The State of Coral Reef Ecosystems of the Main Hawaiian Islands

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INTRODUCTION AND SETTING

The main Hawaiian Islands (MHI) form the southern part of the Hawaiian Archipelago, which is located in the middle of the North Pacific Subtropical Gyre, centered at about 28°N (Figure 8.1). The MHI consist of eight high volcanic islands that range in age from active lava flows on the east side of the Big Island (Hawaii Island) to seven million-year-old Kauai (Figure 8.2). Owing to its location in the middle of the Pacific Ocean, Hawaii's coral reefs are exposed to large open ocean swells and strong tradewinds that have a major impact on the structure of the coral reefs and result in distinctive communities that are sculpted by these dynamic natural processes. Circulation is primarily from east to west and intensifies southward, however, in the lee of the islands, surface currents driven by wind combine with large-scale ocean currents to yield more complicated flow patterns such as eddies (Flament et al., 1996). The average surface water temperature around Oahu is 24°C (75°F) in winter and 27 °C (81°F) in summer.

The geographic isolation of Hawaii has resulted in some of the highest endemism of any tropical marine ecosystem on earth (Kay and Palumbi, 1987; Jokiel, 1987; Randall, 1998). Some of these endemics are dominant components of the coral reef community, resulting in a unique ecosystem that has extremely high conservation value (DeMartini and Friedlander, 2004; Maragos et al., 2004). With species loss in the sea accelerating, the irreplaceability of these species makes Hawaii an important biodiversity hotspot.

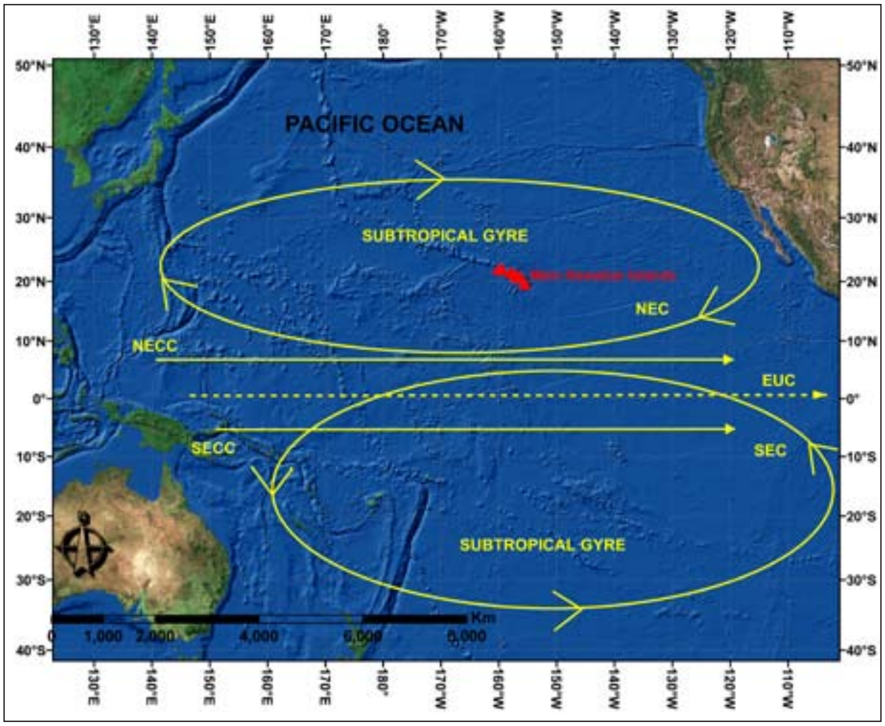

Figure 8.1. Topographic map showing the location of the MHI and the major ocean currents in the region: North Equatorial Current (NEC), South Equatorial Current (SEC), North Equatorial Counter Current (NECC), South Equatorial Counter Current (SECC), Equatorial Under Current (EUC). Source: PIFSC-CRED.

Coral reefs were important to the ancient Hawaiians for subsistence, culture and survival. Today these reefs provide commercial, recreational and subsistence fishing opportunities, create world famous surfing and diving locations, and are vital to Hawaii's approximately $800 million a year marine tourism industry. The economic value of Hawaii's coral reefs was estimated at US$10 billion with direct economic benefits of $360 million per year in 2002 (Cesar and van Beukering, 2004). Despite their economic significance, reefs near urbanized areas have experienced increasing stress from human and land-based impacts due to ever-increasing population pressures.

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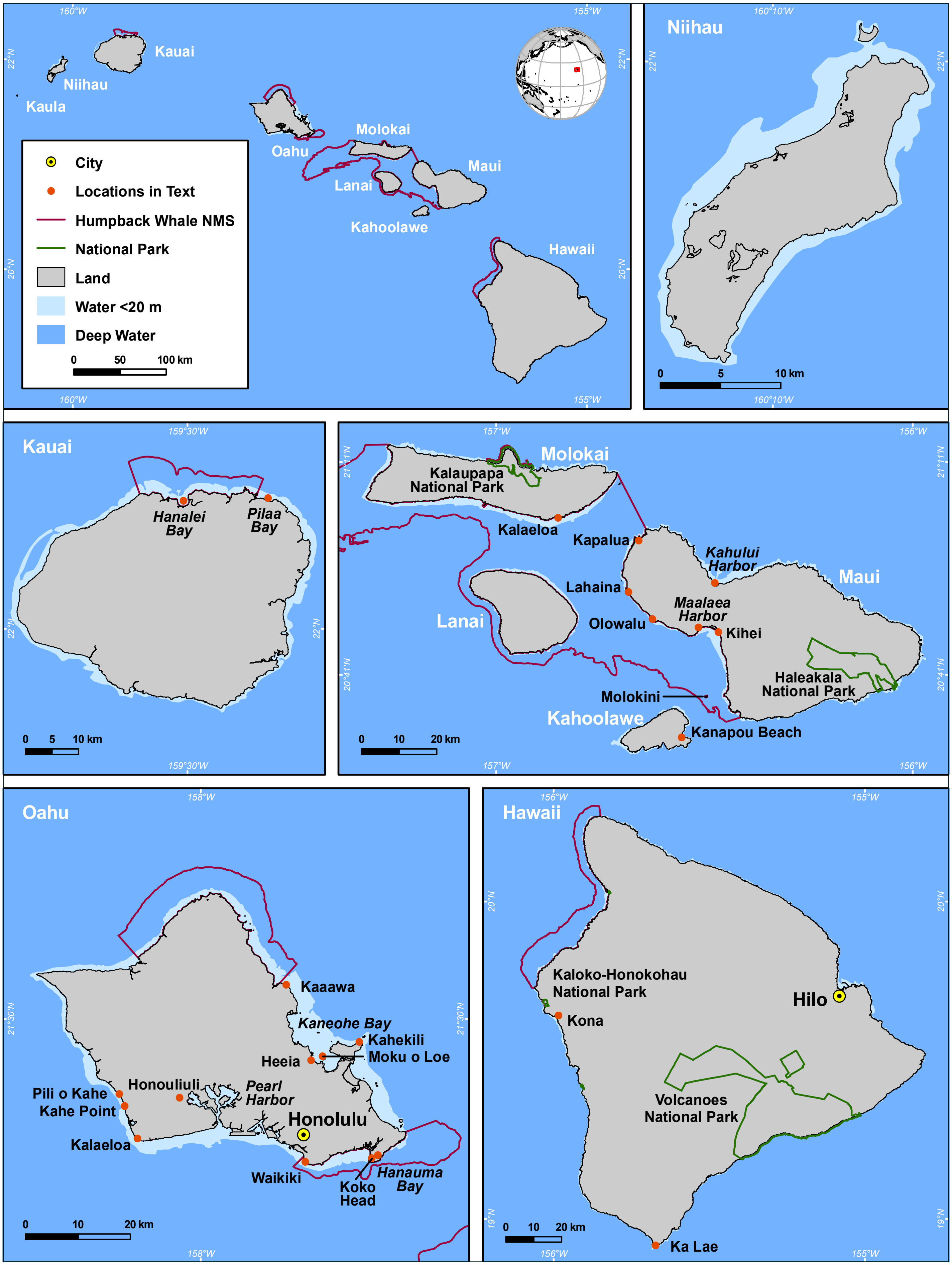

Figure 8.2. Maps of the MHI showing locations mentioned in this chapter. Map: K. Buja.

ENVIRONMENTAL AND ANTHROPOGENIC STRESSORS

Climate Change and Coral Bleaching

As a result of recent bleaching events and increased ocean warming trends, climate change has become an important issue in Hawaii. Climate change is expected to influence water temperatures, ocean pH and sea level with related changes in available coral reef habitat, wave climate and coastal shorelines (U.S. EPA, 1998). Hawaiian waters show a trend of increasing temperature over the past several decades that are consistent with observations in other coral reef areas of the world (Figure 8.3, Coles and Brown, 2003). The average annual sea surface temperatures (SSTs) in Hawaii have increased 0.8°C since 1956, and rising water temperatures are expected to increase the frequency and severity of bleaching events (Jokiel and Coles, 1990).

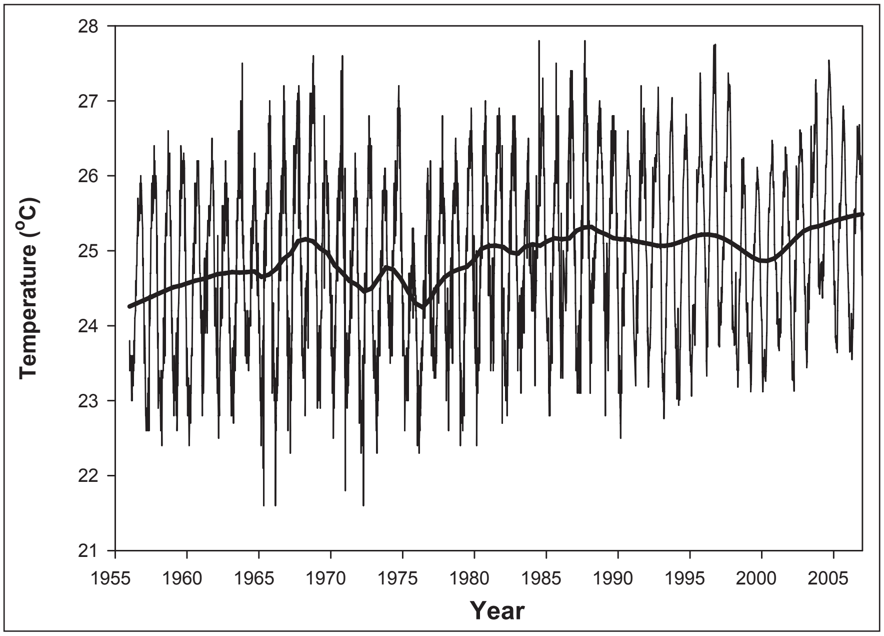

Figure 8.3. Weekly averaged NOAA temperature series taken at Koko Head, Oahu (21°17'N, 157°41'W) and weekly IGOSS-NMC data series that overlapped temporarily. Data sets were merged and smoothed using a LOWESS averaging function. Source: Jokiel and Brown (2004) with extended data from http://ingrid.ldeo.columbia.edu/.

To date, there have only been three documented bleaching events within the Hawaiian archipelago. The first documented large-scale coral bleaching occurred on Oahu during late summer of 1996. This bleaching event was triggered by a prolonged regional positive oceanic sea surface temperature anomaly that developed offshore during the time of the annual summer temperature maximum. High solar energy input and low winds further elevated inshore water temperatures by 1-2°C in reef areas with restricted water circulation (e.g., Kaneohe Bay, Oahu) and in areas where mesoscale eddies retain water masses close to shore for prolonged periods of time. The other two bleaching events occurred on the reefs of the Northwestern Hawaiian Islands (NWHI). In 2002, mass coral bleaching occurred predominantly on the back reefs of the three northernmost atolls (Pearl and Hermes, Midway, Kure; Aeby et al., 2003; Kenyon et al., 2006a). Over 60% of the corals bleached in these shallow, back reef environments. In 2004, another although less severe, event occurred in the NWHI (Kenyon and Brainard, 2006). Please see the NWHI chapter of this report for details.

Diseases

Baseline disease studies were initiated on Oahu in 2004 and Maui in 2005, and multi-agency research cruises in 2005 and 2006 facilitated surveys at all eight main Hawaiian Islands. Analysis of 2004 and 2005 surveys (n=78), revealed eight coral diseases from the three major coral genera (*Porites, Montipora, Pocillopora*). Disease was widespread but occurred at low levels. Differences were found among disease states with some diseases such as *Porites* trematodiasis being very common while other diseases had a limited distribution (Figure 8.4, Aeby et al., unpub. data). Oahu, Maui and the Big Island had the highest occurrence of disease, as well as the highest prevalence (proportion of corals surveyed which had signs of disease; Table 8.1; Aeby et al., unpub data). Disease assessment is now a component of the state-wide coral reef monitoring program and a set of underwater disease identification cards have recently been produced.

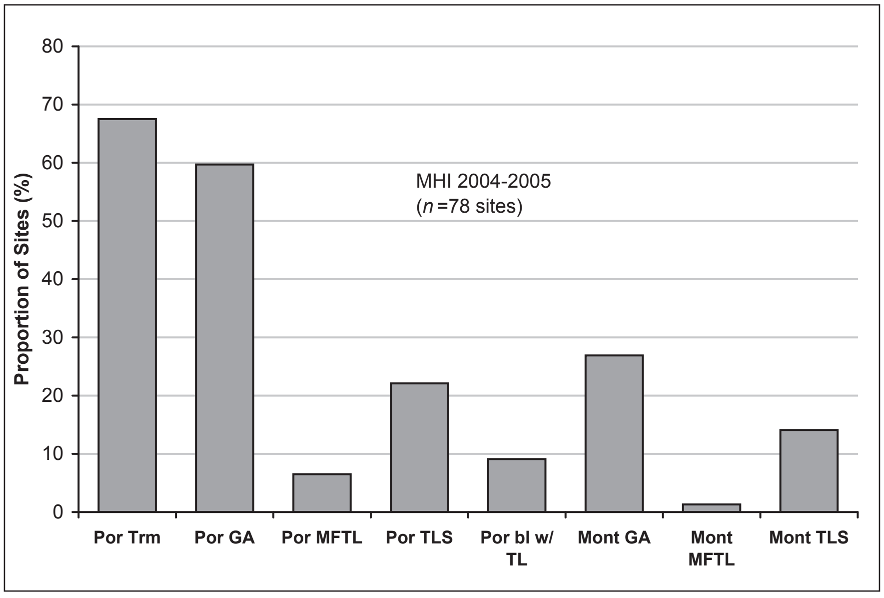

*Figure 8.4. Frequency of occurrence of different coral diseases within the MHI. Por=*Porites*, Mont=*Montipora*, TRM= trematodiasis, TLS=tissue loss syndrome, GA=growth anomaly, MFTL=multifocal tissue loss, WS=white syndrome, Source: Aeby et al., unpub. data.*

Two coral diseases of potential concern are *Porites* growth anomalies (Figure 8.5) and

Montipora white syndrome (Figure 8.5). *Porites* growth anomalies are more widespread in the MHI (59.7% of sites surveyed) compared to the reefs of the NWHI (4.9% of sites; Aeby, 2006; Aeby et al., unpub. data). *Montipora* white syndrome, first found in Kaneohe Bay in 2004, causes acute tissue loss and has now been documented throughout the MHI. Prevalence of this disease is approximately four times higher in Kaneohe Bay (average prevalence=0.27 + 0.08% SE) than in the other main islands (avgerage prevalence=0.06 + 0.02% SE; Aeby et al., unpub. data).

Table 8.1. Differences in disease levels among islands within the MHI. Disease surveys conducted in 2004 and 2005. Source: Aeby et al., unpub. data.

Island	# Sites Surveyed	Depth (ft)	Avg. Coral Cover (%) (± SE)	Frequency of Disease Occurance (%)	Avg. Disease Prevalence (± SE)
Hawaii	19	24-50	29.2 ± 3.2%	100.0	1.20 ± 0.44%
Maui	11	7-50	41.1 ± 7.5%	100.0	1.36 ± 0.37%
Oahu	27	5-60	23.6 ± 3.9%	100.0	1.03 ± 0.25%
Kauai	12	21-56	7.5 ± 1.8%	83.3	0.39 ± 0.21%
Niihau	6	30-50	<1 (<1)	16.7	0.02 ± 0.02%
Lehua	3	38-50	<1 (<1)	33.3	0.02 ± 0.02%
Total	**78**				

The endangered Hawaiian green sea turtle is affected by fibropapillomatosis (FP), a disease that causes external and internal tumors. Recent evidence suggests herpes virus as a probable cause or co-factor of FP (Quackenbush et al., 1998). This disease has been present in turtle populations in Hawaii since the early 1950s (Balazs and Pooley, 1991), but ongoing surveys on Molokai indicate that the prevalence of FP has been declining steadily for the past 5-8 years (Balaz, PIFSC data).

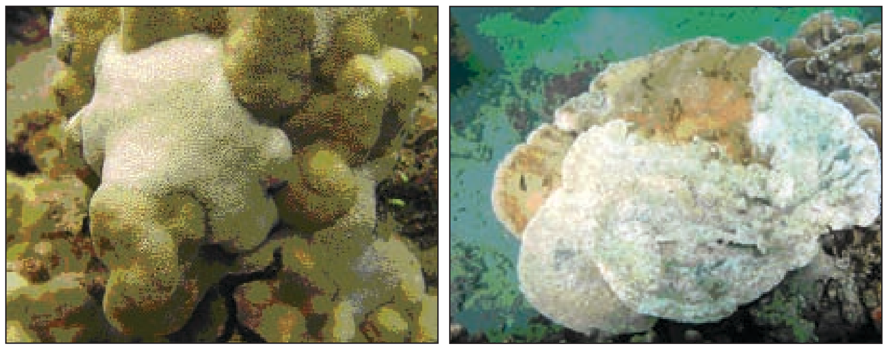

Figure 8.5. Porites lobata *with growth anomaly (left).* Montipora capitata *with white syndrome (right). Photos: G. Aeby.*

A number of diseases have been observed in reef fishes. Two endemic butterflyfishes (*Chaetodon multicinctus* and *C. milliaris*) in Maui had a high prevalence of skin tumors possibly caused by suspected contaminants (Okihiro, 1988). Other studies have examined the possibility of disease transmission between the introduced blue-lined snapper (*Lutjanus kasmira*) and co-occurring native goatfish species (*Mulloidicthys* spp.). Surveys of four different species of goatfishes from Maui and Oahu revealed infections with a protozoan similar to that found in blue-lined snappers with prevalence ranging from 25 to 90%. In contrast, prevalence of the putative bacterium in goatfish is very low (<1%, Work and Aeby, unpub. data).

The first documented disease event in Hawaiian marine algae occurred in West Maui (Spalding, unpub. data). *Halimeda kanaloana* is an endemic, calcified green alga forming expansive meadows over soft, sandy substrate. In July 2006, a 50 m^2 area (approximately) of the meadow began to die (Figure 8.6). Individual plants began to turn yellow and shed their segments, eventually resulting in plant death. Current studies are tracking the spread and survival of *Halimeda* plants in this diseased area, and monitoring for possible recovery.

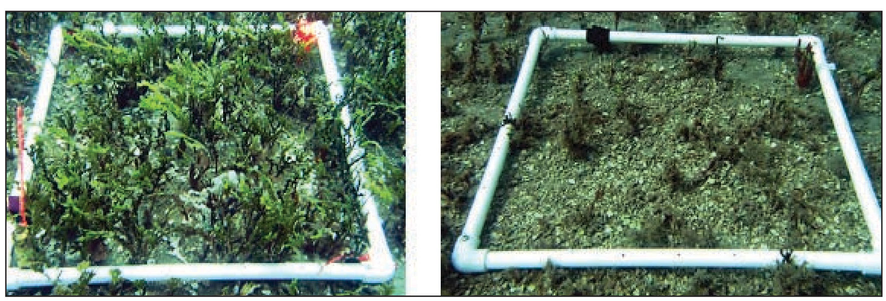

Figure 8.6. Halimeda kanaloana *densities in healthy (left) and diseased (right) areas. The white quadrat is 0.25* m^2*. The diseased area is covered with a thick layer of dead white* Halimeda *segments. Photo: H. Spalding.*

Tropical Storms

A unique set of biogeographical factors and physiological tolerances structure Hawaiian reefs and limit community assemblages to a relatively few hearty species. Breaking waves from surf generated by Pacific storms is typically the most important factor structuring exposed reef communities throughout the MHI (Dollar and Grigg, 2004; Jokiel et al., 2004). Several exceptions exist: areas influenced by recruitment events (Coles and Brown, 2007) and sheltered embayments which are impacted by anthropogenic activities (Dollar and Grigg, 2004). Recent evidence from reef cores indicates that in the last 11,000 years the only substantial accretion presently taking place in Hawaii occurs in sheltered embayments or inside barrier reefs that are protected from storm wave impact (Rooney et al., 2004). These sheltered areas, however, make up less than 5% of the coastal areas of the MHI.

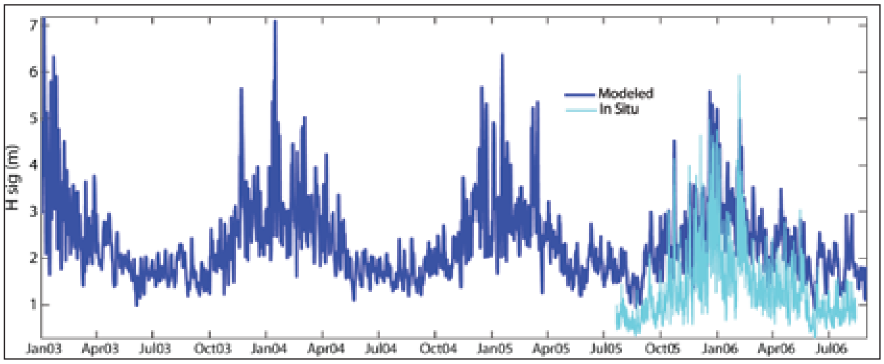

Figure 8.7. In situ *and Wave Watch III significant wave height (m) data from Mana Reef (west Kauai) from January 2003 to September 2006. Note that the* in situ *data are collected near shore and contains wave shoaling, whereas the modeled data are for the open ocean. Source: PIFSC-CRED.*

In general, the Hawaiian archipelago's wave climatology is characterized by large (>5 m), long period (15-25 seconds) surface gravity waves during the winter months and relatively small (1-3 m), short period (7-11 seconds) waves during the summer months (Figure 8.7). Seasonally large waves are due to the combination of an active Aleutian Low, the large area of the North Pacific and the Hawaiian Islands geographic location. Easterly trade winds associated with the North Pacific Subtropical High are the primary source of shorter period and smaller wave heights during summer months. Long period, larger wave events (3-4 m) occur during summer; but are typically ephemeral due to the extended travel distance of wave trains from their source, the Southern Ocean, to the Hawaiian Islands.

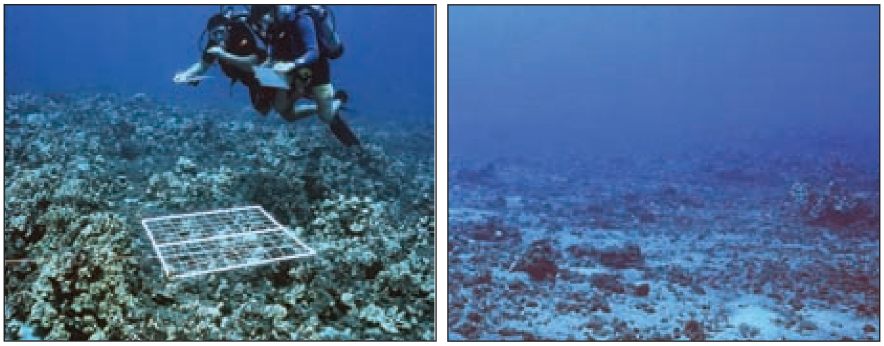

Figure 8.8. Reef structure at Puamana, Maui prior to (left) and after (right) Hurricane Iniki in 1992. Photos: E. Brown.

In recent decades only two major hurricanes (Hurricane Iwa, 1982; Hurricane Iniki, 1992) have struck the islands. Some reefs were reshaped by Hurricane Iniki (Figure 8.8). Since 2005, Tropical Storms Kenneth (2005), Jova (2005), Daniel (2006) and Fabio (2006) have come relatively close to the main Hawaiian Islands, impacting local rain and wind patterns but not causing significant damage or loss (Figure 8.9).

