eggs and larvae from no-take marine reserves to surrounding areas can maintain and improve fishing in adjacent areas because large individuals in the reserve escape capture and their total egg production is much higher than smaller members of the same species. The size and abundance of exploited species also increases in areas adjacent to reserves. Fishermen excluded from marine reserves generally experience significant benefits because fishing in neighboring areas is vastly improved.

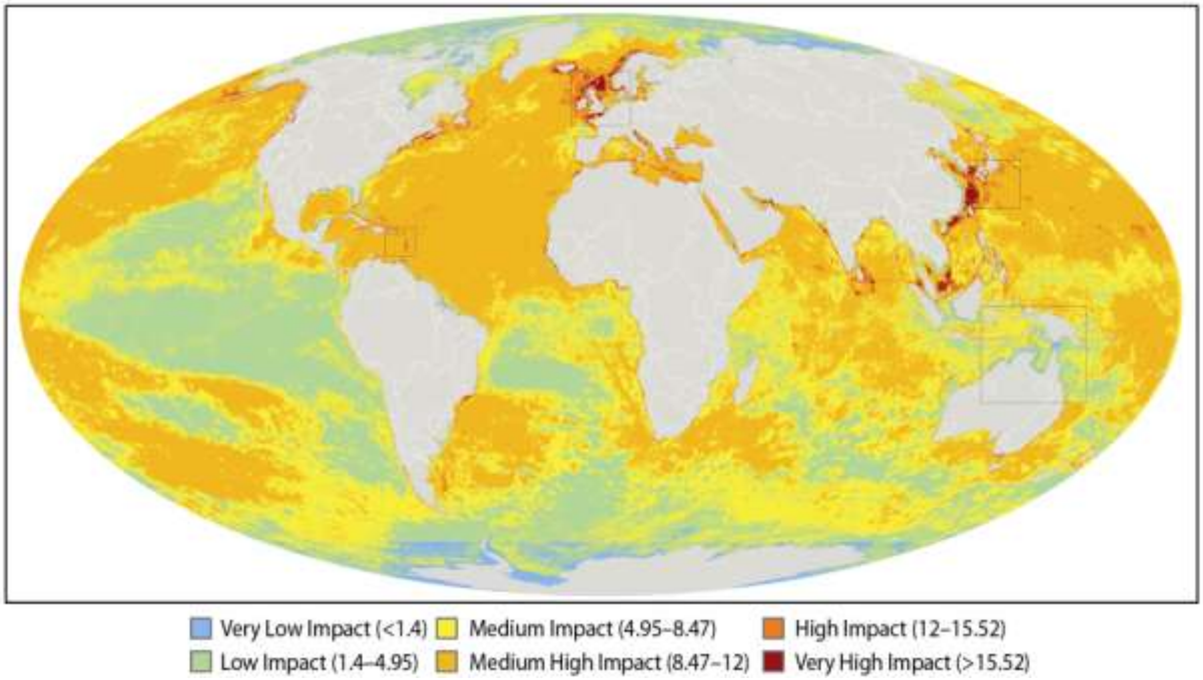
Marine reserves also create economic opportunities that contribute as much or more to Hawai‘i's economy than commercial fishing. This is because marine reserves are excellent sites for ecotourism and ocean wilderness tours, scientific research, marine education, recreational snorkeling and diving, underwater photography, and cultural activities. However, it must be noted that even non-extractive uses can alter and damage reserve ecosystems.

Since it is usually easier to prevent environmental damage than to repair it later, caution dictates that in the absence of sufficient information on which to base safe and reliable estimates of the effect of an activity, the burden of proof must shift to those proposing activities that may have a negative effect on the ecosystem. Only after a proposed user has demonstrated with a reasonable degree of certainty that the proposed use will not impose an unacceptable cost or loss to the resource should that activity be specifically permitted.

Demonstrated Benefits

Marine reserves can produce long lasting and rapid increases in abundance, diversity, and productivity of fish populations.[70] Fish size and reproductive output are known to increase within reserves. Decreased mortality, decreased habitat destruction, decreased extinction, and balanced, healthy ecosystems also result. Marine reserves provide sites for collecting valuable fishery-independent data. Larger reserve sizes result in increased benefits but even small reserves have positive effects if they are part of a network. Size and abundance of harvested species increase in areas adjacent to reserves.

Networks of reserves buffer against localized changes in environment that threaten fish populations and provide significantly greater protection for marine communities than a single reserve. Reserve networks that span large geographic distances and encompass substantial areas protect against catastrophic events and provide stable platforms for dispersal of sustainable marine communities in the long term.



Global map of human impacts to marine ecosystems. Cumulative impacts include: effects of primitive fishing methods in less developed countries, destructive commercial fishing in the open seas, pollution from industrial chemicals, invasive species, nutrient pollution in coastal areas, ocean acidification, oil rigs and other platforms, ocean-based pollution, commercial shipping, population pressure, climate change to sea surface temperature, and increase in ultraviolet radiation. (http://www.nceas.ucsb.edu/GlobalMarine) [2 page spread]

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