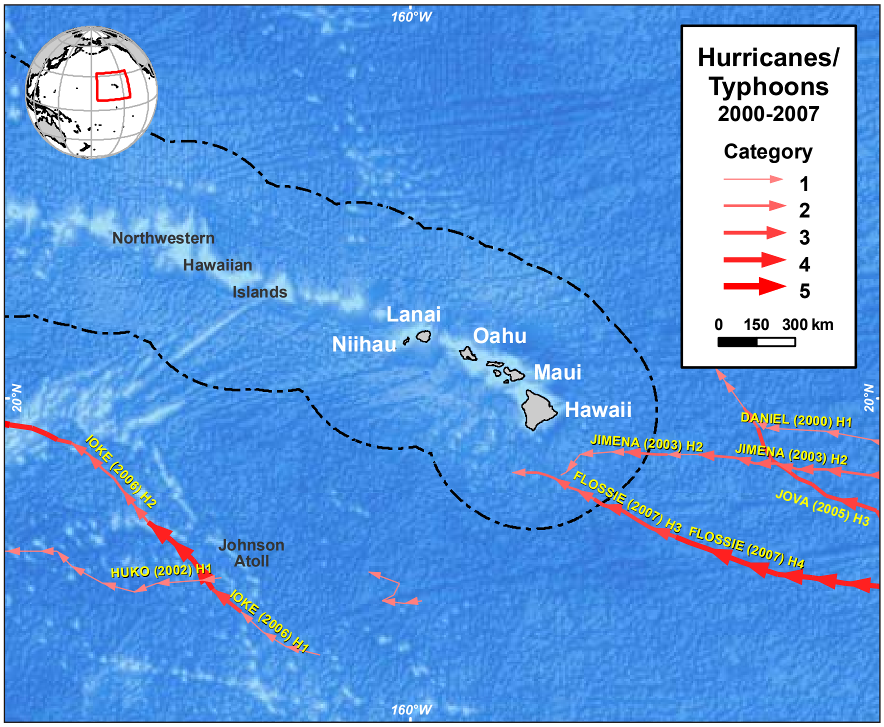

Figure 8.9. A map showing the paths and intensities of tropical storms passing near the MHI from 2000-2007. Map: K. Buja. Source: http://weather.unisys.com/hurricane/.

Recovery from storm events varies by site and is often driven by recruitment events (Coles and Brown, 2007). Recent evidence from consistent long-term sampling on Oahu indicates that coral cover at sites in close proximity (100 m -1 km) respond differently to storm activity and cycle independently of each other (Figure 8.10). This pattern appears to be driven by recruitment pulses of 10-12 years for *Pocillopora meandrina* and 15 or more years for *Porites lobata* that occurred at different time periods within each site.

During El Niño Southern Oscillation (ENSO) events in the MHI, warmer sea surface temperatures in the equatorial Pacific cause the subtropical high to shift closer to the islands, forcing trade winds to subside and suppressing Kona storms and fronts near Hawaii (Figure 8.11). As a result, leeward areas that depend on winter season rain from these storms tend to experience drought. Conversely, during neutral periods and La Niñas, this high-pressure center is absent, enabling Kona storms and fronts to form or migrate into their vicinity (Rooney and Fletcher, 2005). ENSO is a naturally occurring phenomenon, however, there is uncertainty regarding how global warming and the associated climate changes will impact the frequency and/or magnitude of this cycle, and how that will in turn affect coral reef ecosystems.

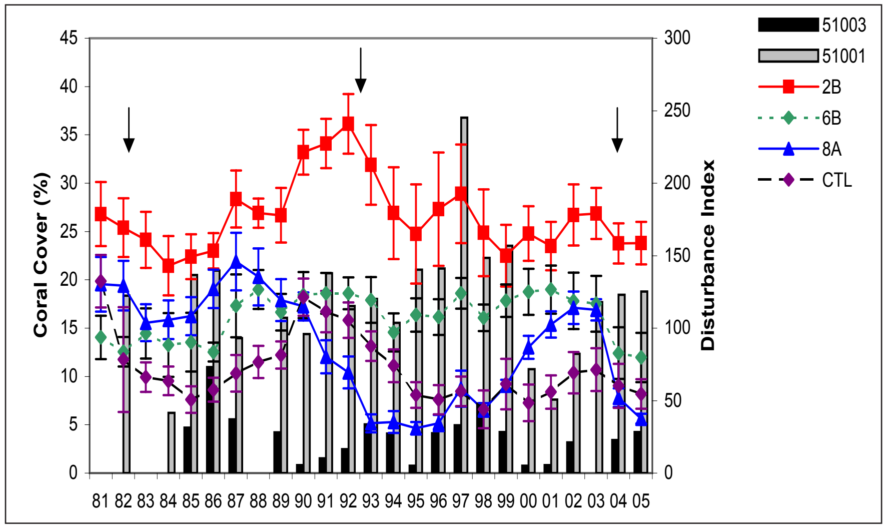

Figure 8.10. Yearly total coral cover from 1981-2005 at coral monitoring sites (line plots), and disturbance indices calculated for wave data from NOAA Buoys 51001(gray bars) and 51003 (black bars) for all data available from 1981 to 2005. Arrows indicate Hurricanes Iwa (1982) and Iniki (1992) and major local storm runoff (2004). Errors bars are ± 1 SE of the mean. Source: Coles and Brown, 2007.

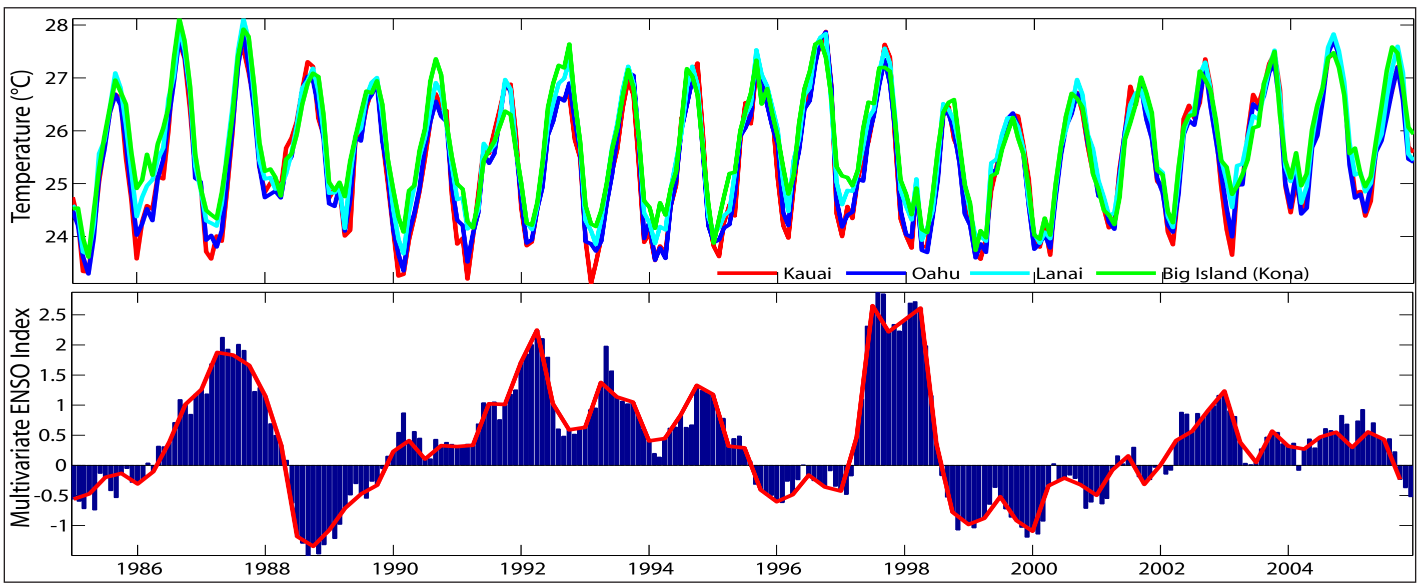

Figure 8.11. Relationship between NOAA Pathfinder SSTs (top) and ENSO Multivariate Index (MEI; bottom) for the MHI from 1985 to 2006. Positive (negative) values of the MEI indicate El Niño (La Niña) conditions Source: PIFSC-CRED, unpub. data.

Coastal Development and Runoff

Hawaii's coastlines continue to be developed for a variety of land uses. Agricultural lands that were once primarily used to grow sugarcane and pineapple are being converted to residential and resort uses across the state. Total acreage of sugarcane decreased almost 50% from 1995 to 2005 with 33,167 ha (81,957 acres) and 16,246 ha (40,145 acres) estimated respectively (State of Hawaii Data Book, 2005). Many of Hawaii's low-lying coastal areas were once wetlands and flood plains before being altered for agriculture and development. More sediment is delivered to nearshore waters as coastal areas are developed, floodplains filled, storm drains constructed and streams channelized (Figure 8.12). Detailed land-use change data are not available for Hawaii, although baseline land cover data were collected in 2000 through the NOAA Coastal Change Analysis Program. The NOAA Pacific Science Center is currently developing a GIS layer of impervious surfaces in Oahu, which is scheduled to be completed by the end of 2007.

Harbor facilities on all the MHI are being improved to accommodate new large cruise ships, an inter-island car/cargo ferry, large container ships, increasing demand for commercial and recreational facilities, and the need to improve harbor entrance safety. In Kahului Harbor on Maui, the proposed expansion of pier space to accommodate additional large ships may displace outrigger canoe teams and surfers. At Maalaea Harbor on Maui, a $10 million expansion of berthing facilities and reconfiguration of the entrance channel has been planned for 40 years. The preferred design is controversial because it will eliminate 6 ha of coral reef and impact a surf site, while providing over 100 new berths for recreational and commercial boats. A new Supplemental Draft Environmental Impact Statement is expected to be released in 2007 to advance this controversial project.

Coastal Pollution

Point Sources

Seven major wastewater treatment plants discharge to the coastal ocean in Hawaii (Table 8.2). All but two of these discharge through deepwater outfalls (>40 m) where there is little potential for impact to coral reefs.

Although deepwater outfalls do not appear to impact the shallow reefs of Hawaii's coastal waters, spills of untreated or poorly treated wastewater are a public health concern for bathers and surfers. A very large spill of more than 184.3 million liters (48.7 million gallons) of untreated wastewater occurred on March 24, 2006 into the Ala Wai canal near Waikiki. The spill continued for over five days and beaches at Waikiki were posted with warning signs for weeks. The number of sewage spills reported by the city and county of Honolulu to U.S. Environmental Protection Agency (EPA) during 2000-2004 was high, ranging from 200-300 spills per year. Most of the reported spills did not discharge to surface waters but were contained on land. Enforcement actions and lawsuits related to sewage spills on Oahu are currently pending.

In addition to discharges from wastewater treatment facilities, individual and general National Pollutant Discharge Elimination System (NPDES) permits are also required for storm water. Major NPDES storm water permits provide coverage for the municipal separate storm sewer system of the City and County of Honolulu, and state highways within the City and County of Honolulu under Hawaii Department of Transportation jurisdiction. Permits also cover airports and harbors throughout the state. The General Permit authorizing discharges of storm water associated with construction activity requires a Notice of Intent be filed with Department of Health prior to the initiation of land disturbance activities greater than one acre (Figure 8.13). The General Permit requires, among other things, that a construction best management practices plan be developed and implemented to minimize erosion of soil and discharge of other pollutants into state waters.

In recent years, erosion from coastal construction sites has damaged coral reefs on the Big Island and on Kauai, resulting in costly lawsuits and enforcement actions. In the Kauai case, a $7.5 million settlement was announced in March 2006 for Clean Water Act violations that resulted in sediment damage to a home, beach and coral reef at Pilaa Bay. The violations involved grading a coastal property and filling streams without the required Clean Water Act permits. Storm water erosion control measures, as required by the permits, may have prevented damage from sediment-laden runoff. This is the largest

Figure 8.12. Coastal runoff in Maunalua Bay, Oahu. Photo: The Nature Conservancy.

Table 8.2. Wastewater treatment plants that discharge to Hawaii's coastal waters. Source: U.S. EPA.

	DESIGN FLOW (millions of gallons per day)	LEVEL OF TREATMENT
Deepwater Discharges(>40 m)		
Sand Island, Oahu	82	Advanced primary
Honouliuli, Oahu	38	Advanced primary
Waianae, Oahu	5	Secondary
Kailua, Oahu	15	Secondary
Hilo, Hawaii	5	Secondary
Shallow Water Discharges (<40 m)		
East Honolulu, Oahu	3.9	Secondary
Ft. Kamehameha, Oahu	13	Secondary
Wailua, Kauai	1.5	Secondary

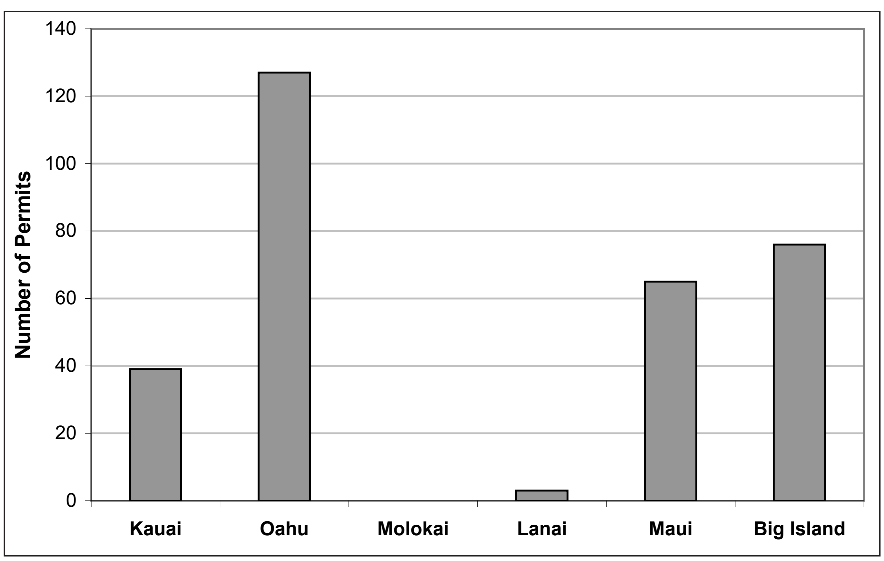

Figure 8.13. Number of NPDES Construction General Permits granted from 2005-2006. Source: HIDOH.

stormwater settlement for violations at a single site, by a single landowner in the U.S. It involved EPA, the Department of Justice, Hawaii Department of Health, Kauai County and Earth Justice. The settlement calls for payment of $2.2 million in penalties and $5.3 million to prevent erosion and restore damaged streams at the construction site. In a related state enforcement action, the Hawaii Board of Land and Natural Resources fined the property owner an additional $4 million for natural resources damages to the beach and coral reef.

Nonpoint Sources

Sediment is probably the leading land based pollutant causing alteration of reef community structure in the MHI (Figure 8.14). Several major sources of erosion have been removed or reduced, which will likely lower the potential for negative effects in the future. Examples include the closure of large agricultural plantations, cessation of live fire training on the island of Kahoolawe, and culling programs for feral ungulates on the islands of Lanai and Molokai.

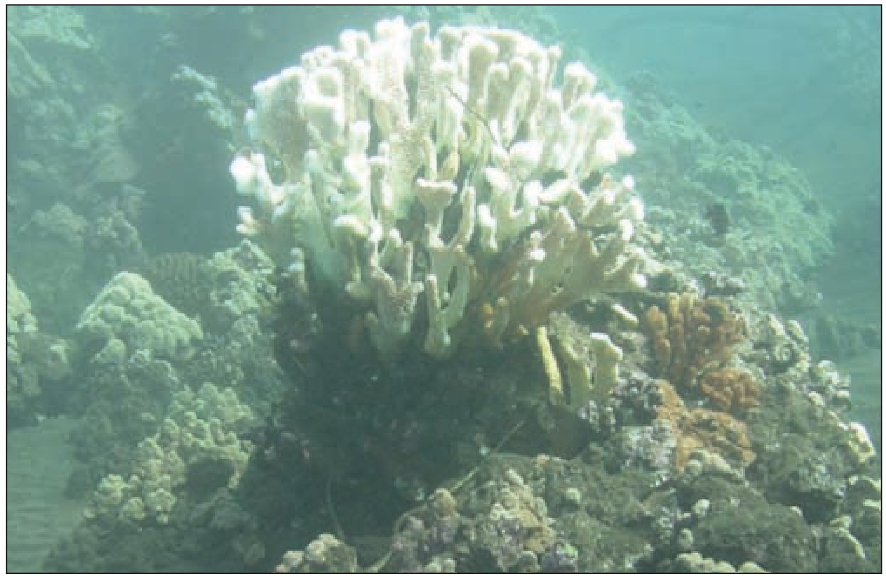

Figure 8.14. Sediment covering the reef at North Kohala, Hawaii. Photo: B. Walsh.

In many areas of Hawaii, nearshore water chemistry is a mixture of oceanic water and freshwater emanating from both submarine groundwater discharge at or near the shoreline and surface water runoff. Hawaii's groundwater and surface water discharge are equivalent to about 20% of rainfall (Yuen and Associates, 1992), except on Kauai, which has a higher rate due to greater overall rainfall. Groundwater in Hawaii typically contains two to three orders of magnitude higher concentrations of dissolved nitrogen and phosphorus than seawater. Thus, groundwater nutrients are an important factor of nearshore marine water chemistry. The groundwater nitrogen load reflects natural background and anthropogenic sources from wastewater and fertilizers. Calculations using values from U.S. Geological Survey (USGS) groundwater models show that ambient groundwater contributes about 1,800 tons of nitrogen annually to the nearshore ocean along the west coast of the Big Island.

On neighbor islands, most of the sewage treatment plants discharge secondary treated wastewater into the ground through 15-60 m deep injection wells. In some cases, a portion of the effluent is reused for irrigation, providing additional opportunity for nutrient and particulate removal. Plumes from these injection wells have generally not been identified and traced. However, a recent tracer study on Maui identified the plume from the Kihei injection well down-gradient from the injection well between the treatment plant and the shore (Hunt, 2007). Models predict that the wastewater plumes mix with groundwater and discharge to the ocean fairly close to the shoreline in water less than 30 m deep.

Cesspools are a potentially harmful source of untreated wastewater, and Hawaii has an estimated 100,000 cesspools, more than any other state in both relative and absolute terms (EPA, unpub. data). The effects of nutrient and pathogen seepage on coral reefs is not known. Hawaii Department of Health (HIDOH) has issued new administrative rules that either ban or severely restrict the use of cesspools throughout the state. New cesspools are completely banned on the islands of Oahu and Kauai. On the islands of Maui, Molokai and Hawaii, new cesspools for individual homes only are allowed in certain areas. Through support from the Hawaii Coastal Zone Management Program, the University of Hawaii Water Resources Research Center is working on a project to provide information to promote the effective use of traditional, as well as innovative on-site wastewater treatment systems in rural and urban settings and to ensure that the technology is protective of water quality and the environment.

While there is no state-wide nutrient budget to assess the total magnitude of anthropogenic nutrient subsidies to groundwater, Soicher and Peterson (1997) developed a comparison for a relatively small region of West Maui. In this region, 91.3% of the nitrogen delivery to the ocean is associated with anthropogenic activities. It is of interest to note that since this estimate was compiled, sugarcane and pineapple farming have largely ceased. While there have been no documented impacts to the reefs in West Maui as a result of the additional nutrients, this coastline is known to have nuisance algal blooms.

Toxic pollutants are seldom measured in Hawaii's marine waters. In southern Kaneohe Bay, Hunter et al. (1995) reported elevated concentrations of lead, copper, chromium and zinc in oyster tissues near stream mouths. High levels of dieldrin and chlordane were also found in oyster tissues at some sites. In the Hanalei River and Estuary, the USGS reported trace levels of dieldrin, chlordane and DDE in fish and clams (Orazio et al., 2003). No polyaromatic hydrocarbons (PAHs) were detected in the water and only trace levels were found in sediments at one station. All organic contaminants were below EPA toxicity levels and in most cases were below limits of detection.

Tourism and Recreation

Tourism is Hawaii's primary industry, and visitor arrivals have shown a dramatic increase since 1970 (Figure 8.15). 2005 was a record-breaking year for Hawaii's visitor sector in terms of arrivals, visitor days and tourist expenditures, with nearly 7.5 million visitors and $11.9 billion in expenditures. Total visitor days also increased 7.7% to 68.2 million days (Hawaii DEBDT, 2005).

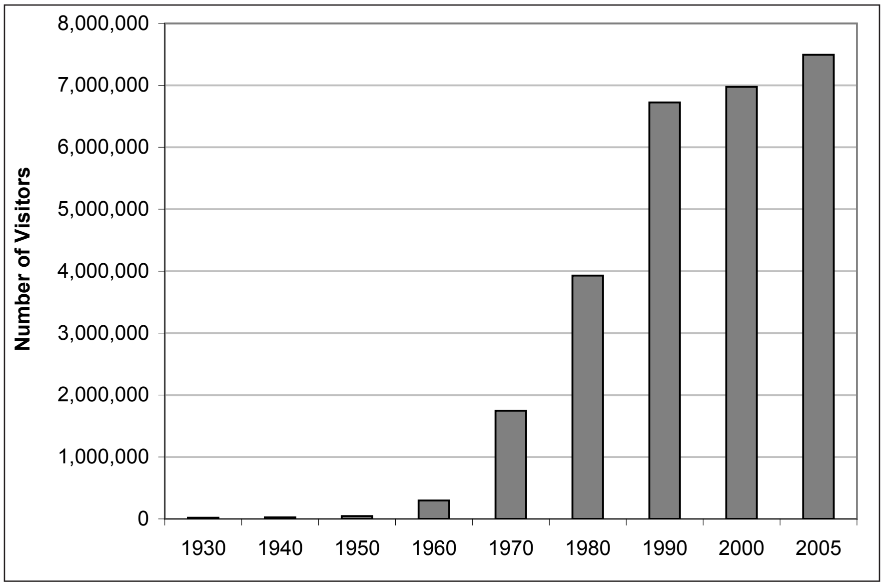

Figure 8.15. Number of visitors to Hawaii, 1930-2005. Source: Hawaii DBEDT.

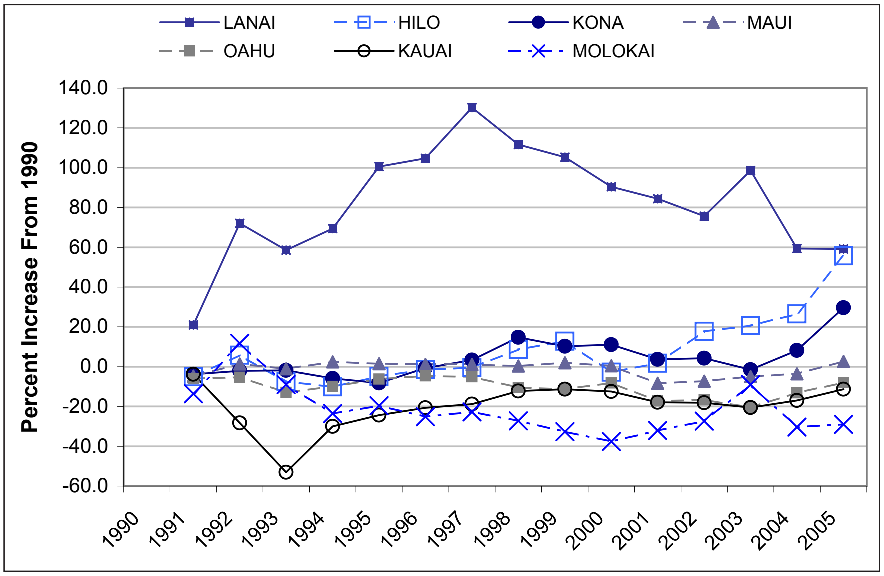

Figure 8.16. Percent increase in tourist arrivals from 1990 at major airports on Hawaii. Source: Hawaii DBEDT.

Visitation to Hawaii is growing as the sector expands, with the three Hawaii-based inter-island cruise ships that carry over 2,000 passengers a trip, and the 2007 launch of an inter-island ferry. It is believed that the ferry service will increase outer island visitation levels not only by international and domestic tourists but also by the resident population. The island of Maui continues to attract the bulk of its visitors from the domestic market and accounted for 25.3% of the state total visitor days in 2005. The Big Island had the largest increase in the number of visitors at 18.8%, with growth from both the domestic and international markets. With the elimination of pineapple agriculture and the development of two world-class resorts, the island of Lanai has seen a huge increase in tourism although the total numbers are still small compared to the larger, more developed islands (Figure 8.16).

Recent market research and polling results have shown that increased tourism is having a negative effect on local residents as visitors increasingly seek out remote locations that were traditionally used by residents (MTP Inc., 2006). Sixty-two percent of all respondents in 2006 indicated that they felt the islands were being run for tourists at the expense of local people, representing a 14% increase in negative attitudes in just four years. In 2005, 44% of households surveyed indicated that preservation of natural and open space was worse than in previous years (MTP Inc., 2006). In addition, on the days when the cruise ships are in port, popular sites are experiencing heavy use during the pulse of activity that occurs while the cruise ship passengers are ashore. In communities across the state, residents are seeking mechanisms to limit further use to minimize potential user impacts.

Over 82% of Hawaii's tourists participate in some form of ocean recreation, from sunbathing and swimming, to snorkeling and surfing, to jet skiing and parasailing (Hawaii DBEDT, 2005). Most, if not all, of this activity occurs around Hawaii's coral reefs that generate almost $364 million each year in added value (Cesar and van Beukering, 2004). In 2005, nearly 42% of all visitors participated in diving or snorkeling activities during their stay in Hawaii, however participation by visitors from the East such as Japan was markedly lower at 19.5% (Hawaii DBEDT, 2005). Participation in snorkeling and scuba diving was 10% lower in 2005 than in 2002. Many of Hawaii's Marine Life Conservation Districts are important destinations for diving and snorkeling tourism (Figure 8.17). Often the most popular sites

Figure 8.17. Left: Hanauma Bay receives nearly one million visitors a year and is one of the most visited marine reserves in the world. Photo: L. Kumabe Maynard; Right: Hawaii's coral reefs provide world famous surfing spots like the Banzai Pipeline on Oahu's north shore. Photo: John Stahl.

are lacking in or have minimal shore side facilities, which increase the potential for impacts affecting the nearshore resources. New forms of ocean recreation are constantly arising and management agencies are faced with growing challenges to define the carrying capacity of the areas and how to gauge and monitor impacts.

Most Hawaii residents also engage in some form of ocean recreation on a regular basis. Results of a state-wide stratified random survey of 1,600 households conducted in 2004 and 2005 showed that ocean swimming, recreational fishing, surfing, snorkeling and subsistence fishing were the major uses of the nearshore marine environment in Hawaii (Figure 8.17, Table 8.3; Hamnett et al., 2006). The percentage of households involved in ocean activities was 10-20% higher for ethnic Hawaiians, and these households reported significantly higher average frequencies of participation per year.

Table 8.3. Uses of the nearshore environment by Hawaii residents. Source: Hamnett et al., 2006.

ACTIVITY	HOUSEHOLDS	AVERAGE PER YEAR
Ocean swimming	66%	28
Recreational fishing	31%	10
Surfing	29%	18
Snorkeling	32%	6
Subsistence fishing	10%	5

Fishing

Coral reefs have always been an important component of human existence in Hawaii (Kamakau, 1839; Titcomb, 1972). Following statehood, Hawaii saw a rapid growth in tourism, an increasingly urban resident population, and the continued development of shoreline areas for tourism and recreation (Shomura, 2004). These developments resulted in changes in the character of the coastal fisheries as they became dominated by recreational anglers and a greater number of part-time commercial fishers who curtailed their fishing to take advantage of more lucrative economic activities (Friedlander, 2004).

Commercial Fishing

Data from the nearshore commercial fishery show total catch by handlines declining since the early 1990s, while the catch by spearfishing has increased during this same time period (Figure 8.18). Lay gillnet catch showed a peak in the early 1980s, declined sharply afterwards and has remained relatively constant since the late 1990s. Seine nets have the highest catch rates per trip among gear type, followed by lay gill net, spear and handlines (Figure 8.18). From 1966 to 1971, the average catch per trip by seine nets, excluding coastal pelagic species, was 736 lbs, while the average declined to 480 lbs/ trip from 2001 to 2006 (Figure 8.19). During the former time period, the catch was composed of surgeonfishes (28%) followed by bonefish (24%), jacks (19%) and Pacific threadfin (11%). Since 2001, the catch composition has been dominated primarily by goatfishes (34%) and surgeonfishes (34%) and shows a shift towards lower valued species.

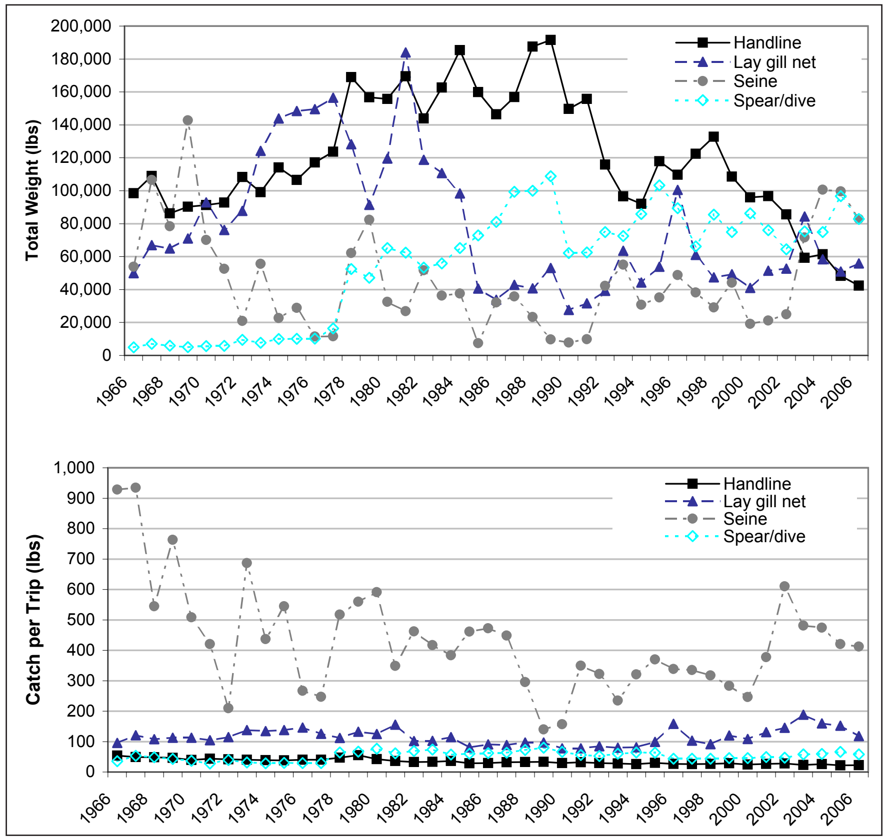

Figure 8.18. Total catch in pounds for the major gear types (top); catch per trip in pounds of the dominant gear types (bottom). Source: Hawaii DAR commercial catch records.

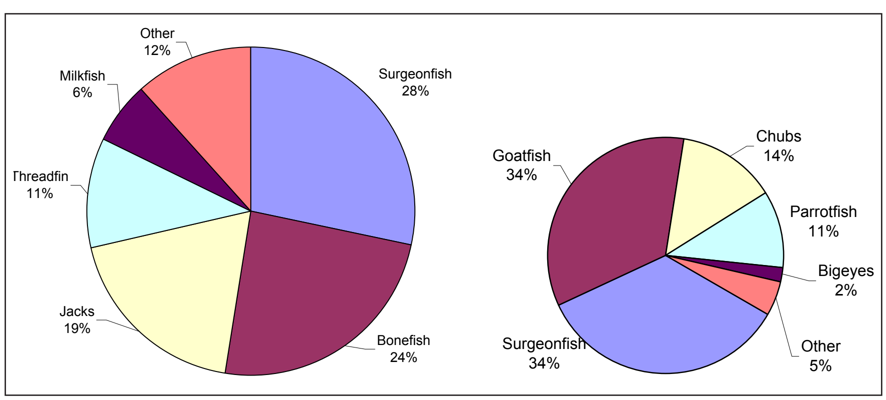

Figure 8.19. Species composition for seines for 1966 to1971 and 2002 to 2006. Pie size is proportional to total average annual catch per unit effort for each time period. Source: Hawaii DAR commercial catch records.

Recreational Fishing

The catch of coral reef species in Hawaii is dominated by recreational and subsistence fishers who are not required to report their catch (Friedlander and Parrish, 1997; Everson and Friedlander, 2004; Zeller et al., 2005). The increase in the number of registered vessels (Figure 8.20), many of which are used for fishing, and changes in the demographic and economic situation in Hawaii has likely led to an increase in the non-commercial catch of coral reef species over time.

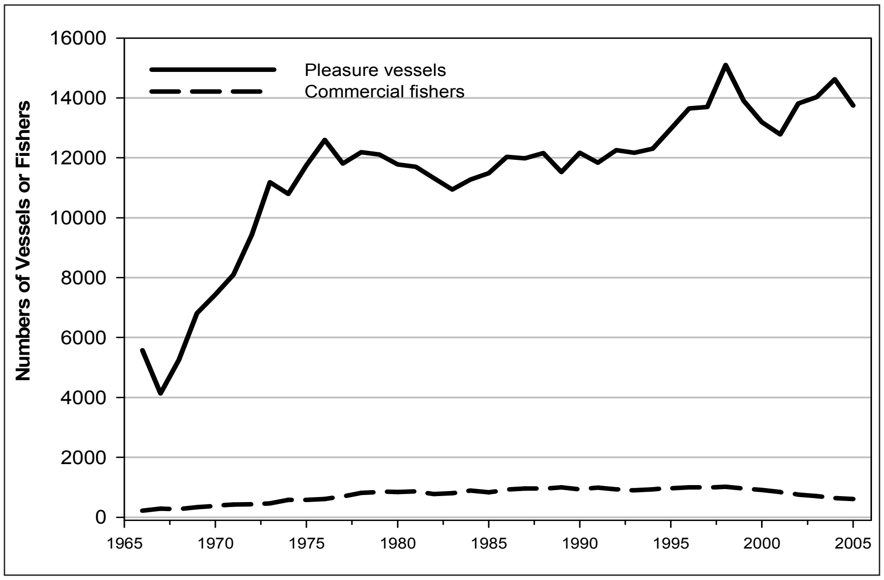

Figure 8.20. Numbers of registered pleasure vessels in Hawaii and registered commercial fishers who recorded some coral reef catch. Source: Hawaii DBOR.

Beginning in 2001, the National Marine Fisheries Service (NMFS) and the Hawaii Division of Aquatic Resources (DAR) began collecting marine recreational fishery data, administered through the Hawaii Marine Recreational Fishing Survey (HMRFS). Results from the 2006 survey show the recreational catch was dominated, numerically, by goatfishes, surgeonfishes and jacks (Table 8.4). Jacks are highly prized in Hawaii and the contribution by weight of these species is disproportionately high when compared to their numerical abundance. In contrast, the catch of goatfishes is dominated by seasonal runs of juveniles that tend to congregate in nearshore areas where they are easily captured but contribute less by weight than their numbers suggest. Hawaii's nearshore fisheries target hundreds of species with dozens of gear types and numerous landing locations, and the difficulties inherent in quantifying such patchily distributed recreational fishing effort over enormous areas of shoreline suggest that the results from the HMRFS should be used with caution.

Table 8.4. Expanded catch by recreational anglers based on HMRFS data for 2006. PSE stands for proportional standard error, expresses the percent standard error of the estimate. Source: HMRFS, http://www.hawaii.gov/dlnr/dar/surveys/.

FAMILY	SPECIES (COMMON NAME)	TOTAL NUMBER CAUGHT	PSE	% OF TOTAL
Goatfishes	Yellowstripe goatfish	726,895	17.8	24%
Surgeonfishes	Convict tang	432,182	25.5	14%
Jacks	Bluefin trevally	311,328	15.9	10%
Flagtails	Hawaiian flagtail	156,415	31.9	5%
Damselfishes	Damselfishes	129,943	45.8	4%
Wrasses	Razorfishes	129,292	22.7	4%
Surgeonfishes	Goldring surgeonfish	111,221	62.7	4%
Wrasses	Other wrasses	91,702	18.5	3%
Mullets	Striped mullet	89,105	79.9	3%
Snappers	Bluestripe snapper	66,631	27.9	2%

A survey of 1,600 households in 2004-2005 found that about 31%, or more than 130,000 households went recreational fishing while subsistence fishers took over 103,000 fishing trips during that year (Hamnett et al., 2006). Over 96% of the respondents from households that went fishing in 2004 said overfishing was a threat to the coral reef ecosystem, and those that fished more often considered it more of a threat than those who fished less. Additionally, all fishing households ranked overfishing a higher threat than households who did not fish (Table 8.5).

Table 8.5. Opinion of fishing households about overfishing in Hawaii. Heavy fishing was defined as more than ≥32 recreational or ≥59 subsistence trips per year. Source: Hamnett et al., 2006.

	THINKS OVERFISHING IS A THREAT	THINKS OVERFISHING IS A SERIOUS THREAT
Light fishing households	96%	66%
Heavy fishing households	97%	74%

Trade In Corals and Live Reef Species

The commercial aquarium fishery in Hawaii has developed into one of the state's major inshore fisheries, with reported landings of over 990,000 specimens and a reported value to collectors of $1.93 million in 2006 (DAR commercial catch reports, unpub. data). As the aquarium industry is composed of both collectors and wholesalers, the overall economic value of the aquarium fishery to the state is estimated to be around 3-6 times higher than the value of the reported catch (Walsh et al., 2004).

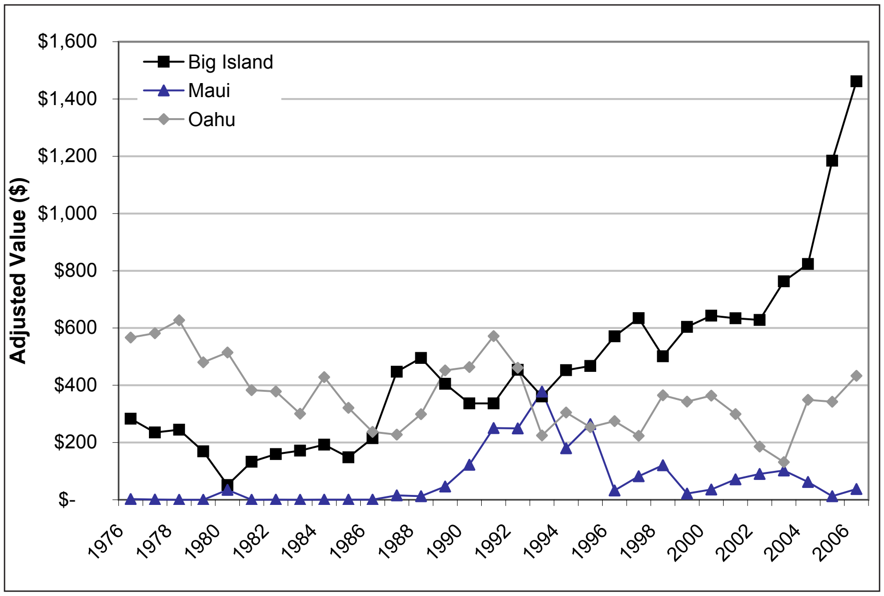

Figure 8.21. Adjusted value (2005) of reported catch of aquarium trade organisms (fish, invertebrates, algae) by island. Data shown only for Hawaii Island, Maui and Oahu. Average reported catch from all other islands combined is $2,400 per year. Source: DAR commercial catch reports, unpub. data

Having been relatively stable between about 1990 and 2000, the catch and value of the fishery have nearly doubled in the past five years due in part to both an increased number of collectors and to several years of high recruitment, and therefore availability, of juveniles of the primary target organism, yellow tang (*Zebrasoma flavescens*). The importance of the Big Island to the fishery has increased since 1990, but that process has accelerated in recent years. The Big Island contributed 75.6% of the reported value of the fishery in fiscal year 2006; the Oahu catch was 22.4%, all other islands combined made up only 2.0% (Figure 8.21).

The overall aquarium catch in fiscal years 2004 through 2006 comprised 203 taxa of fish and 54 taxa of invertebrates, but a relatively small number of species dominated the catch. The top 10 taxa constituted 85.4% of the catch and 86.2% of the value over the last three years, and the yellow tang alone, made up 43.5% of catch and 57.1% of the value (Table 8.6). The catch of hermit crabs has increased dramatically in recent years and they are now the major part of the catch, but because of their low value ($0.11/crab in 2006), feather duster worms are still the most important invertebrate group by value.

Table 8.6. Top 10 collected animals by dollar value. Dollar/year and number caught/year are averages for fiscal years 2004 to 2006. These 10 taxa constituted 85% of total catch by number, 86% by value. Source: DAR commercial catch data.

TAXA	COMMON NAME	ADJ $/YR	% of TOTAL	# CAUGHT/ YEAR	DOLLAR VALUE/INDIVIDUAL
Zebrasoma flavescens	Yellow tang	896,048	57.1	366,317	2.45
Ctenochaetus strigosus	Goldring surgeonfish	93,202	5.9	44,202	2.11
Ctenochaetus hawaiiensis	Black surgeonfish	91,016	5.8	5,867	15.51
Acanthurus achilles	Achilles tang	69,663	4.4	12,399	5.62
Naso lituratus	Orangespine unicornfish	52,997	3.4	13,149	4.03
Sabellastarte sanctijosephi	Featherduster worm	45,485	2.9	43,143	1.05
Centropyge potteri	Potter's angelfish	38,627	2.5	7,380	5.23
Chaetodon tinkeri	Tinkers butterflyfish	29,560	1.9	379	78.06
Hermit crabs	Hermit crabs	23,759	1.5	221,178	0.11
Forcipiger flavissimus	Forcepsfish	11,682	0.7	4,966	2.35

Collection of live rock (e.g., marine substrate where living material is visibly attached), live coral, anchialine shrimp, and marine shells is poorly documented and difficult to quantify. Collection and trade of live coral and live marine rock are illegal, however, some trade still occurs, as evidenced by a number of active enforcement cases.

There are several commercial and research operations working on or actively culturing marine ornamentals, including a variety of native and alien fish and invertebrate species, artificial live rock (molded concrete, seasoned near the mouth of brackish water fish ponds so that corals and other organisms settle on them), sea horses and tridacnid clams. As yet, such trade has had no discernible effect on wild fisheries. At least one commercial operation is growing post settlement fishes for later sale. This same company is also trading in two introduced species of marine algae which are currently invasive and problematic in Hawaii.

Hawaii has had an active fishery for black coral since 1958 when this resource was discovered in abundance off Lahaina, Maui (Grigg, 1965). The majority (90%) of the harvesting targets *Antipathes cf. dichotoma*; although two other species, *A. grandis* (9%) and *Myriopathes ulex* (1%), are also harvested commercially (Oishi, 1990; Figure 8.22). This fishery is currently valued at $30 million at the retail level (Grigg, 2004). Sales have slowed since September 11, 2001 due to changes in the global economy (C. Marsh, pers. comm.).

*Figure 8.22. Black coral (*Antipathes grandis*) in the Auau Channel Maui at 65 m. Source: Hawaii Undersea Research Laboratory.*

Grigg (2004) noted changes in the fishery including: 1) an increase in demand for black corals; 2) a gradual reduction in black coral biomass over time; 3) an invasion of a non-native soft coral (*Carijoa riisei*) in certain areas of the black coral habitat; and 4) decreased recruitment. Studies conducted by DAR in the Auau Channel population suggest four changes in the population: 1) a continuing decline in the proportion of larger, older colonies above age 19; 2) fewer corals in age classes less than nine years in 2004; 3) increasing mortality rate of 30.9% for post-harvest age classes from 1975 to 2004; and 4) a decrease in recruitment during the period between about 1998 and 2004 (Figure 8.23). The most likely cause of diminished recruitment is a combination of harvest and *Carijoa* impacts, but natural fluctuations in recruitment may be a factor. To address this issue, both DAR and Western Pacific Regional Fishery Management Council are revising regulations to increase the minimum size, create a total allowable catch and create black coral protected areas.

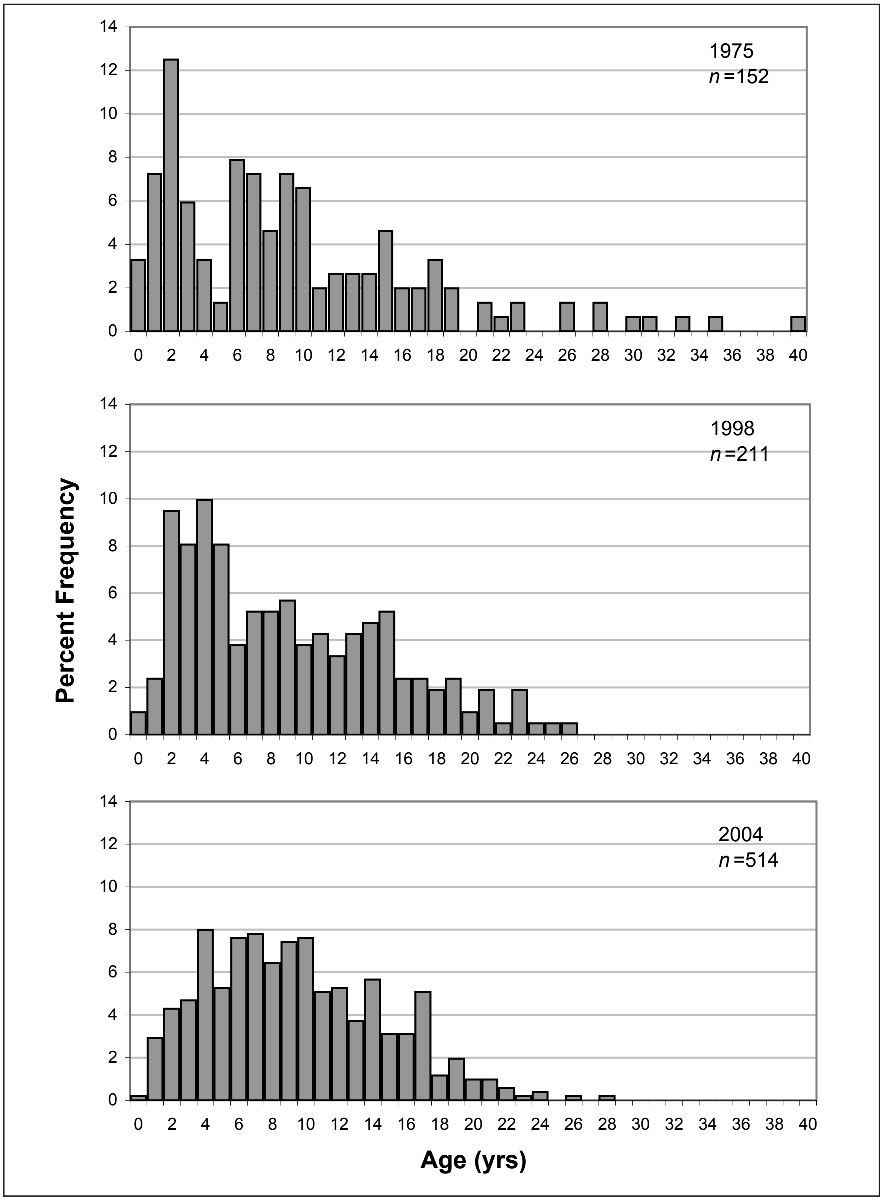

Figure 8.23. Age frequency distributions of black coral from 1975 to 2004. Sources: Grigg, 1975 and 2001; DAR, 2004.

Ships, Boats and Groundings

More than 16,000 recreational and commercial vessels are currently registered in Hawaii. On average, three to five ship groundings are reported each year in the MHI, but these values are likely an underestimate as many recreational vessel groundings go unreported. In most cases, responsible parties have not had to cover the cost for vessel salvage, and restitution for damage is rarely made. Cruise ships currently make over 400 port calls annually in Hawaii, and this figure is expected to triple in the next few years. The limited port facilities have raised concerns about anchoring areas and potential reef damage.

A partial list of documented groundings that occurred around the MHI since 2005 was provided by Hawaii DAR (Table 8.7). A notable grounding occurred on February 2, 2005, when the 555 ft *Cape Flattery* ran aground on a submerged coral reef off the west coast of Oahu carrying over 30,000 tons of cement. Over 6 ha (15 acres) of coral habitat were severely damaged by the grounded ship and salvage efforts (http://www.nmfs.noaa.gov/habitat/ead/capeflattery.htm). Restoration involved securing over 800 corals to 105 cement bases to restore 3-D structure as habitat for fish and invertebrates, and provide opportunity for colony and area recovery in the future. Restored aggregate sites have been mapped, measured and marked for future monitoring of aggregate stability, survival and coral growth.

Table 8.7. Partial list of documented vessel grounding in Hawaii since 2005. Source: Hawaii DAR.

BOAT NAME	LOCATION	GROUNDING DATE	BOAT TYPE	INCIDENT TYPE	DAMAGE(S)	STATUS
Dolfijn	Lahaina, Maui	10/31/04	private vessel	coral reef grounding	reef structural damage	removal, pending
Cape Flattery	Barbers Point, Oahu	2/2/05	555 ft bulk cargo vessel	cargo vessel grounding	reef structural damage	NRDA case pending
Two Star	Honolulu, Oahu	10/15/05	commercial longliner	coral reef grounding	reef structural damage	54' vessel removed
Misty Blue	Honolulu, Oahu	10/18/05	private recre-ational	coral reef/shoreline grounding	reef structural damage	32' vessel removed
Seven Stars	Papaikou, Hawaii	11/11/05	commercial longliner	shoreline grounding	undetermined	69' vessel not re-moved
Kai Anela	Molokini MLCD, Maui		commercial scuba charter	sinking	reef structural damage	DLNR case pending
Shangrila	Ahihi-Kinau NAR, Maui		commercial snorkel charter	anchor damage	reef structural damage	DLNR fined $7,304
Kaukani	Maui		unknown	illegal mooring		DLNR case pending
Sky Sun	Kapoho, Hawaii	12/15/05	commercial longliner	shoreline grounding	undetermined.	67' vessel removed
Aukaka	Kohala, Hawaii	3/27/06	commercial fishing	coral reef grounding	undetermined.	41' vessel removed
Wahine Kapaloa	Niihau	12/30/06	commercial fishing	shoreline grounding	undetermined.	44' vessel removed

Marine Debris

Marine debris from marine and terrestrial sources continues to wash up on Hawaii's shores daily (Figure 8.24). Several formal programs and numerous community groups have initiated efforts to remove marine debris from shorelines and nearshore reef areas (Table 8.8). Marine debris, specifically derelict fishing gear (DFG), continues to present a potentially lethal entanglement hazard to various marine species of concern, including the critically endangered Hawaiian monk seal, the threatened green sea turtle and the endangered humpback whale. DFG may also cause damage to sensitive reef habitat, serve as vectors for non-native species introductions and present a hazard to navigation. In 2005, NOAA's Pacific Islands Fisheries Science Center, sponsored by the NOAA Marine Debris Program, began a project to survey for and conduct removal efforts of DFG on the shores of the MHI. Following its removal from coastal habitat, DFG is processed and incinerated to create electricity as part of Oahu's "Trash to Energy" program. Launched in January of 2006, the Honolulu Derelict Net Recycling Program (a dedicated port reception bin for derelict net at Pier 38, Honolulu Harbor) has resulted in over 15 tons of derelict net and used monofilament longline recycled to create electricity through Hawaii's supportive marine debris partners. The electricity produced enough power to supply the following:

Figure 8.24. Marine debris laden shores of Kanapou Beach, Kahoolawe. Photo: NOAA Marine Debris Program.

- Main Hawaiian Islands project—about 16 homes for a year (117,182 kWh)
- Waiohinu-Ka Lae coast—about 17 homes for a year (127,590 kWh)
- Port Reception—about seven homes for one year (47,986 kWh)

Table 8.8. Marine debris removal programs in Hawaii. DFG = derelict fishing gear. Source: NOAA PIFSC.

PROGRAM	YEAR	LOCATION	DEBRIS INFORMATION
MHI aerial survey and debris removal NOAA PIFSC (funded by NOAA Marine Debris Program)	2006	Big Island, Kauai, Lanai, Molokai, Maui and Oahu	700 individual debris sites, the majority on windward shores
	May 2006	Oahu	225 DFG conglomerates, nearly 19 tons (37,317 lbs)
	February 2007	Lanai	156 conglomerates, totaling 19 tons (38,360 lbs), northern and eastern shores
Waiohinu-Ka Lae coast cleanup Hawaii Wildlife Fund (funded by NOAA Marine Debris Program)	2005	Waiohinu-Ka Lae coast, Big Island	41 tons of debris from 14 km of coastline, 88%=DFG
"Get the Drift and Bag It!", Ocean Conservancy's annual International Coastal Cleanup	2005	Statewide (>2,000 volunteers)	16.5 tons along 140 km of shoreline in one-day effort. 150 divers removed >670 kg from 5 km of underwater habitat
Kahoolawe Island Reserve Commission	2006	Kanapou Beach, Kahoolawe	4.5 tons from the shoreline
Honolulu Derelict Net Recycling Program and Port Reception Bin (funded by NOAA Marine Debris Program)	2005	Pier 38, Honolulu Harbor	15.5 tons of derelict net and monofilament line recycled to create electricity

In the 2005 "Get the Drift and Bag It!" event, a part of the Ocean Conservancy's annual International Coastal Cleanup, over 2,000 volunteers across the state collected nearly 16.5 tons of marine debris along 140 km of shoreline in this one-day effort. Of all the debris types noted, cigarettes, caps and lids and food wrappers were the most common, accounting for 55% of the debris removed (the Ocean Conservancy, 2006).

Additionally, many small-scale beach cleanups take place on every island at least a few times a month, and are hosted by various non-profits, communities and school groups. In addition to continued removal of marine debris, outreach and education efforts, along with partnership building, need to be increased to address this issue locally, as well as nationally and internationally with Pacific Rim communities that share the impacts and responsibility for marine pollution.

Aquatic Invasive Species

The Hawaii Marine Algae Group (HIMAG) has worked since 2002 to develop methods to manage non-indigenous species and invasive algae and develop capacity among interested community groups to better manage nearby coastal regions. This group includes DAR, University of Hawaii Departments of Botany and Biology and The Nature Conservancy. The target group of invasive species includes eight algae, six of which have a known history of introduction to the state of Hawaii, and are detailed in Table 8.9.

The community-based alien algae cleanup events that began in Waikiki in 2002 (Figure 8.24) have since spread to other locations where motivated communities have partnered with the above agencies to stage their own alien algae remediation efforts. Community groups and teachers such as Paepae O Heeia, stewards of Heeia Fish Pond (Kaneohe, Oahu),

Table 8.9. Summary information for invasive and non-indigenous algae in Hawaii 2006. Source: HIMAG.

KNOWN INVASIVE ALGAE	ORIGIN/MECHANISM OF INTRODUCTION	IMPACT REGIONS IN MHI	METHODS FOR MANAGEMENT
Acanthophora spicifera (Rhodophyta)	Guam/Hull fouling on vessel in Pearl Harbor Naval Station	MHI, especially intertidal regions	Under development by USFWS-funded research
Avrainvillea amadelpha (Chlorophyta)	Unknown. Genus has cosmopolitan distribution in warm waters	Malama Bay from Hanauma Bay to Kahe Pt, Oahu	Under development by HCRI-funded research
Dictyota flabellata (phaeophyte)	San Diego, CA/Hull fouling on vessel in Barber's Pt., Oahu	Potential risk to reef community Kalaeloa, Oahu	None
Eucheuma denticulatum (Rhodophyta)	Philippines/Permitted introduction	Kaneohe Bay to Kaaawa, O'ahu	Super sucker
Gracilaria salicornia (Rhodophyta)	Hilo Bay/Inter-island introductions to Oahu, Molokai	Waikiki and Kaneohe Bay, Oahu. Eastern leeward reef Molokai	Super sucker
Gracilaria tikvahiae (Rhodophyta)	Florida/Permitted introduction	Marsh regions on Oahu	Under study with HCRI-funded research
Hypnea musciformis (Rhodophyta)	Florida/Non-permitted introduction	Kihei and Kahului Maui	Daily/periodic bulldozer use for beach cleanups
Kappaphycus alvarezii (Rhodophyta)	Philippines/Permitted introduction	Kaneohe Bay, Oahu	Periodic manual removal

and Michelle Kapana Baird of Kaiser High School (Maunalua Bay, Oahu) are currently restoring native nursery and reef habitats in their local areas. Their efforts are contributing significantly to the scientific understanding of these invasive species by working closely with University of Hawaii researchers. These efforts are also helping to improve best management practices in controlling the threat of invasive marine algae throughout the state.

In addition, the HIMAG group continues to refine the remediation process involving the "Super Sucker", an underwater vacuum set upon a floating platform, capable of efficiently removing large amounts of alien marine algae in remote locations using a small group of highly trained technicians and scientists (Figure 8.25). This operation continues to restore native reef habitat in Kaneohe Bay. Guided and supported by the HIMAG group, early success of the Super Sucker has also resulted in the fabrication of a second operation led by the DAR, endearingly dubbed "Super Sucker Jr." to compliment the efforts of the original unit in other high-priority locations. Lastly, very small units have also been developed by the HIMAG group, known as "Mini Suckers", designed to operate with community groups in shallow areas along the coastline. These small units have done well to bridge the gap among the range of restoration approaches from efficient alien algae control techniques to critical education and outreach of these serious threats to Hawaii's nearshore marine environment.

Figure 8.25. Community algae cleanup in Kaneohe Bay (left) and Supersucker used to vacuum invasive algae in Kaneohe Bay, Oahu (right). Photos: E. Co.

DAR has conducted extensive surveys to document the distribution of key alien algae species and prioritize specific areas for control efforts (Figure 8.26). These survey areas include the Hilo coast, south Molokai, South Oahu (Barbers Point to Hanauma Bay) and Windward Oahu (Kahuku to Waimanalo).

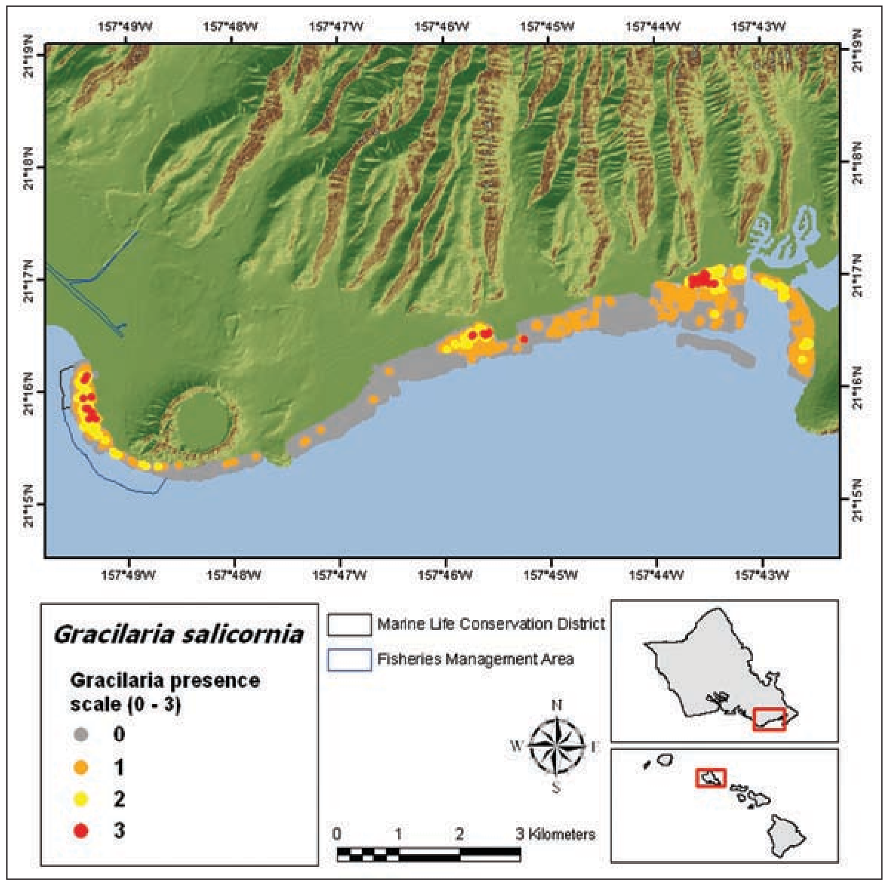

Figure 8.26. A map of Maunalua Bay shows the distribution of the invasive algae Gracilaria salicornia. *Data: Hawaii, DAR.*

A compendium of all alien species in Hawaii is being developed by Eldredge and Carlton and will include all invertebrates, algae and fishes. A recent introduction of concern is the Orange Keyhole Sponge (*Mycale armata thiele*) which was unknown in Hawaii prior to 1996 (Figure 8.27). A two-year study suggests that growth and spread of *M. armata* in Kaneohe Bay, Oahu may be slowly extending beyond its area of highest concentration in the southern portion of the bay (Coles et al., 2007).

In addition, DAR began an effort in 2004 to eradicate the snowflake coral, *Carijoa riisei*, from areas of Kauai. This attempt has mostly concentrated on wrapping pier pilings in Port Allen Commercial Harbor to eliminate the presence of *C. riisei* from the harbor. *Carijoa's* distribution is limited to pier pilings in the harbor; however, there are four confirmed locations with small populations of *Carijoa* outside Port Allen on Kauai. Surveys suggest that *Carijoa* is not currently widespread and may be at a level that can be eradicated if methods can be developed.

Nearly 16,000 fish of 12 species, particularly snappers and groupers, were intentionally introduced to Hawaii in the late 1950s and early 1960s, but only three, the blue-lined snapper (*Lutjanus kasmira*), the peacock grouper (*Cephalopholis argus*) and the black-tailed snapper (*Lutjanus fulvus*), have become established to any large extent. The first two species have proven to be particularly controversial as they have adapted well to Hawaiian waters and are often blamed for depletion of desirable species due to competition or predation.

Blue-lined snappers were only introduced to Oahu but have subsequently spread to form patchy distributions throughout the entire archipelago (Randall, 1987; Sladek-Nowlis and Friedlander, 2004). In Hanalei Bay, Kauai, densities of blue-lined snapper are high but have decreased in the past few years from a peak in 1999 (Figure 8.28. Friedlander et al., 2002; Friedlander and Brown, 2006). Density of blue-lined snapper is two orders of magnitude lower in Kona, Big Island, but has shown an increase in number in the past few years (Figure 8.28).

Studies of blue-lined snapper diets have not detected appreciable predation on native species in shallow-water habitats (Oda and Parrish, 1982; DeFelice and Parrish, 2003). However, at high densities, blue-lined snapper appear to alter the schooling behavior of the native yellowfin goatfish (*Mulloidichthys vanicolensis*) by displacing them higher into the water column (Schumaker and Parrish, 2005). Although blue-lined snappers consume some fish in their diets, most of their diet is composed of small, cryptic species of no commercial or recreational value (Schumaker, unpub. data).

Approximately 2,385 peacock grouper were introduced to the MHI in the late 1950s and now occur on all of the MHI and in low numbers in the NWHI. Although it was introduced to augment declining populations of food and game fishes, it has not been well received by most fishermen due to concerns about ciguatera poisoning. Peacock grouper have been blamed for a multitude of problems on the reefs, most notably a decline in important aquarium fish and putative impacts on food fishes and invertebrates.

On the Kona coast, peacock grouper populations increased between 1999 and 2006. However, in 2006, there was a marked downturn in abundance. This recent decline may be related in part to an unusual fish die off in West Hawaii which first became apparent in May 2006. Peacock grouper were by far the most common species to die, but a number of other species, comprising a wide range of families, feeding types and depth ranges, also perished. Similar undocumented reports of floating fish (typically peacock grouper) were received from Maui, Oahu and Molokai. Necropsy from the National Wildlife Health Center, USGS in Honolulu reported swim bladder distension, a variety of incidental lesions and, in two cases, atrophy of the liver. No gross or microscopic lesions were considered severe enough to cause death and the cause of death remains unknown.

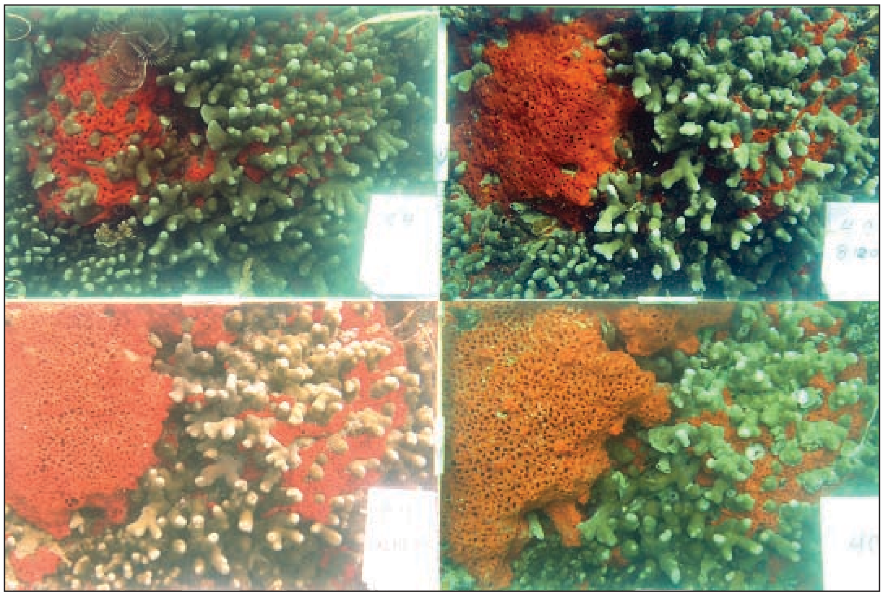

Figure 8.27. Mycale armata *overgrowth in Kaneohe Bay from 2004 to 2006. Source: Coles et al., 2007.*

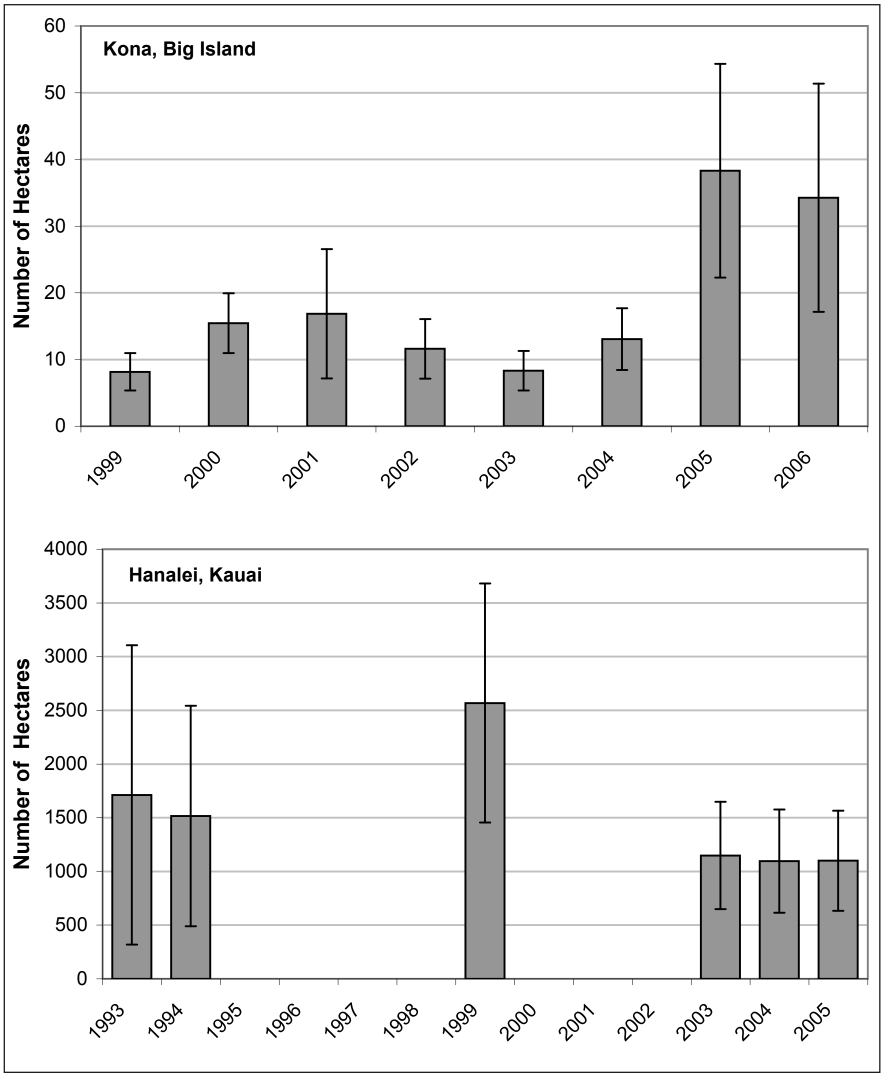

*Figure 8.28. Density of blue-lined snapper (*Lutjanus kasmira*) in Hanalei, Kauai and Kona, Big Island. Values are means and standard error. Note differences in y-axis scale. Source: Hawaii DAR; Friedlander; unpub. data.*

Security Training Activities

Members of the public have limited or no access to the shoreline and nearshore waters within and around military or security areas on Oahu (Pearl Harbor, Kaneohe Bay Marine Corps Base Hawaii and Honolulu Reef Runway) and Kauai (Barking Sands Pacific Missile Range Facility).

Offshore Oil and Gas Exploration

No offshore oil and gas exploration occurs in Hawaiian waters.

Other

Crown-of-thorns Sea Stars (Acanthaster planci)

Crown-of-thorns sea stars (COTS) are corallivores that have caused significant coral damage throughout the Indo-Pacific. Their abundance is monitored on the reefs of Hawaii during benthic and towed-diver surveys. Towed-diver surveys indicate that COTS occur on reefs throughout Hawaii at low levels (average=3.4 COTS/hectare; PIFSC-CRED, unpub. data). However, there have been several reports of localized outbreaks of COTS around the islands. During a recent outbreak in July 2005 (Figure 8.29), hundreds of COTS were found within a one km^2 area of reef off the north shore of Oahu (Kenyon and Aeby, in review). In August 2006, towed-diver surveys also identified several smaller, localized outbreaks on Mana Reef off the leeward coast of Kauai (PIFSC-CRED unpub. data).

Figure 8.29. Localized outbreak of COTS off Oahu. Photo: J. Kenyon.

CORAL REEF ECOSYSTEMS—DATA-GATHERING ACTIVITIES AND RESOURCE CONDITION

Current coral reef monitoring, research and assessment activities, including those that are represented in this report, are summarized in Table 8.10. Monitoring locations are shown in Figure 8.30.

Table 8.10. Monitoring programs investigating coral reef ecosystems in the MHI.

PROGRAM AND OBJECTIVES	START DATE	FUNDING	PARTNERS
DAR marine managed area monitoring program	1970s	USFWS	DAR
Kahe Point Coral monitoring of long-term trends in coral community	1973	HECO	HECO, AECOS, Sea Engineering
Hanalei Bay Marine Communities Investigation Trends in benthic and fish assemblages	1992	NOAA, DAR, USGS, Hanalei Heritage River	NOAA, DAR, Hanalei Heritage River Hui, HIMB
Coral Reef Assessment and Monitoring Program (CRAMP) Monitoring of benthos and fish statewide	1997	USGS, EPA	UH-Manoa, NOAA, DAR
Reefcheck Volunteer community-based monitoring protocol to measure coral reef health	1996	NOAA, CZM, DAR	Oceanwide Sci. Instit., Waikiki Aquarium, Windward C.C., Hawaii Pacific Univ., Hanauma Bay Edu. Center, MOP
DAR Statewide Coral Reef Monitoring Program. Integrated monitoring of fish, benthos, and coral condition on Oahu, Maui and Big Island	1999	NOAA, HCRI	UH-Hilo, UH-Manoa, NPS
Reef Watchers Program Volunteers monitor and provide data on nearshore and inter-tidal sites	1999	CZM/DBEDT, NFWF, NOAA, Harold Castle Foundation, HCF, TNC, CCN DAR, TNC, CCN	DOE, UH-Hilo, Washington State University and West Hawaii partici-pating residents
USGS Study of Coral Reefs in the Pacific Mapping, monitoring, remote sensing, sediment transport studies, collection of tide, wave and current data.	2000	USGS	USGS, UH-Manoa, HIMB, DAR, NPS
The Reef Environmental Education Foundation (REEF) Volunteer scuba divers and snorkelers collect information on marine fish populations	2001	CZM, NFWF, PADI – Proj-ect Aware, NOAA, NMSP	Maui Comm. College MOP, Project SEA-Link, Hawaii Coral Reef Net-work, DAR
Fish Habitat Utilization Program (FHUP) Fish habitat utilization patterns, MPA effectiveness statewide	2002	NOAA DAR,	NOAA, UH-Manoa, UH-Hilo, HIMB, NPS
Kapoho Reef Watch Monitor human use, water quality and marine biota around Waiopae tide pools	2003	HCF, NFWF, TNC, Harold K. L. Castle Foundation	Vacationland Hawaii Comm. Assoc, Kapoho Kai Water Assoc. Cape Ku-mukahi Foundation, NOAA, USFWS
Nuisance algae in W. Maui; linkages of physical and biological processes related to nuisance algae	2003	NOAA, HCRI	NOAA, DAR, UH-Manoa, USGS, HIDOH
MHI Rapid Assessment and Monitoring Program Mapping, assessment, monitoring of benthos, fish, coral disease, oceanography.	2005	NOAA	UH-Manoa, UH-Hilo, HIMB, Bishop Museum, DLNR DAR
National Park Service Long-term monitoring of benthos and fish at four parks	2006	NPS	NOAA, UH-Hilo
Alien Algae Mapping for presence/absence and relative abundance	2006	DAR/ HISC	UH-Manoa / NOAA statewide with focus on Oahu, Molokai, and Hawaii
DAR Study on impact of lay gill net regulations on Maui and Oahu (2007-2011). Broad spatial scale surveys of herbivorous fish and benthic algae around sites on Oahu and Maui subse-quent to ban on use of lay gillnets enacted in early 2007	2007	USFWS	TNC

AECOS – AECOS Inc. Environmental Consulting Company
CCN – Community Conservation Network
CZM – Hawaii Coastal Zone Management
DAR – Hawaii Department of Land and Natural Resources, Division of Aquatic Resources
DOE – Hawaii Department of Education
HIDOH – Hawaii Department of Health
EPA – Environmental Protection Agency
HCF – Hawaii Community Foundation
HCRI – Hawaii Coral Reef Initiative Program
HECO – Hawaii Electric Company
HIMB – Hawaii Institute of Marine Biology
MOP – Univ. of Hawaii Marine Options Program
NOAA – National Oceanic and Atmospheric Administration
NFWF - National Fish and Wildlife Foundation
NMSP – National Marine Sanctuary Program
NPS – National Park Service
PADI – Professional Association of Diving Instructors
UH – University of Hawaii
USFWS – U.S. Fish and Wildlife Service
USGS – U.S. Geological Survey
VHCA – Vacationland Hawaii Community Association

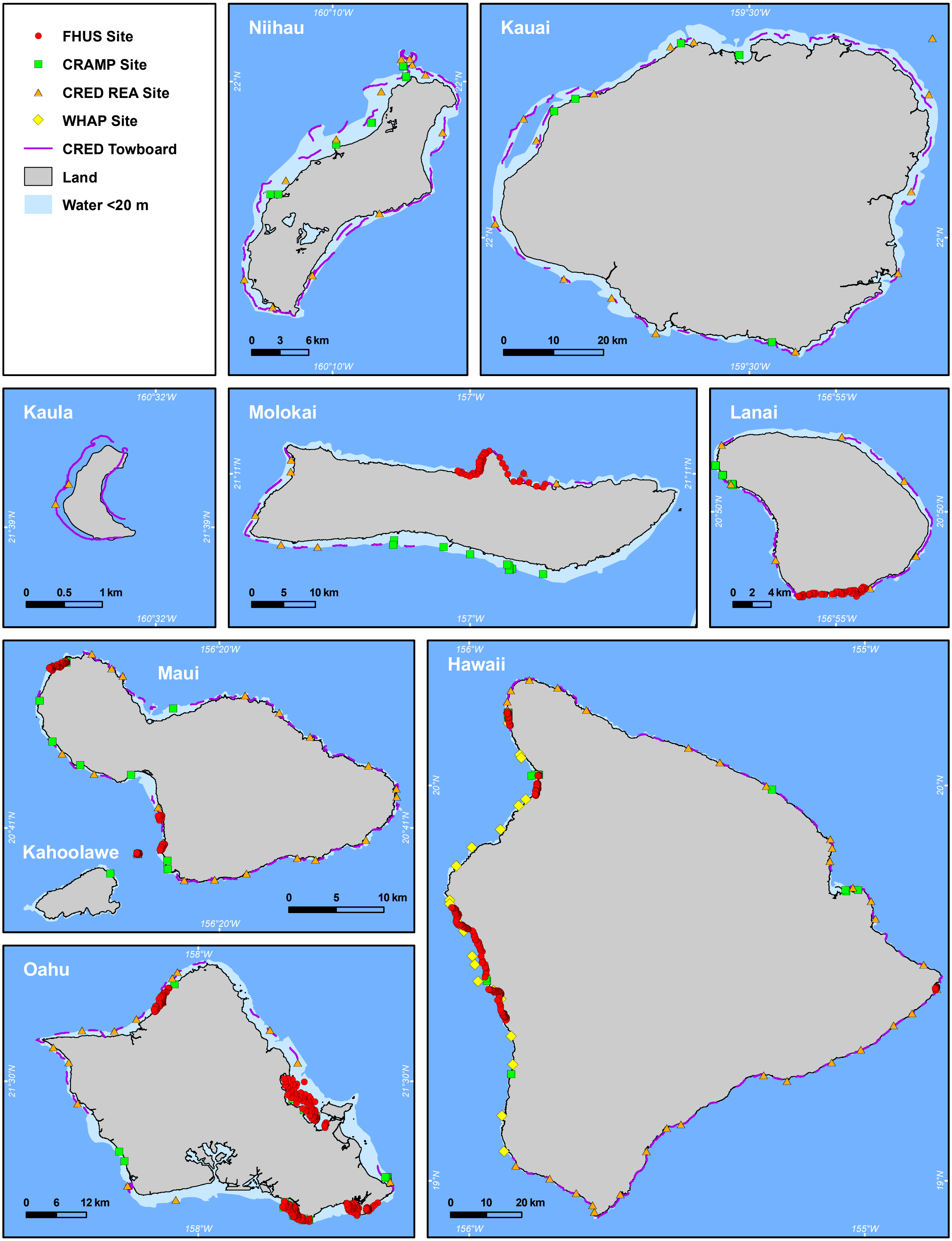

Figure 8.30. Monitoring locations in the MHI. Map: K. Buja.

WATER QUALITY AND OCEANOGRAPHIC CONDITIONS

There are no comprehensive, state-wide water quality monitoring programs that specifically assess sediment or chemical impacts to coral reef areas in Hawaii. Water quality monitoring is undertaken for a variety of purposes across different spatial and temporal scales by federal and state resource agencies, private consultants, non-governmental organizations (NGO's) and University researchers. Examples of these monitoring activities are highlighted below.

PIFSC-CRED Monitoring

NOAA's PIFSC-CRED has begun monitoring coral reefs and water quality throughout the MHI once every 1 to 2 years as part of the Reef Assessment and Monitoring Program (RAMP) cruises and provides a snap-shot of water quality parameters at a limited number of locations. As part of the RAMP effort, the PIFSC-CRED Oceanography Team analyzed water samples for concentrations of chlorophyll a and the nutrients nitrogen, phosphorus and silicon.

Hawaii Department of Health Monitoring

Water quality at beaches is regularly monitored for bacteria that indicate a risk to human health. Pollutant concentrations normally decrease sharply with distance from shore, and offshore water quality in Hawaii is generally good. HIDOH regularly monitors indicator bacteria (*Enterococcus*) at swimming beaches. In recent years, HIDOH has also collected data on turbidity, nutrients and chlorophyll a at shoreline stations in knee-deep water and in perennial streams. HIDOH uses these data, and other available data that meet specific quality criteria, to identify streams and coastal segments that are "water quality impaired" (e.g., where state water quality criteria are regularly exceeded). A list of impaired waters is reported to the EPA every two years, as required by the Federal Clean Water Act. Although the listings are a function of available data rather than the result of a comprehensive, state-wide sampling design, it is not surprising that the number of listed waters corresponds, roughly, with island population size (Table 8.11).

Table 8.11. The Hawaii 2006 Draft Section 303(d) list identifies the number of water quality impairments for both streams and coastal waters. Source: HIDOH.

	NUMBER OF LISTINGS				
ISLAND	***Enterococcus***	**Total Nitrogen**	**Nitrate + Nitrite**	**Total Phosphorus**	**Turbidity**
Kauai	18	12	13	1	39
Oahu	31	79	62	47	95
Molokai	0	0	0	0	4
Lanai	0	0	1	0	4
Maui	6	24	32	11	75
Hawaii	9	20	15	13	35
TOTALS	**64**	**135**	**123**	**72**	**252**

HIDOH has just released the final 2006 integrated report of assessed waters in Hawaii (HIDOH, 2008). The 2006 Integrated Report is the first effort by the HIDOH to integrate its reporting requirements for the Federal Clean Water Act. It includes Hawaii's 2004 list of impaired waters and data collected from state surface water bodies over the past six years. It reports that overall quality of Hawaii's waters is very good and the majority of the coastal waters and upland surface waters are in good condition (HIDOH, 2008). The overall quality of Hawaii's groundwater is generally considered excellent and the chemical contaminant concentrations that have been detected in public groundwater/drinking water sources are generally below state and federal drinking water standards (HIDOH, 2008).

The impaired coastal waters are primarily harbors, semi-enclosed bays and protected shorelines, where mixing is reduced and resident time of pollutants is long when compared with exposed coasts. Several bays that have coral reefs, such as Kaneohe Bay and Pearl Harbor (Oahu), Nawiliwili Bay (Kauai) and Hilo Bay (Hawaii), are included on the list. Because offshore water quality is generally good and few data sets are available to characterize water quality around reefs, deeper and offshore waters where coral reefs occur are generally not included on the list. The most widely distributed coastal pollutants are nutrients, sediments and *Enterococcus* (see Table 8.11).

HIDOH's 2006 list of impaired waters contains a total of 93 streams segments and 219 coastal areas. One stream was entirely de-listed and several modifications were made within listings. Seventeen new streams were listed. For coastal waters, 42 new water bodies were listed, two were de-listed and six previously listed water bodies were listed for new pollutants. In total, there were 534 coastal water bodies, of which 270 (51%) had available data for assessment. The breakdown for the individual islands is: Kauai, 38 (45%); Oahu, 98 (54%); Molokai, 38 (8%); Lanai, 8 (44%); Maui, 76 (61%); and Hawaii, 47 (53%; HIDOH, 2008).

As a requirement of a grant from the EPA, Hawaii must submit an annual notification of any beach postings and advisories. All beach postings for 2006 were related to sewage spill events and therefore postings were performed by the respective city or county personnel. In some cases, Hawaii Department of Health Clean Water Branch Monitoring staff assisted in the posting of signs. If a sewage spill involves a group (such as hotels, restaurants, condos, etc.) that is unfamiliar with posting of warning signs, the HIDOH will post the signs and monitor the spill in the interest of rapid response to protect the public. In 2006 a total of 15.19 mi of Oahu's beaches were posted due to Raw Sewage Advisories for a total of 464 days. No raw sewage advisories were issued for the counties of Maui, Kauai and Hawaii.

The HIDOH began issuing Brown Water Advisories in 2004 to warn the public of the dangers of storm water discharges into the nearshore waters and flooded areas. The total beach miles and total numbers of days posted because of brown water advisories in each county and statewide are presented in Figure 8.31.

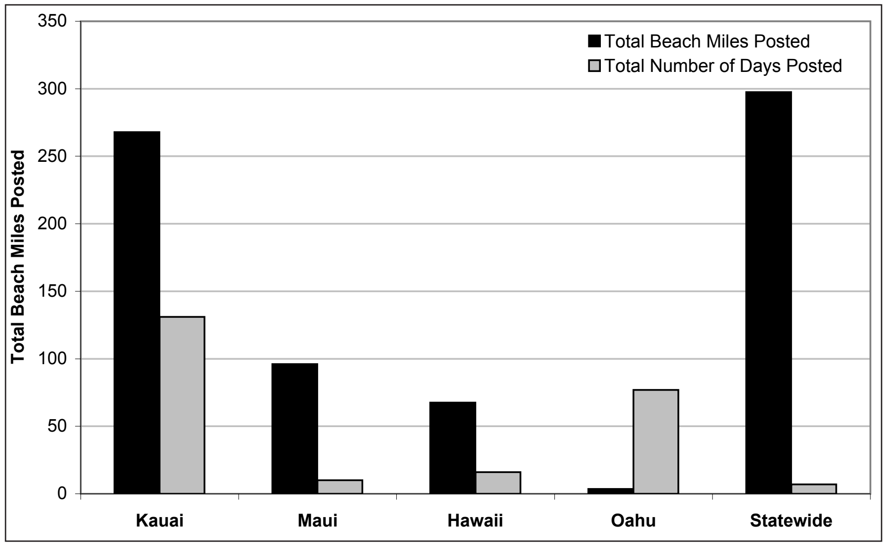

Figure 8.31. Brown Water Advisories posted by the Hawaii DOH in 2006. Source: HIDOH, 2006.

USGS Monitoring

USGS completed an assessment of water quality of streams and groundwater on Oahu from 1999 to 2001 (Anthony et al., 2004). They found toxic contaminants in streams that drain urban and agricultural lands, and in groundwater supplies (although few chemicals exceeded drinking water standards in groundwater). In Oahu's urban streams, some of the highest levels of termite treatment chemicals in the U.S. were reported. The USGS conducted no analyses in the marine environment where ocean mixing and dilution occur. Based on the USGS findings, screening of estuaries and coastal waters for toxic contaminants such as chlordane, dieldrin and diazinon is warranted. Sediment particles containing toxic contaminants are easily transported to the ocean in storm flows and may be deposited at stream mouths and on reef flats.

Monitoring by Private Entities for Permit Condition

Offshore water quality data are collected through a multitude of water quality monitoring programs associated with permit requirements for specific activities. These include the assessment of point source discharges, such as sewage outfalls and cooling water discharges, required for NDPES permits. Results for NPDES permit monitoring are submitted to the HIDOH. Nonpoint source inputs from land-based sources, such as resorts and golf courses, are monitored through a variety of state and local permit requirements. Data generally include constituents listed in the State of Hawaii Water Quality Standards: dissolved inorganic nutrients (nitrate + nitrite [NO_3^- + NO_2^-]), ammonium [NH_4^+], orthophosphate [PO_{4+}^{3-}], and silica [Si]), chlorophyll a, salinity, turbidity, pH, temperature and dissolved oxygen. In total, approximately 3,000 ocean water samples are analyzed annually by private entities as required by permit conditions. These permit-related data have not been synthesized by island or region into a comprehensive database or report.

University of Hawaii Biogeochemistry Research

Kaneohe Bay remains a site of innovative work to establish the links between water quality and effects to reef communities. A team of scientists from the Department of Oceanography at the University of Hawaii at Manoa and from NOAA/Pacific Marine Environmental Laboratory in Seattle, Washington, is examining how changing water conditions, due to input of nutrient rich storm runoff and physical oceanographic processes, drive phytoplankton blooms and cause changes in the direction of CO_2 transport between the ocean and atmosphere. The biogeochemical and physical conditions of the water column on coral reefs in Southern Kaneohe Bay are being characterized by an instrument array called the Coral Reef Instrument Monitoring and CO_2 Platform (CRIMP-CO_2). It provides near real-time data at five to 10 minute intervals.

The CRIMP-CO_2 deployment in November 2005 coincided with a La Niña event that was marked by high intensity rainfall for more than forty days (February to April 2006). The effects of the extreme weather and physical forcing on the biogeochemistry of the bay during the winter-spring of 2006 were significant, leading to several large phytoplankton blooms and subsequent drawdown of nutrients and CO_2.

Extreme rain events in 2006 delivered large pulses of materials to Kaneohe Bay that increased available nutrients from approximately 0.03 μM dissolved inorganic nitrogen (DIN) and approximately 0.02 μM dissolved inorganic phosphorus (DIP) during background conditions to >34 μM DIN and >0.9 μM DIP in surface waters of the south bay. Sudden shifts in the DIN:DIP ratio (approximately 2-3 to >100 in some cases) in bay waters associated with these pulses triggered significant algal blooms evidenced by chlorophyll a concentrations reaching 10-12 mg/m^3 throughout large areas of the affected area. Increases in dissolved O_2 and a draw down of CO_2, commensurate with the nutrient inputs, were observed at CRIMP-CO_2 buoy (http://www.pmel.noaa.gov/co2/coastal/kbay/).

Data collected during two storm periods in winter 2006 indicate that South Kaneohe Bay waters switched from being a net source to a net sink of atmospheric CO_2 during these events. The sea to air flux was found to vary between extremes of approximately +0.4 and -0.3 mmol CO_2/m^2/hour during the winter season. Regardless of the large but generally short-lived deviations when the bay water acted as a sink for atmospheric CO_2, southern Kaneohe Bay remained a net source of CO_2 to the atmosphere throughout the period of December 2005 to January 2007.

BENTHIC HABITATS

In 2003, NOAA's CCMA Biogeography Branch (CCMA-BB) produced shallow water benthic habitat maps covering 60% of the coastline of the MHI from aerial photographs and hyper-spectral imagery (Coyne et al., 2003). In 2007, CCMA-BB used IKONOS imagery to expand and update these shallow water benthic habitat maps to include the entire coastline of the MHI (Figure 8.32; http://ccma.nos.noaa.gov/ecosystems/coralreef/main8hi_mapping.html). Other types of shallow water and coastline data (e.g., LIDAR bathymetric data, aerial photography, shoreline imagery) are available for download from the University of Hawaii's Coastal Geology Group at http://www.soest.hawaii.edu/coasts/data/index.html.

Since the late 1980s, multibeam bathymetric data have been collected in the MHI by numerous ships and organizations. These data have been synthesized into a 50 m gridded bathymetric map by scientists at the University of Hawaii's School of Ocean and Earth Science and Technology.

In 2005 and 2006, the PIFSC-CRED program surveyed 2,688 km^2 of seafloor in 10 to 1,000 m water depths in the MHI. Multibeam data collection efforts at Niihau, Penguin Bank, N. Molokai and the Kohala Coast of the Big Island concentrated on shallow environments <100 m. Penguin Bank, a large bank on the southwest side of Molokai, lies in water depths between 15 and 100 m and is the only large, flat, submerged bank in the MHI. Multibeam bathymetric data from Penguin Bank shows a mostly flat banktop with limited complex areas associated with sand waves and dunes and only a few near-shore features that may be associated with coral (Figure 8.33). Although the multibeam bathymetry and derived products show a flat, somewhat uninteresting banktop, the Penguin Bank backscatter data reveals the presence of more complex structures (Figure 8.33).

Since 1998, several large-scale monitoring programs have been initiated around Hawaii to address different issues concerning the condition of coral reef ecosystems (Table 8.10). A meta-analysis was conducted of the most spatially diverse programs, Coral Reef Assessment and Monitoring (CRAMP)/DAR, PIFSC-CRED, Fish Habitat Utilizations Study (FHUS) and West Hawaiian Aquariumfish Project (WHAP), to obtain an assessment of the coral reef assemblage around the MHI. CRAMP/DAR focused on a comprehensive description of the spatial differences and the temporal changes in coral reef communities in the MHI. PIFSC-CRED surveyed reefs that were wave exposed and otherwise difficult to access with the shore-based small craft used by other monitoring programs (e.g., CRAMP/DAR, WHAP). FHUS examined the efficacy of marine protected areas in Hawaii in terms of fish assemblages and benthic habitat characteristics. WHAP investigated reef areas targeted by the aquarium trade along the West Hawaii coastline.

Spatial Assessment Methods

CRAMP/DAR

Fixed transects and fixed photoquadrats were surveyed at two reef areas, a shallow (about 3 m) and a deep (about 10 m) station at each of 30 state-wide sites at least twice since 1999. Total mean percent coral cover by station, mean percent coral cover by species within a station and species richness were documented. The monitoring site data were supplemented in the spatial dimension by a rapid assessment technique. Detailed methods are provided in Friedlander et al. (2003), Brown et al. (2004) and Jokiel et al. (2004). A total of 692 transects were surveyed across the state using these methods.

PIFSC-*CRED*

In 2005, benthic surveys were conducted around the MHI at a total of 72 sites, with two 25-m transect lines laid at each site. In 2006, an additional 36 sites were surveyed and 17 sites were revisited, totaling 108 unique sites. Video transects were recorded along transect lines as a durable record. The line-intercept method was used to quantify substrate composition at 0.5 m intervals. All corals whose center fell within 0.5 m on each side of the transect lines were enumerated by species and assigned to one of seven size classes based upon maximum colony diameter: <5 cm, 5-10 cm, 10-20 cm, 20-40 cm, 40-80 cm 80-160 cm, >160 cm (Kenyon et al. 2006b). Percent coral cover, richness, relative abundance, colony density, and size-frequency distributions were derived. Directed observations on coral disease, predation and bleaching were conducted along the same transect lines.

FHUS

Sampling was conducted in all 11 marine life conservation districts (MLCDs), the University of Hawaii Marine Laboratory Refuge, and adjacent habitats from 2002 to 2004 (Friedlander et al., 2006, 2007a, 2007b). In addition, marine areas adjacent to four national parks were surveyed in 2004 and 2005. Locations of assessment sites were determined using a stratified random sampling approach by four major habitat strata (colonized hard bottom, uncolonized hard bottom, unconsolidated sediment and macroalgae). Within each major habitat type, sampling was further stratified by management regime (MLCD and MLR, Fisheries Management Area, or FMA, and open access). Only hard bottom habitats were used in this analysis (859 transects).

Benthic cover was assessed along a 25-m transect line. Each transect was stratified into 5 x 5 m segments, with *in situ* 1 m^2 visual quadrats randomly allocated within each segment. Twenty-five randomly selected intersections were marked on each quadrat grid and used for substrate identification. Each intersection was identified using substrate categories of sand, coralline algae, turf algae, macroalgae, and coral. Coral and macroinvertebrates were identified to species level and algae to genera. Percent cover values for each substrate category and coral species were derived by dividing the number of occupied points by the total number of intersections (25) within each quadrat.

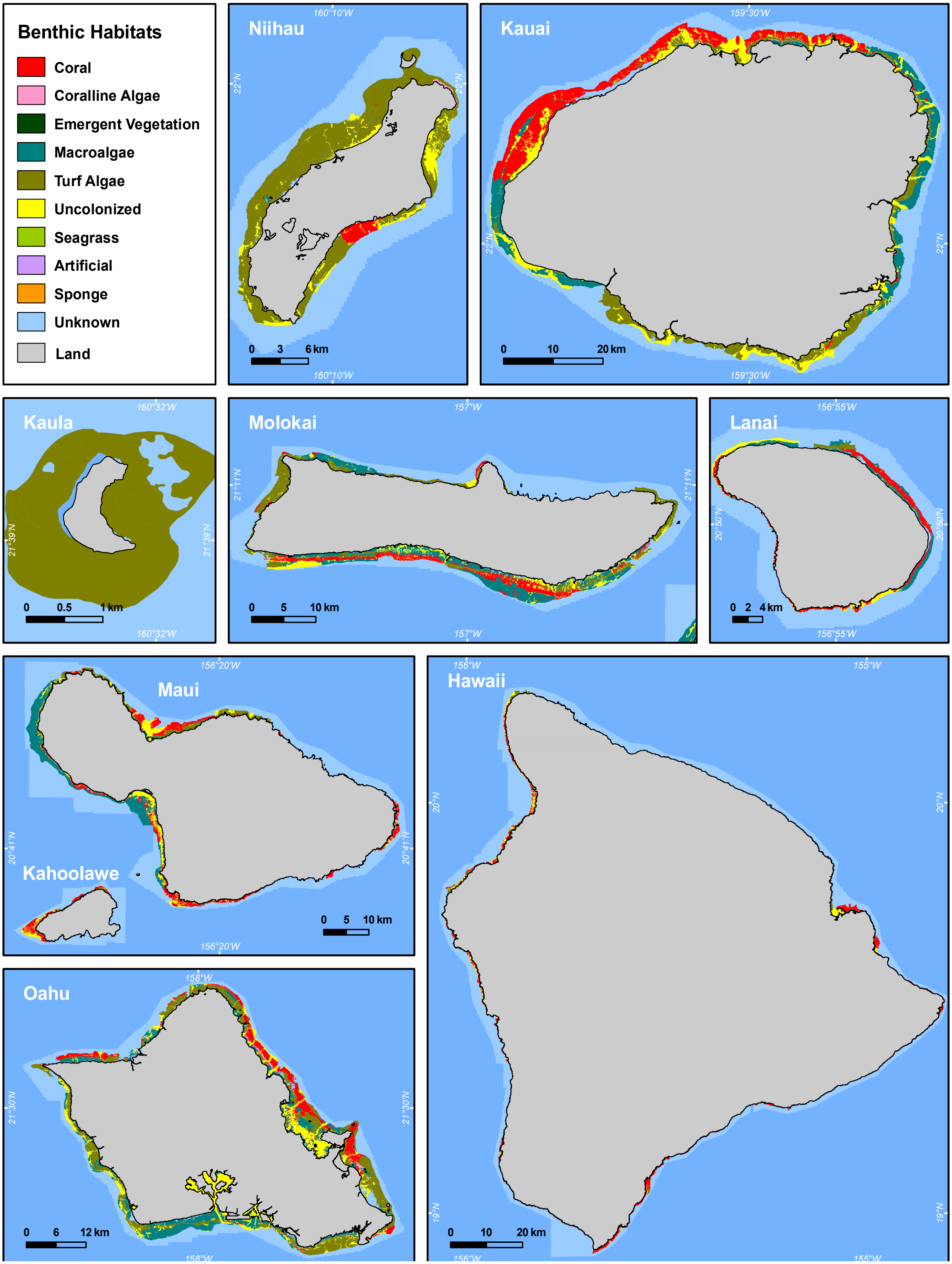

Figure 8.32: Nearshore benthic habitat maps were developed by CCMA-BB based on visual interpretation of aerial photography and hyperspectral imagery. For more information visit http://ccma.nos.noaa.gov/ecosystems/coralreef/main8hi_mapping.html. Map: K. Buja.

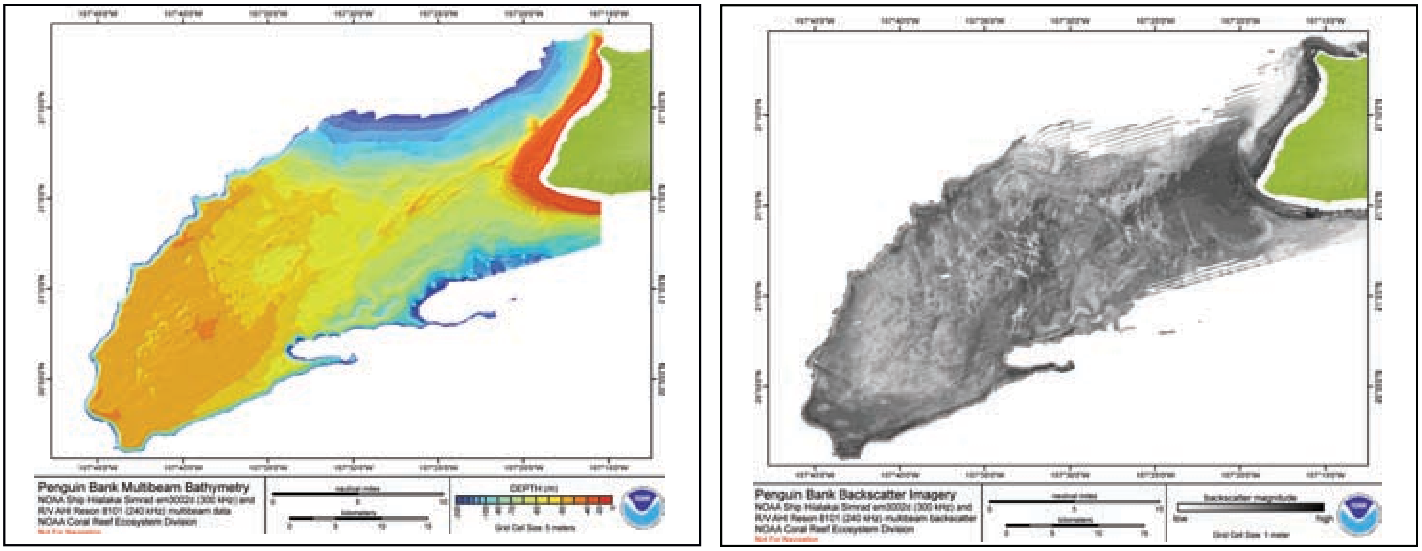

Figure 8.33. Penguin Bank bathymetry and backscatter data. Source: PIFSC-CRED.

WHAP

The abundance of coral, macroalgae and other living substrata were estimated at 23 sites using a digital video camera along four 25 m transect at each site. Percentage cover estimates of substrate types were obtained from contiguous still frames using the program PointCount 1999. Tissot et al., (2004) provided detailed methods which were comparable to the CRAMP/DAR protocol outlined in Brown et al., (2004). Total coral cover was statistically similar among the reference, FMAs, and open access areas in depths ranging from 6-15 m. The new DAR Main Hawaiian Islands monitoring program has incorporated the various methods listed above into an integrated and comprehensive approach.

Results and Discussion

Average coral cover across 1,682 independent transects/sites in the MHI was 19.9% ± 0.6% SE, with seven of the 29 coral species accounting for most of the cover (19.3%; Figure 8.34). The dominant species were: *Porites lobata* (8.5%), *Porites compressa* (3.8%), *Pocillopora meandrina* (2.5%), *Montipora capitata* (2.3%), *Montipora patula* (1.6%), *Montipora flabellata* (0.3%) and *Pavona varians* (0.3%). The remaining 22 species covered only 0.6% of the substrate.

Coral cover was highest in the southern portion of the archipelago (e.g., Molokini and Kahoolawe) and lowest in the northern part (Table 8.12). Some exceptions did exist, such as the moderate coral cover at Kaula rock (23.5% ± 6.9% SE) and Hawaii (24.6% ± 0.9% SE), but in general coral cover decreased with increasing geologic age (r=-0.64).These results validate previous studies (e.g., Grigg, 1983; Jokiel et al., 2004) that have suggested this relationship, but with a considerably smaller sample size.

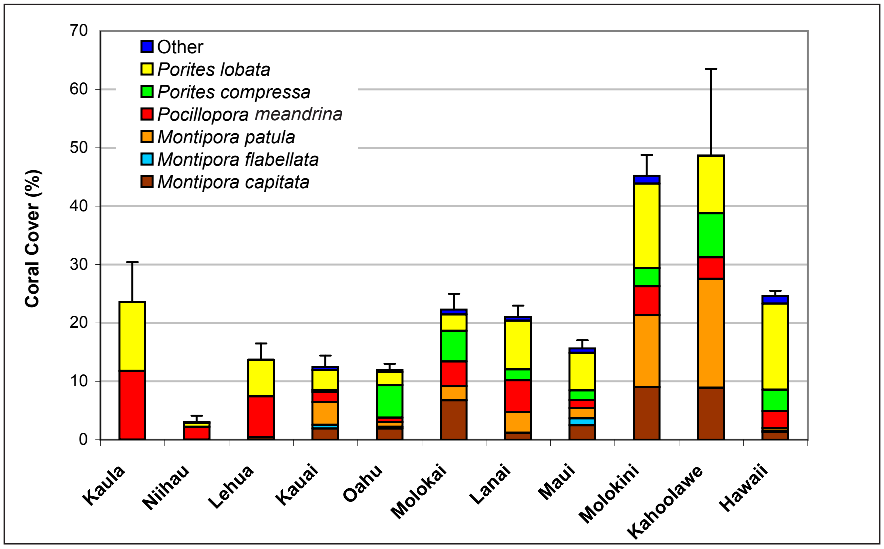

Figure 8.34. Mean percent coral cover at each island in the MHI along a geological (longitudinal) gradient from oldest (west) to youngest (east). Coral cover was calculated from 1,682 transects/sites surveyed between 2001 and 2006. Data sources include CRAMP/DAR (n=692), PIFSC-CRED (n=108), FHUS (n=859) and WHAP (n=23). Mean percent cover ± 1 SE.

Table 8.12. Mean percent coral cover (± 1 SE) and sampling effort by island. N=number of independent sites sampled at each island. Islands ordered from oldest geologically (top) to youngest (bottom). Geologic ages from Clague and Dalrymple, 1987. Sources CRAMP/DAR, PIFSC-CRED, FHUS and WHAP.

ISLAND	MEAN CORAL COVER (%)	SAMPLING EFFORT (N)	GEOLOGIC AGE (MYA)
Kaula Rock	23.5 ± 6.9	2	5.8
Niihau	3.0 ± 1.1	17	5.6
Lehua	13.7 ± 2.8	5	5.6
Kauai	12.5 ± 2.0	114	5.2
Oahu	11.9 ± 1.1	437	4.0
Molokai	22.3 ± 2.7	133	2.1
Lanai	21.0 ± 2.0	84	1.6
Maui	15.6 ± 1.4	254	1.3
Molokini	45.2 ± 3.6	63	1.0
Kahoolawe	48.7 ± 14.8	20	1.0
Hawaii	24.6 ± 0.9	553	0.6

Light and temperature conditions favorable to coral growth diminish with increasing latitude and increasing island age which helps explain the observed coral cover pattern.

There was also a negative correlation (-0.57) with mean species richness and geologic age of the islands. Sampling effort varied by island with some islands (e.g., Kahoolawe and Hawaii) under sampled compared to other islands (e.g., Molokini and Oahu; Table 8.12). Consequently, coral cover estimates by island will improve as programs extend their spatial coverage.

Waves appear to be the most important factor structuring coral reef assemblages in Hawaii (Grigg, 1983; Jokiel et al., 2004). Sites exposed to the larger west and northwest swells on the older islands (e.g., Kauai and Oahu) generally had lower coral cover (Figure 8.35), species richness and diversity (Jokiel et al., 2004). Storlazzi et al. (2005) showed that waves in Hawaii can reach destructive levels that will damage corals and restrict species distributions.

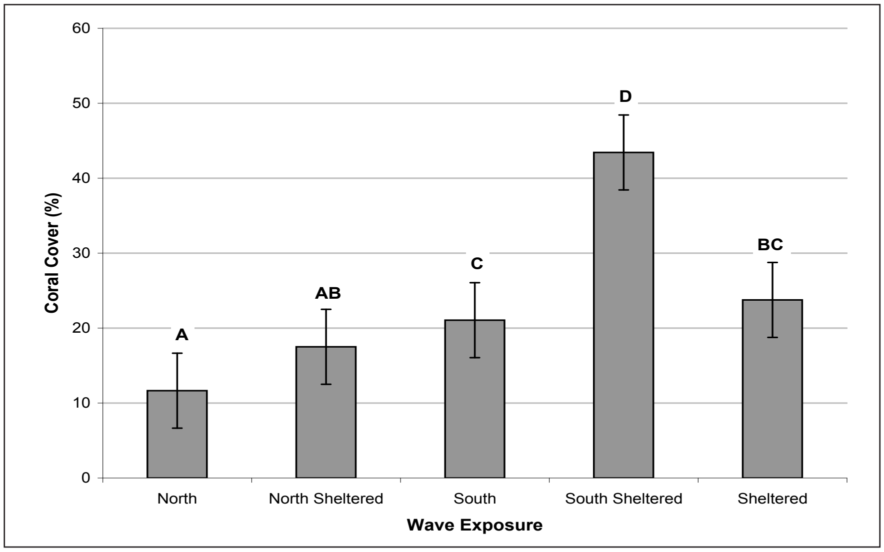

Figure 8.35. Mean percent coral cover on hard bottom habitats in various wave exposure regimes in the MHI. Exposures with the same letter designation are not significantly different (Tukey's HSD multiple unplanned comparisons test, α=0.05). Wave exposure codes for each site were based on methods described in Friedlander et al. (2003). Error bars are standard error of the mean. Sources: CRAMP/DAR, PIFSC-CRED, FHUS, WHAP.

Another important factor influencing coral communities are anthropogenic activities that have been associated with the decline of coral reefs around the globe (Richmond, 1993). In Hawaii, the relationship of coral cover to human populations in the upland watershed indicated that larger populations generally had lower coral cover on the reefs adjacent to the watershed (Figure 8.36). Notable exceptions were found, however, including sites on patch reef crests in Kaneohe Bay with high coral cover (>90%) that are next to populated areas. In comparison, reefs fronting Honolulu and Waikiki beach were almost devoid of living corals (Mean 2.0 % ± 0.4% SE). Temporal patterns in coral cover at some of these sites can clarify anthropogenic impacts and reduce the location bias of humans choosing to settle near areas of good coral cover.

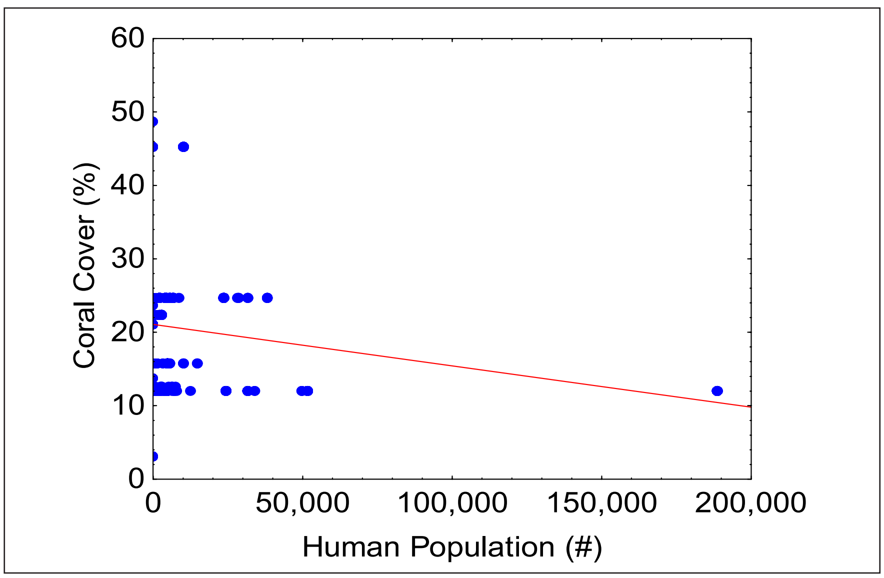

Figure 8.36. The relationship of mean percent coral cover by island in the MHI to the human population within the adjacent watershed. Percent cover=21.1–0.00006(human population), n=1,682, r^2= 0.11, p<0.001. Sources: CRAMP/DAR, PIFSC-CRED, FHUS and WHAP.*

Long-Term Monitoring at Selected Sites

Sites in Hawaii that have been monitored over a longer time period (>10 years) are included for historical perspective (see Table 8.13). Coral cover has been surveyed sporadically over the years using different methods at each of the sites, but studies (i.e., Brown, 2004) comparing methods produced similar results both spatially and temporally.

The long-term trends at the selected sites show that the majority of the stations (19 out of 27) experienced a decline in percent coral cover over their respective study periods. Among islands with more than one long-term site, the change in coral cover was not significantly different ($F_{2,22}$=3.16, p=0.06, Figure 8.37). Several of these sites (e.g., Kahe Point and Pili o Kahe) have experienced cyclical changes in coral cover that can be explained by recruitment events among predominant corals (Coles and Brown, 2007). Possible explanations for the major declines (>10%) include reef slumping (e.g., Kaalaea and Jokiel et al., 2004), eutrophication (e.g., Kahekili; Smith et al., 2005) and sedimentation (e.g., Honolua Bay; Dollar and Grigg, 2004). Sites such as Hanauma Bay, Honolua Bay, Kahekili and Olowalu are high human use areas and changes at these reefs have important management implications. In addition, long-term data sets on coral cover are uncommon and provide benchmarks for changes in ecosystem components in Hawaii.

Table 8.13. Average percent coral cover at selected sites that have been surveyed at time periods spanning 10 or more years. Overall percent change (Δ) from the initial survey to the last survey is shown in the last column. Data sources for each station are listed below. Asterisks (*) indicate sites within Kaneohe Bay.

			YEAR																														
ISLAND	SIZE	DEPTH (M)	71	74	75	76	79	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00	01	02	03	04	05	06	Δ
Kauai	Hanalei Bay[1,2,3]	3																		15						16	26		17	17	7	5		-9
		5																		6						6					8	8		2
		7																		17						23					23	16		-1
		8																		20						28	30		26	36	29	29		10
		8																		8						17					11	12		4
		14																		21						17					25	19		-1
		16																		15						25					22	18		3
Oahu	Kahe Point[2,4]	3						20	19	16	16	16	19	22	20	18	17	12	10	5	5	5	5	9	7	9	13	15	17	17	8	6		-14
Oahu	Pili o Kahe[2,4]	3						20	12	10	10	8	9	10	12	12	18	17	16	13	11	8	8	8	7	9	7	8	10	11	9	8		-12
Oahu	Kaalaea[2,5,6*]	2	92							82							79									62	51	49	67	59		58		-35
		8	7							11							9									3	2	4	3	3				-4
Oahu	Heeia[2,5,6*]	2	33							64							62									36	23	18	24	22				-11
		8	1							15							2									8	7	7	5	7				6
Oahu	Moku o Loe[2,5,6*]	2	6							45							21									30	20	16	13	14				9
		9	0							4							3									8	7	6	4	9				9
Oahu	Hanauma Bay[2,7,8]	3				28													47	28		28		28	33	24	26		22					-6
		10				38													40	36		33		32	25	27	27		22					-15
Maui	Honolua Bay North[2,8,9,10,11,12]	3		39			23											51	56		41	35	28	28	24	15	17	15	14	8	10	8	9	-30
	Honolua Bay South[2,8,9,10,11,12]	3		43			36														42	42	38	33	28	21	27	23	24	21	23	11	9	-34
Maui	Kahekili[2,11]																				52	42	51	42	49	44		29	33	32	35	29	38	-14
																					58	45	50	56	51	30		22	21	25	29	24	31	-28
Maui	Puamana[2,11]	3																			4	7	7	10	12	15	18	16	13	10	9		10	6
		13																12	13	1	1	1	0	0	1	3	3	5	6	5	6	4	5	-7
Maui	Olowalu[2,11,13]	3													31						32	30	23	30	30	23	25	22	23	16	21	17	19	-13
		8																			55	56	47	57	51	55	54	53	51	51	52	51	54	-1
Hawaii	Puako[8,14]	3							66									42	42	43		47		58	60									-5
		10							63									46	41	43		44		59	45									-18

DATA SOURCES *[1] Friedlander et al., 1997; [2] Jokiel et al., 2004; [3] Friedlander and Brown, 2006; [4] Coles, 1998; [5] Maragos, 1972; [6] Hunter and Evans, 1995; [7] Anderson, 1978; [8] Hunter, 1999; [9] Environmental Consultants, 1974; [10] Torricer et al., 1979; [11] Brown, 2004; [12] Dollar and Grigg, 2004; [13] Ambrose et al., 1988 ; and [14] Hayes et al., 1982.*

Halimeda Meadows

Halimeda kanaloana is an endemic, calcified green alga forming expansive meadows over soft, sandy substrate in Hawaii. *H. kanaloana* meadows cover hundreds of kilometers of the sea floor around the Maui Nui island complex (Maui, Lanai, Molokai and Kahoolawe) from 10 to 90 m depths. Isolated patches have also been observed in south Oahu at 35 and 50 m depths. *H. kanaloana* meadows provide structural complexity up to 30 cm in height and often have densities of >250 individuals m^2. *H. kanaloana* and its associated epiphytic organisms may serve as a food source for other fish and invertebrates. For instance, large schools of predatory jacks have been observed preferentially foraging in *H. kanaloana* meadows from 30 to 60 m depths off west Maui (H. Spalding and F. Parrish, pers. obs.). Endangered hawksbill sea turtles forage for invertebrates found in this habitat. These meadows also provide habitat for cryptic sand-dwelling fish such as wrasses (Labridae), gobies (Gobiidae), eels (Congridae), pufferfishes (Tetraodontidae), boxfishes (Ostraciidae) and octopus (Octipodidae; F. Parrish, H. Spalding and R. Langston, pers. obs.).

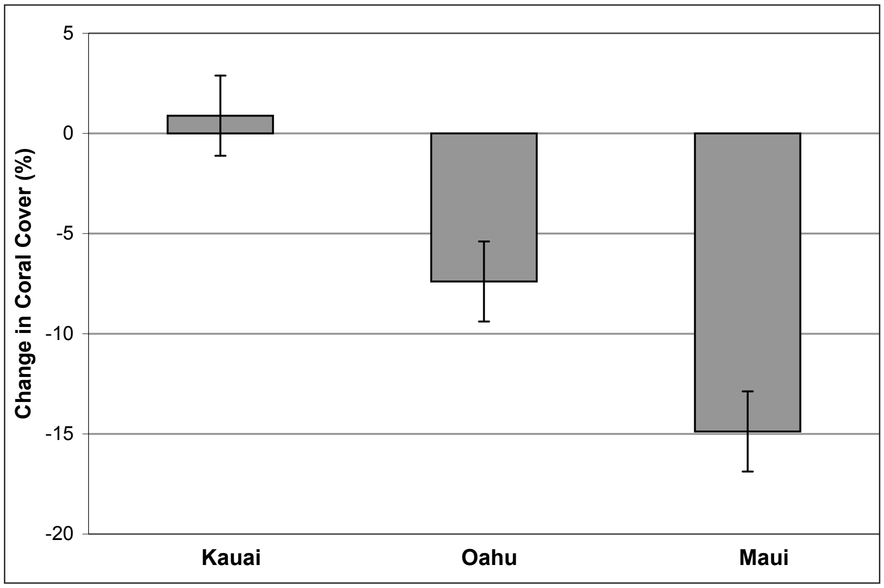

Figure 8.37. Change in mean percent coral cover by island at long-term (>10 years) monitoring sites in the MHI. Error bars are standard error of the mean. Data sources in Table 8.13.

Current research suggests that these meadows produce a large amount of sand for the Maui Nui island complex, with approximately 800 g of calcium carbonate produced per m^2 year. These meadows may be sensitive to repeated disturbances such as anchoring. *Halimeda* plants have the ability to quickly regrow within a few months from superficial scarring causing the removal of the upright plant body (thallus). However, if a disturbance causes the removal of the entire *Halimeda* holdfast, it may take many months to a year to regrow to original densities. *Halimeda* meadows in areas targeted for cruise ship anchoring may be particularly vulnerable.

Deep Coral Reefs (30–100 m)

Hawaii has many unstudied coral reefs in deep water (30-100 m). Recently, reefs on Niihau (60-70 m), north Kauai (30-50 m), north Oahu (30-50 m; J. Rooney, pers. obs.), west Oahu (120 m; Pyle, pers obs.) and several areas around Maui Nui (30-100 m; T. Montgomery, pers. obs.) have been documented using drop cameras, ROVs, submersibles and mixed gas divers (Figure 8.38). These areas vary in species composition and biodiversity depending on location but often are comprised of high coral cover intermingled with macroalgae. Some sites are dominated by monospecfic stands of hermatypic corals (*Montipora* spp., *Porites* spp. and *Leptoseris* spp.). Recently, *Leptoseris* spp. was documented well below 100 m depth (Kahng and Maragos, 2006) and has been found to be a highly dominant genus in the 70–90 m range of Maui Nui. Macroalgae species may also play a significant role in these ecosystems (H. Spalding, pers. obs.). Little is known of the many potentially new species of invertebrates.

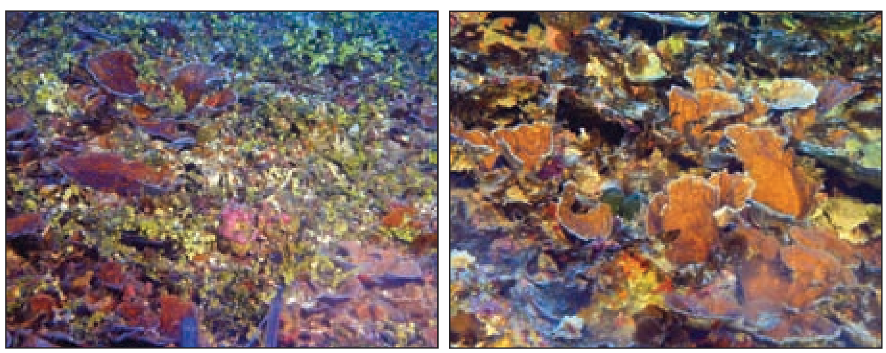

Figure 8.38. Deep reefs off Maui at 70 m (left) and in the Auau Channel at 75 m (right). Photos: Hawaii Undersea Research Laboratory; T. Montgomery via a drop camera.

ASSOCIATED BIOLOGICAL COMMUNITIES

Comparison of Fish Biomass and Trophic Structure Among Islands

Fish biomass by trophic group was examined across the major inhabited MHI. Data were complied from six comprehensive studies that surveyed fish at 188 locations with a total of 1,427 transects. Mean biomass by trophic group was calculated at each location and grand mean biomass by island was computed by weighting each location within an island by the number of transects conducted at each location.

The island of Niihau, including Lehua and Kaula rocks, are some of the most remote areas within the MHI and also had the highest fish biomass observed among the surveys (Figure 8.39). Although Molokai had the second highest biomass observed among islands, there were notable differences in biomass between the populated south shore and remote north shore areas. The south shore of the island experiences relatively high fishing pressure due to the subsistence community nearby. By contrast, the relatively remote north shore has high fish biomass and an abundance of apex predators as a result of lower human population density and seasonal refugia due to large waves which restrict fishing activities. The Big Island, as the name implies, has many remote locations relative to the overall human population and the reefs are healthy compared with the more densely populated areas of Oahu and Maui. Although parts of Maui suffer from overfishing and intense coastal development, there are a number of remote locations on the north and east shores that harbor healthy fish populations. Oahu had the lowest overall fish biomass among the populated islands and apex predators are virtually absent, likely due to intense fishing pressure.

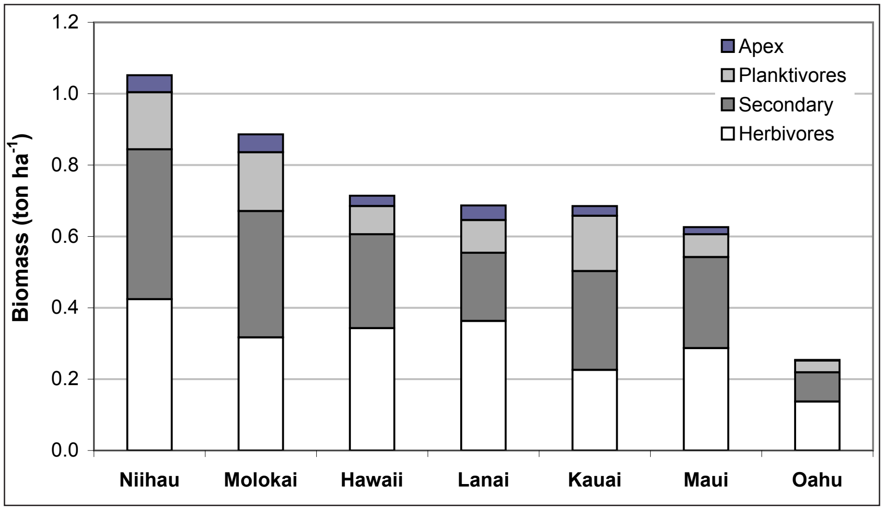

Figure 8.39. Fish biomass (t ha^{-1}) among islands. Niiahu includes Lehua and Kaula rocks. Sources: CRAMP/DAR, PIFSC-CRED, FHUS and WHAP.

Twenty Year Retrospective Study of Fish Populations at Honaunau, South Kona, Big Island

Fish assemblages in three habitats at Honaunau, South Kona were surveyed over four summers in 1975 to 1978 and then resurveyed using identical methods in 1998 to 2001. In broad terms, assemblage structure was similar between survey periods (Table 8.14). The top four numerically dominant fish families (surgeonfish, damselfish, wrasse and butterflyfish) in 1975-1978 were also the most common families twenty years later.

Table 8.14. Overall fish assemblage comparison at Honaunau. Source: DLNR/DAR

TOTAL # OF FISH SPECIES	1975-1978	1998-2001	%Δ	p
Total number fish species	124	128	↑3.2	
Mean number species/year	92	90.8	↓1.3	0.39
Mean number species/transect	58.2	59.5	↑2.2	0.61
Diversity (H')	2.71	2.61	↓0.06	0.27
Mean number fish/transect	790.9	493.6	↓37.6	0.06
Total number transects	**45**	**60**		

Nine of the 10 most abundant species in 1975-1978 were also among the 11 most abundant species in 1998-2001 (Table 8.15). There was a significant change in overall assemblage trophic structure (Figure 8.40; x^2=24.99, p<0.001) between the periods driven by significant deceases in the numbers of corallivores (-65%, p<0.05) and detritivores (-56%, p<0.001, t-tests). The later group consists primarily of a single very common species, the yellow eyed kole, *Ctenochaetus strigosus*.

Table 8.15. Comparison of fish species abundance between survey periods. Asterisks (*) represent trends that are statistically significant at α = 0.05. Source: DLNR/DAR.

SPECIES	HAWAIIAN/ COMMON NAME	1975-1978	1998-2001	%Δ
Ctenochaetus strigosus	Kole	1	1	↓55*
Zebrasoma flavescens	Lauipala	2	3	↓34
Chromis vanderbilti	Blackfin chromis	3	2	↓09
Acanthurus nigrofuscus	Māiii	4	5	↓34*
Chaetodon multicinctus	Kikakapu	5	8	↓76*
Thalassoma duperrey	Hinalea lauwili	6	6	↓44*
Chromis agilis	Agile chromis	7	4	↑25
Paracirrhites arcatus	Pilikoa	8	9	↓40*
Stegastes fasciolatus	Pacific gregory	9	11	↓53
Chromis hanui	Chocolate-dip chromis	10	29	↓88*

The most substantial assemblage change was that overall mean fish abundance declined by 37% (p=0.06; Table 8.14). Various families of fishes responded differently; nearly all species of small bodied surgeonfishes, butterflyfishes and angelfishes de-

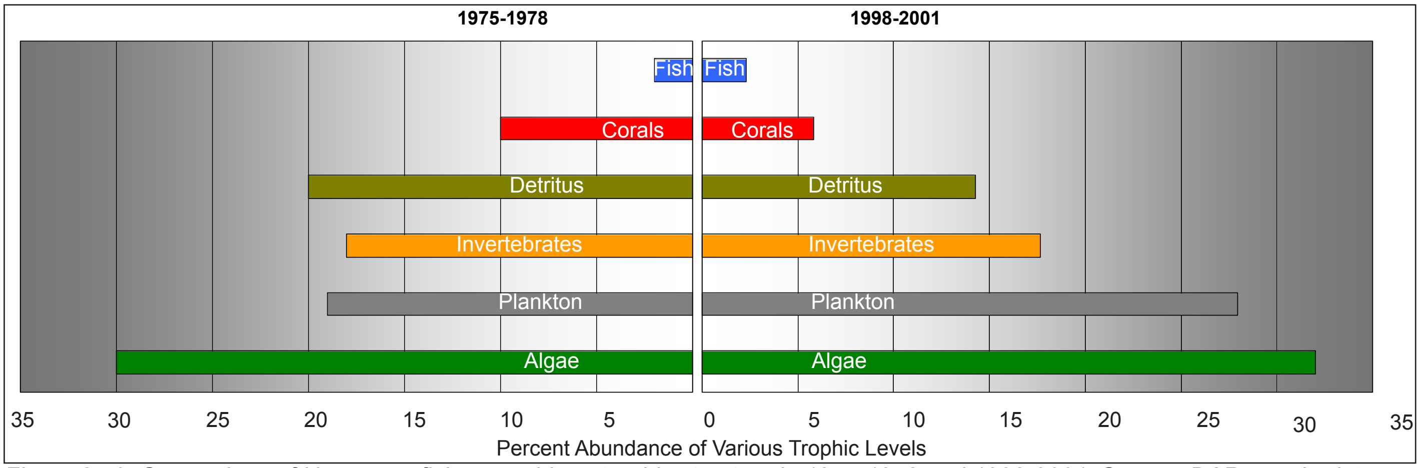

Figure 8.40. Comparison of Honaunau fish assemblage trophic structure in 1975-1978 and 1998-2001. Source: DAR unpub. data.

clined in abundance while other families, including typical food fishes such as parrotfishes (Scaridae) and soldierfishes (Myripristidae), increased. The increase in these latter species occurred during a period when the population of Hawaii County and the South Kona District increased respectively by 97% and 72%. Visitor counts at the adjacent Puuhonua o Honaunau National Historical Park also increased during this time by 18%. Based on information provided by area residents there is reason to believe that increased recreational use of the bay and adjacent shoreline by sunbathers, swimmers, snorkelers and divers may have reduced the level of fishing activities within the bay. Thus the increased abundance of certain food fishes may be in part related to a relaxation of fishing pressure.

Although three major storms influenced Honaunau between survey periods, the most recent benthic analysis indicated a healthy, vibrant reef system with high coral cover and high spatial complexity. Habitat alteration is thus unlikely to be a factor in the widespread decline of many smaller bodied fishes. Commercial aquarium fishing is however implicated in this decline (Figure 8.41). Of the 20 most collected aquarium species, 18 declined in abundance (p<0.001) with intensively collected species generally having experienced the greatest declines. Two collected species, blue stripe butterflyfish (*Chaetodon fremblii*) and bandit angelfish (*Apolemichthys arcuatus*) were repeatedly recorded during the 1975-1978 surveys but totally absent during 1998-2001 surveys.

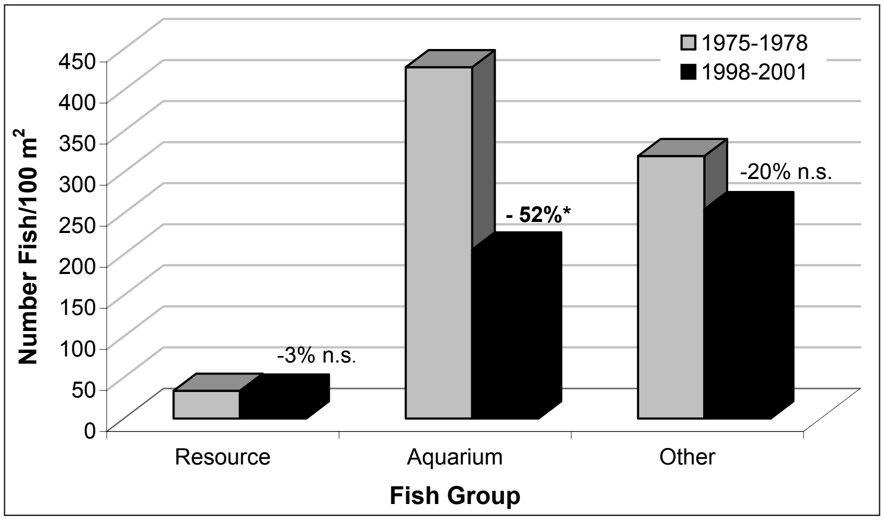

Figure 8.41. Comparison of various fish functional groups at Honaunau over two survey periods. Asterisk (*)=p<0.05, t-test. Source: DLNR/DAR.

In contrast to the aquarium species, there were no comparable consistent changes in other non- or less collected groups: 17 of 29 “food fishes” were lower while 12 were higher (p=0.46). For another 47 species regarded as neither food nor aquarium species, 26 declined while 21 became more abundant (p=0.56).The introduced peacock grouper, *Cephalopholis argus* (roi) was initially rare but increased 17-fold in the twenty years between survey periods (from 0.4 to 6.9 fish/1000 m^2). The potential impact of this increase on other species at Honaunau over this period is presently under evaluation.

Preliminary Assessments of Fish Stocks in the MHI

Preliminary assessments for 55 fish species targeted in the commercial, recreational and ornamental fisheries within the MHI were developed by comparing their abundance to the Northwestern Hawaiian Islands Marine National Monument, a large, virtually unfished reference area. Underwater visual censuses were used to survey shallow-water reef fishes in the heavily fished MHI and in the NWHI (Sladek Nowlis et al., in review). Nearly three-quarters of the species examined in the main Hawaiian Islands appeared to be depleted (Figure 8.42). Large mobile predators were especially affected, but many other target and non-target species appeared to be in poor condition as well. When no-take areas in the MHI were used as a reference area, only 13% of the species appeared to be in poor condition, showing that these small no-fishing zones serve poorly as unfished reference areas, particularly for stocks in the worst condition. With the help of a larger and therefore more appropriate unfished reference area, there is strong evidence of negative ecological effects in Hawaiian shallow water reef assemblages that are likely caused by fishing. These preliminary assessments of individual stocks warrant further investigation before making a final assessment of the status of any the species involved.

By comparing size frequency distributions for certain species in the NWHI and MHI, natural and fishing mortality rates were developed. Since the NWHI populations experience little fishing pressure, those mortality rates represent natural mortality (M) while the MHI populations experience both natural and fishing mortality (F). Preliminary analysis of the blue trevally (*Caranx melampygus*) using mean observed sizes indicated that M is moderate, approximately 0.27, according to the estimated total mortality in the unfished NWHI (Figure 8.43). In the MHI, a total mortality rate was estimated at 0.69 and therefore an F of 0.42. It is common to use F30, a fishing mortality rate that allows a typical member of the population to produce 30% of its reproductive potential in the absence of fishing. For this species, F30 was estimated to be 0.22, suggesting that recent fishing rates were nearly twice a reasonable proxy for maximum sustainable yield. One measure of recent fishing is the current spawning potential ratio (Figure 8.42). This calculation indicates that blue trevally in MHI are currently only producing 11% of their reproductive potential. These results are consistent with analyses of the relative biomass densities of this species in the MHI and NWHI that indicated the MHI population may have dropped to 2% of its unfished abundance (Sladek Nowlis et al., in review).

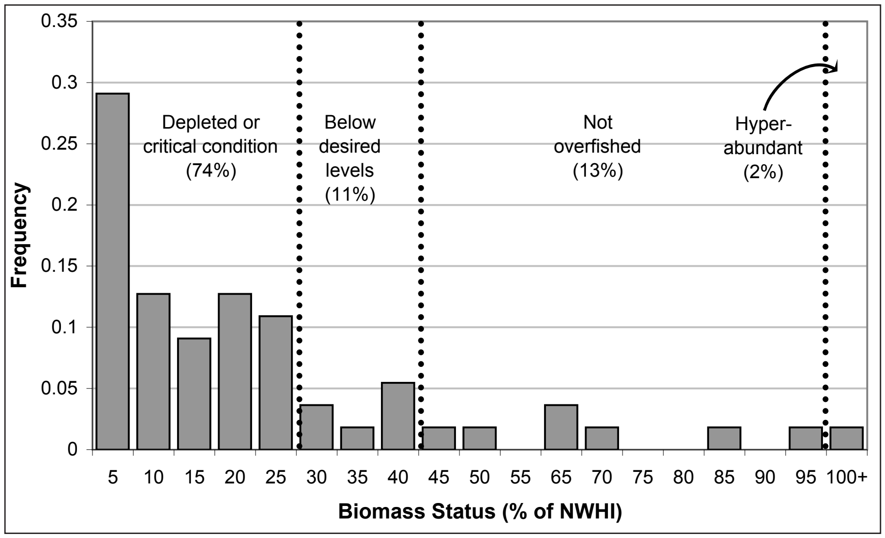

Figure 8.42. Stock status of 55 species in the MHI compared to the NWHI as an unfished reference area. Source: Sladek Nowlis et al., in review.

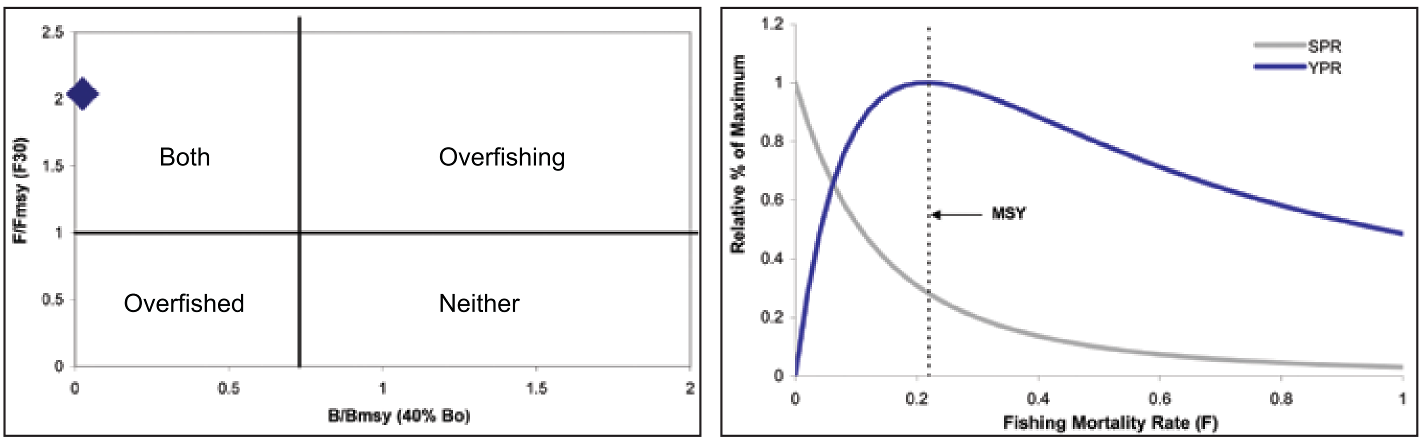

*Figure 8.43. Left panel shows fishing mortality rate (F), biomass estimates (B) and right panel shows spawning potential ratio (SPR), and yield per recruit (YPR) for blue trevally (*Caranx melampygus*). Source: Friedlander, unpub. data.*

Resistance and Resilience In Hanalei Bay, Kauai Fish Assemblages Since 1992

A limited number of data sets exist in Hawaii to examine the resilience and resistance of coral reef ecosystems to natural disturbance. Hanalei Bay on the north shore of the island of Kauai has been monitored since 1992 providing a unique data set in which to examine changes in the composition of the coral reef community over time (Friedlander et al., 1997; Friedlander and Brown, 2006). Hanalei Bay is directly exposed to large winter swells with high surf, as well as frequent heavy winter rainfall and high river discharge.

From 1991 to 1994, an extensive marine resource assessment was conducted in Hanalei Bay to characterize benthic habitat types, examine the spatial and temporal distribution of the marine biota, and describe the fishery within the bay (Friedlander and Parrish,1997; Friedlander and Parrish, 1998a and 1998b). Permanent sites were resurveyed in 1999, 2003, 2004 and 2005 to examine the temporal dynamics in coral reef community structure in Hanalei Bay since 1992.

Reef fishes in Hanalei Bay demonstrate distinct assemblage structures and characteristics based on hardbottom habitat type. The highest number of fish species was associated with deeper habitats that had high structural complexity. Low numbers of species were observed on reef flats that were distant from sand areas and had low habitat relief.

Certain habitats changed more dramatically than others from 1992 to 2005 and had clearly separate faunal assemblages. An ordination plot showed the deep slope habitat and the spur and groove habitats had high concordance among years (Figure 8.44). In contrast, the low relief and shallow slope habitats showed more dramatic changes among years but the assemblage in more recent years shows similarly with 1993 and 1994. This plot highlights the resistance of deeper and more complex habitats to interannual variability. While the low relief and shallow habitat types are more variable, they show resilience.

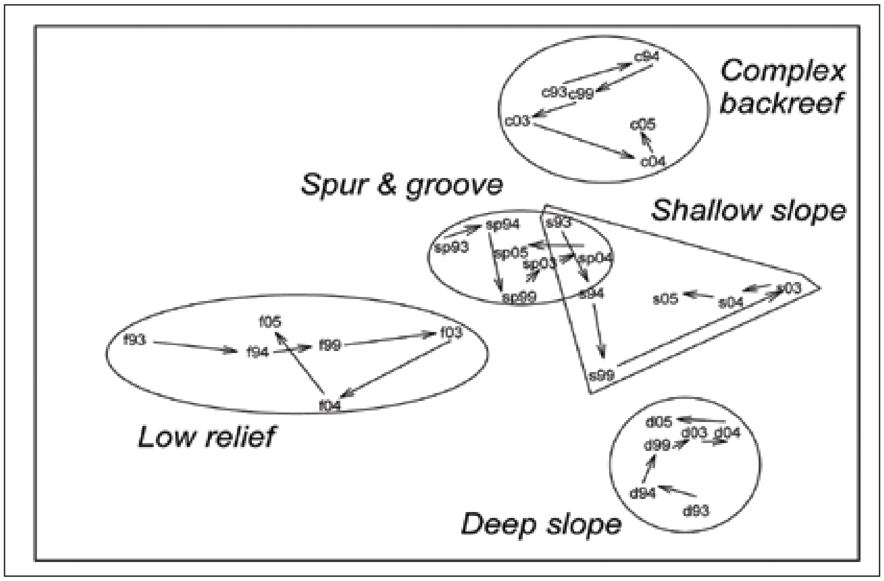

Figure 8.44. Hanalei Bay fish assemblage (number of individuals) changes over time in various habitat types. Source: Friedlander and Brown, in review.

CURRENT CONSERVATION MANAGEMENT ACTIVITIES

Hawaii's Marine Protected Areas

Within the MHI, there are 34 state-managed areas which limit fishing activities in nearshore marine waters: 11 MLCDs (areas designed to conserve and replenish marine life), 20 FMAs (areas designed to resolve conflicts among users, including fishers), and three other marine managed areas: Ahihi-Kinau Natural Area Reserve (NAR), Kahoolawe Island Reserve and Coconut Island Hawaii Marine Laboratory Refuge (HMLR). In addition, members of the public have limited or no access to the shoreline and nearshore waters within and around military or security areas on Oahu and Kauai (Pearl Harbor, Kaneohe Bay Marine Corps Base Hawaii, Barking Sands Pacific Missile Range Facility and Honolulu Reef Runway) or in the Hawaii Volcanoes National Park.

The large number of restricted-access or restricted-fishing areas in the MHI gives the impression of a substantial network of actively managed and protected marine areas, but the reality is that the majority of those areas are small and, nearly all allow some or several forms of fishing within their boundaries; some types of fishing are even permitted within six of the 11 MLCDs. In total, only 0.4% of nearshore MHI waters <60 ft deep (an approximation of the inshore habitats which are the primary targets for fishing of reef and reef-associated species) are in no-take MPAs (Figure 8.45). An additional 3.6% are in partially protected areas, and 6.5% are in areas with no access or restricted access to members of the public. The remaining 89.5% of nearshore waters are not spatially managed for fishing or specially restricted.

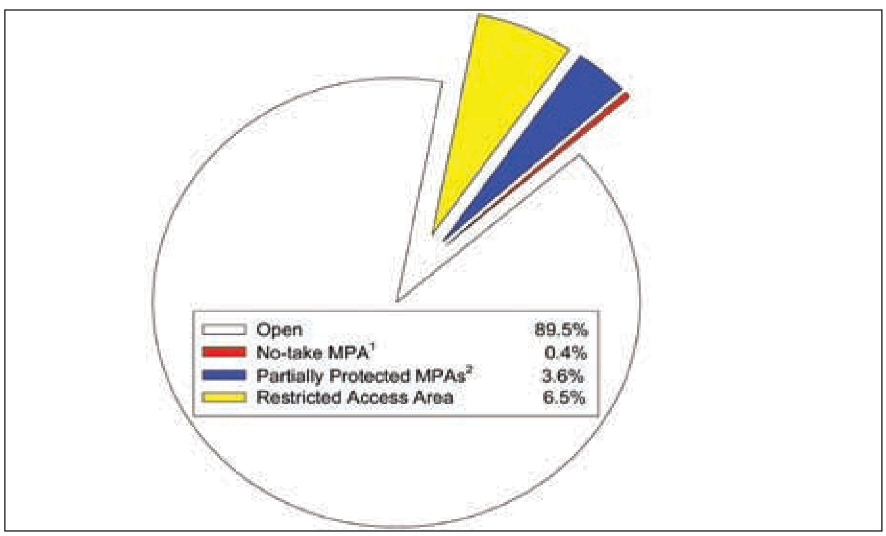

*Figure 8.45. MMAs and restricted-access areas by management category (<60 ft deep nearshore marine areas) in the MHI. **Notes: (1)** no-take portions of MLCDs, plus Ahihi-Kinau NAR and Coconut Island HMLR; **(2)** mostly FMAs and portions of MLCDs where some fishing is allowed, plus various harbors, wharfs and piers; **(3)** Military and security zones with no access to the public (total of 2.7%), with access by permits which require background security checks (total of 1.6%), Kahoolawe Island Reserve (1.7%) which limits access to the public and allows subsistence fishing by permit only, and Hawaii Volcanoes National Park (0.5%), in which shoreline fishing is restricted to native Hawaiians and their guests. Source: DLNR/DAR, unpub. data.*

The proportion of nearshore MHI waters in no- and negligible-take areas including fully protected MLCDs, extremely limited access reserves and no-access zones is only 4.8% (Table 8.16). The large majority of that is in military and security no-access zones on Oahu and Kauai or in the Kahoolawe Island Reserve, and so the extent of complete no-take areas on other islands is extremely limited: only 1.7% of nearshore habitat around Maui Island and 0.2% around Hawaii Island.

Outside of those no-access or no-take areas there are only limited additional restrictions on most fishing gears. Therefore, the great majority of MHI nearshore waters are open to common recreational fishing gears: for pole and line 94.7%, for throw-net 94.4%; and for spearfishing 94.9% of nearshore waters are open (see Table 8.16). Prohibitions on other gears are more extensive: 8.0% of nearshore waters are closed to aquarium-fish collecting, and 27.5% are currently closed to lay-gillnet fishing. The percentage of nearshore waters closed to lay-gillnet fishing increased by nearly 20% in March 2007, when lay-gillnet restrictions were enacted on portions of south/southeast Oahu and on the whole of Maui Island.

Table 8.16. Area closure by management type and type of fishing. Source: DLNR/DAR, unpub. data.

	CLOSED	OPEN
State managed no-take areas[1]	0.4 %	
State-managed areas with severely limited access[2]	1.7 %	
Military/Security no-access areas	2.7 %	
TOTAL – all fishing or access prohibited or heavily restricted	**4.8 %**	**95.2 %**
Area restrictions by fishing gear (including areas above)[3]		
Lay gillnet	27.5 %	72.5 %
Throw-net	5.6 %	94.4 %
Pole and line	5.3 %	94.7 %
Spear-fishing	5.1 %	94.9 %
Aquarium-fish collecting	8.0 %	92.0 %

Notes: (1) no-take portions of MLCDs, plus Ahihi-Kinau NAR & Coconut Island HMLR **(2)** Kahoolawe Island Reserve **(3)** 1.6% of near-shore waters are in military-restricted access areas (Kaneohe Bay MCBH & southern portion of Barking Sands PMRF) where only active duty servicemen or locals with permits may fish, and 0.5% in the Volcanoes National Park, where only native Hawaiians and guests may fish from shore. For purposes of above calculations, military and security access areas accessible by permit are considered open to fishing, but Hawaii Volcanoes is considered closed to predominantly shoreline gears: pole & line and throw-net.

Evaluation of Marine Protected Area (MPA) Efficacy

Hawaii has developed a system of eleven Marine Life Conservation Districts (MLCDs) to conserve and replenish marine resources around the state that vary in size, habitat quality and management regimes, providing an excellent opportunity to test hypotheses concerning MPA design and function using multiple discreet sampling units. NOAA's Digital benthic habitat maps for all MLCDs and adjacent habitats were used to evaluate the efficacy of existing MLCDs using a spatially-explicit stratified random sampling design (Friedlander et al., 2006; 2007a and 2007b). Results showed that a number of fish assemblage characteristics (e.g., species richness, biomass, diversity) vary among habitat types, but were significantly higher in MLCDs compared with adjacent fished areas across all habitat types. Overall fish biomass and the number of large fishes (>20 cm) was greater than adjacent areas open to fishing by more than 200% and 150%, respectively (Figure 8.46). Areas on Oahu and Maui showed the largest differences between MPAs and fished areas, presumably due to higher fishing pressure and poorer habitat quality associated with the areas (Figure 8.47).

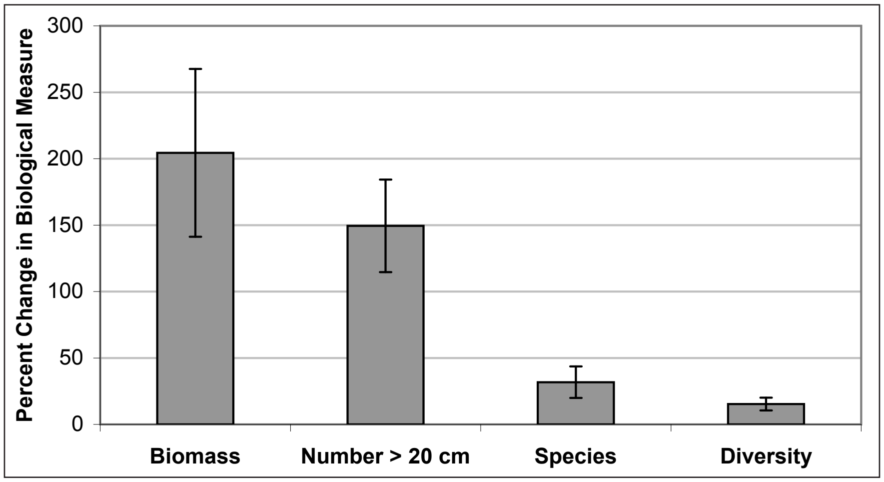

Figure 8.46. Percent change in biological measures between MLCDs and adjacent areas open to fishing. Values are means and standard error. Source: Adapted from Friedlander et al., 2007a

In addition, apex predators and other resource species were more abundant and larger in the MLCDs, illustrating the effectiveness of these closures in conserving fish populations within their boundaries. Based on biomass ratios inside and outside MLCDs, all protected areas appear to conserve fish biomass, in varying degrees, within their borders compared to adjacent areas open to fishing. Habitat type, protected area size and level of protection from fishing were all important determinates of MLCD effectiveness with respect to their associated fish assemblages. Although size of these protected areas was positively correlated with a number of fish assemblage characteristics, all appear too small to have any measurable influence on the adjacent fished areas. These protected areas were not designed for biodiversity conservation or fisheries enhancement yet still provide varying degrees of protection for fish populations within their boundaries. Implementing this type of biogeographic process, using remote sensing technology and sampling across the range of habitats present within the seascape, provides a robust evaluation of existing MPAs and helps define ecologically relevant boundaries for future MPAs.

Effectiveness of a MPA Network to Manage the West Hawaii Aquarium Fishery

The aquarium collecting industry in Hawaii and especially West Hawaii has long been a subject of concern and controversy. Growing public perception of dwindling fish stocks due to over-collecting eventually developed into a severe multiple use conflict with particular animosity between aquarium collectors and the dive tour industry. In January 2000, a network of nine Fish Replenishment Areas (FRAs) which prohibit aquarium collecting was established in West Hawaii to address declines of aquarium-collected reef fishes and escalating conflict. FRAs comprise 35.2% of the coastline and were designated with substantial community input.

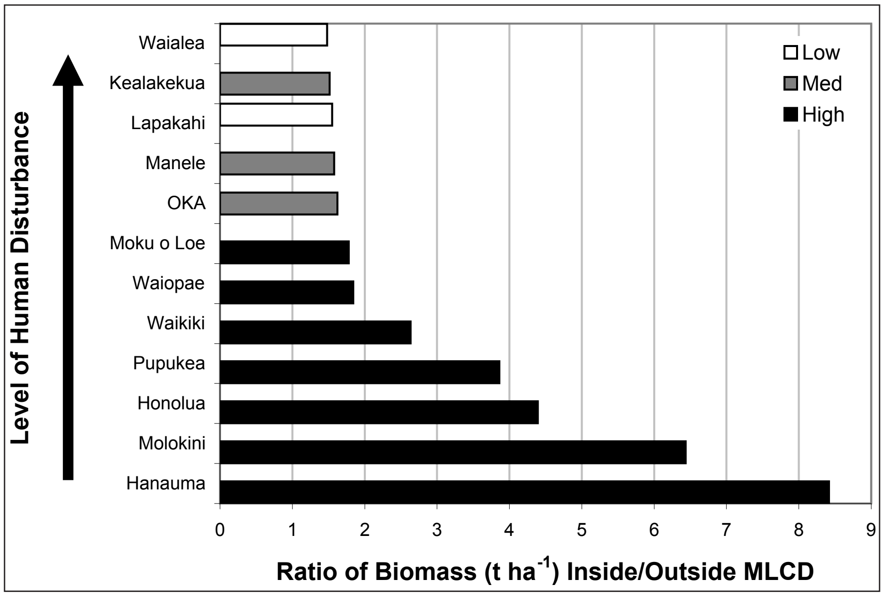

Figure 8.47. Ratio of biomass (t ha^{-1}) inside MLCDs and Moku o Loe Refuge versus outside areas open to fishing. Hardbottom habitats only. Source: Friedlander et al., 2007.

To assess the effectiveness of the FRA network and its impact on the aquarium fishery a multi-agency monitoring effort, called WHAP, was undertaken. Since 2005, monitoring has been undertaken by DAR alone. WHAP employed a Before-After-Control-Impact Design which compares fish densities in FRA sites before and after closure to densities in sites not subject to fish collecting ("control" areas). Seven years after closure of the FRAs, eight of the 10 most heavily collected species (representing 97% of all collected fishes) increased in density relative to control areas, three of those increases being statistically significant (Table 8.17), and the number one collected species, which comprises approximately 80% of the total catch, yellow tang (*Zebrasoma flavescens*), increased by 103% in absolute terms, and 54% relative to control sites. Only one species, the multiband butterflyfish (*Chaetodon multicinctus*) declined significantly in abundance in FRAs relative to control areas.

Table 8.17. Changes in abundance of 10 most collected aquarium species at nine monitoring stations in FRAs in West Hawaii. Species ordered by total reported catch in years 1999 to 2006. FRAs were closed to aquarium collecting in 2000. Source: DLNR/DAR.

COMMON NAME	SCIENTIFIC NAME	MEAN DENSITY (#/100 m^2)		OVERALL % CHANGE IN DENSITY	R[3]
		Before[1]	After[2]		
Yellow tang	*Zebrasoma flavescens*	14.7	30.0	+103%	**+53%***
Kole	*Ctenochaetus strigosus*	31.0	37.5	+21%	+03%
Achilles tang	*Acanthurus achilles*	0.24	0.15	-38%	+03%
Clown tang	*Naso lituratus*	0.75	0.94	+26%	+08%
Chevron tang	*Ctenochaetus hawaiiensis*	0.23	0.39	+71%	**+74%***
Forcepsfish	*Forcipiger flavissimus*	0.50	0.57	+15%	**+41%***
Fourspot butterflyfish	*Chaetodon quadrimaculatus*	0.03	0.09	+168%	+18%
Ornate wrasse	*Halichoeres ornatissimus*	0.94	0.73	-22%	-09%
Multiband butterflyfish	*Chaetodon multicinctus*	5.7	4.7	-17%	**-27%***
Hawaiian cleaner wrasse	*Labroides phthirophagus*	0.88	0.47	-47%	+2%

Notes: (1) "Before" densities are densities before establishment of reserve network; **(2)** "After" densities represent average density over 2005/2006; **(3)** "R" represents change in density within FRAs relative to 'control' sites, e.g., to sites which were already protected in 1999 and whose status did not change over the period we have data from. An R value was calculated separately for each species in each of the nine surveyed FRAs (R in each case being change in that FRA relative to mean chance in control areas). R values displayed are the mean R/species. *R values are considered significant at alpha of 0.1, when 90% confidence intervals of the mean of R does not overlap zero.

The effect of the FRAs on the aquarium fishery itself has been positive. Compared to before the establishment of the FRAs, there are now substantially more collectors working in the fishery (Figure 8.48), and the total number of fish caught and the total value of the fishery are approximately twice what they were prior to creation of the reserve network (Figures 8.48 and 8.49). Compliance by collectors to the FRAs has generally been good and incidents of harassment and conflict between collectors and other ocean users has been markedly reduced.

The increased densities of aquarium fishes in FRAs, and especially of the yellow tang, indicate that the FRAs have been effective at replenishing aquarium fish stocks in West Hawaii after seven years of closure. Additionally, the results of this ongoing study demonstrate that, to date, the fishery has dramatically improved since the establishment of the West Hawaii FRAs. Moreover, the existence of the FRA network has resulted in reduced conflicts, greater public support for management, and better enforcement of regulations.

Spillover from West Hawaii MPA Network

Due to the lack of fishery mortality of large individuals of the primary aquarium target species, yellow tang, (adults are too large for aquarium collecting, and it is not a desired food fish), it is an ideal species for examining spillover in an MPA network. Recruit yellow tangs preferentially settle out in mid-depth reef areas dominated by finger coral, *Porites compressa*, but move to shallower nearshore habitats upon reaching sexual maturity at around 3-4 years of age (J. Claisse, pers. comm.). By surveying shallow water stocks of this species it is possible to get a reasonable measure of total reproductive stock size.

A specialized type of fish survey was undertaken to assess adult stocks of yellow tang both within the reserves and in outside areas. These surveys utilized a diver propulsion device termed "Jetboots", which consist of leg mounted propulsive units and a tank mounted battery pack (Figure 8.50).

Each survey consisted of a timed 18 minute transect in which fish within a 5 m wide belt were counted. Sixteen sites along the West Hawaii coastline were surveyed five times each. The sites surveyed were in three general locations; one set was within protected areas closed to aquarium collecting, another group was close to the borders of protected areas (within 2 km of nearest boundary) and the third was in areas open to harvesting and >2 km from the nearest reserve boundary.

Adult yellow tang populations at most Jetboots survey sites were high (>20 /100 m^2, Figure 8.51). There was also a generalized pattern for higher abundance within protected areas and fewer adult yellow tangs in open areas, indicating that the MPA network has increased breeding stocks within reserve boundaries. Open sites close to boundaries tended to have intermediate numbers of yellow tangs, strongly suggestive of spill-over of adults from the protected areas. Mean ± SE densities per 100 m^2 in areas within different categories were: FRAs (aquarium closed areas) 26.3 ± 0.8% SE; MPAs (long-term protected) 22.5 ± 1.4% SE; boundary sites (<2 km from reserve boundaries) 25.1 ± 3.6% SE; and open sites >2 km from nearest reserve boundary 17.8 ± 2.4% SE. Anomalous sites either

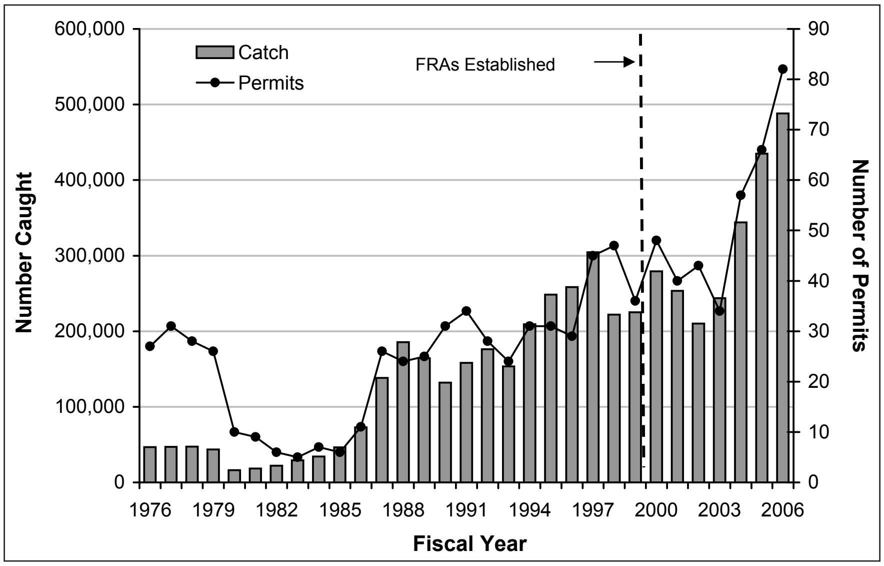

Figure 8.48. Number of aquarium permits and number of collected animals in west Hawaii from 1976 to 2006. Source: DLNR/DAR.

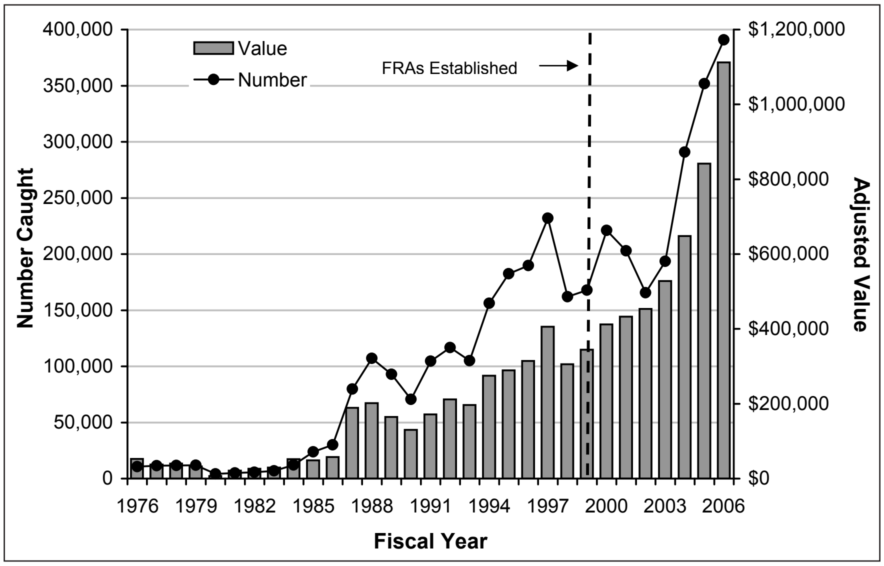

Figure 8.49. Number and value of yellow tang caught in the west Hawaii aquarium fishery from 1976 to 2006. Source: DLNR/DAR.

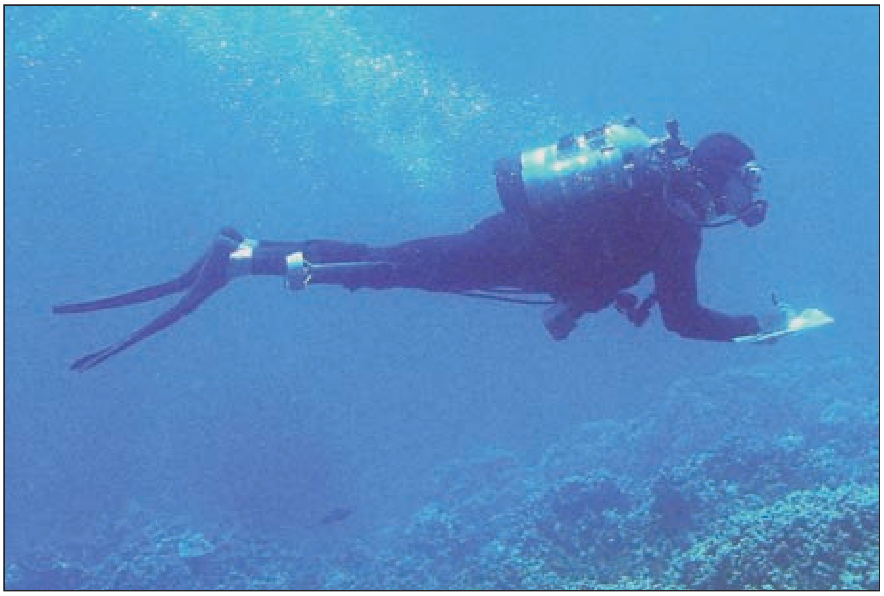

Figure 8.50. "Jetboots" equipped diver conducting nearshore fish survey on the Kona coast of the Big Island. Photo: DLNR/DAR.

had atypical amounts of physical relief (very high relief sites tending to have high adult yellow tang density, low relief sites having relatively low densities) or were adjacent to shallow sandy areas which lacked suitable adult yellow tang habitat (e.g., highest density of any site was a boundary site close to a large inshore sandy area unsuitable for adult yellow tangs). The three sites with lowest adult densities were furthest from a protected area (Figure 8.51).

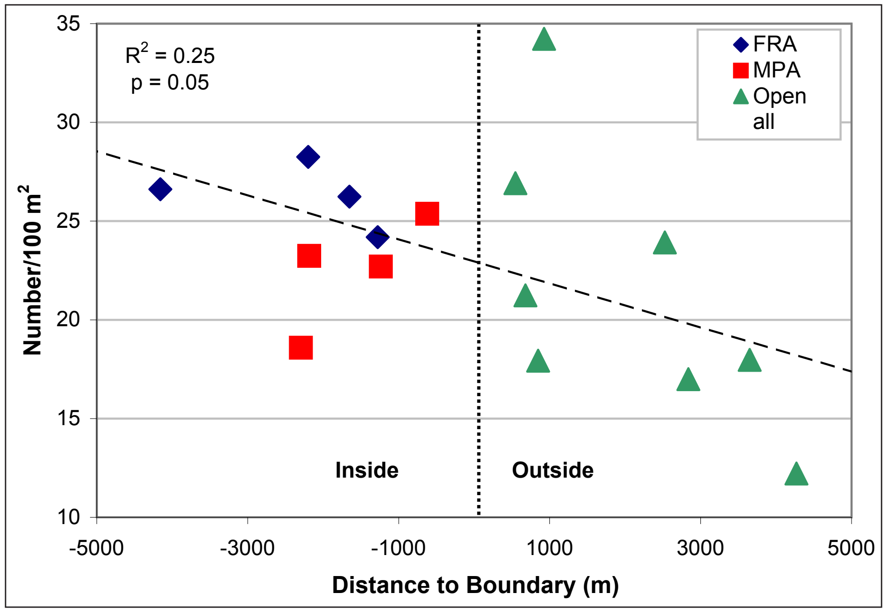

Figure 8.51. Abundance of adult yellow tangs at jetboots survey sites inside and outside of West Hawaii marine protected areas (n=5). MPA refers to protected areas established in varying years prior to 2000. Aquarium collecting and some other types of fishing are prohibited in MPAs. FRA denotes Fish Replenishment Areas established at the beginning of 2000 which are closed only to aquarium collecting. Source: DLNR/DAR.

These results provide strong evidence that adult stocks are now higher within reserves and in areas close to reserve boundaries than in areas which receive no benefit from adjacent reserves. Given that yellow tang are long-lived fishes, with a maximum lifespan of >35 years (J. Claisse, pers. comm.), and closures have only been in effect for only seven years there is considerable scope for further increases in adult stocks over time. Numbers of fishers and total catch have increased dramatically since the reserves were established and, therefore, the West Hawaii reserve network is providing a crucial buffer against future overexploitation of this species. As long as the FRA network remains in place and there continues to be high compliance, healthy stocks of adult yellow tangs should be maintained over large portions of the West Hawaii coastline. Because of larval dispersal, those healthy adult stocks in reserves and boundary areas will ensure the continued supply of new juveniles to the fishery and therefore the sustainability of the fishery.

Local Action Strategies (LAS)

Hawaii used a collaborative planning process to develop six LAS to address key threats to coral reefs. The six key threat areas focused on initial LAS development were outreach and education, land-based sources of pollution, coral reef fisheries management, recreational impacts to reefs, aquatic invasive species, climate change and marine disease. This planning process supported and expanded on existing efforts already underway in the state. In cases where coordinating bodies did not already exist, steering committees were formed to facilitate the development and implementation of the particular LAS. These committees include members from state and federal government agencies, non-governmental organizations, academia, businesses and community groups. The committees: 1) assessed ongoing activities and the effectiveness of current management strategies; and 2) held a series of stakeholder workshops to discuss the issues, gaps and needs for addressing focus issues. Each LAS varied in the extent to which new initiatives were developed or existing efforts were supported or enhanced. Each LAS was developed using an extensive stakeholder input process.

Local Action Strategy to Address Land-based Pollution Threats to Coral Reefs

Hawaii's Local Action Strategy to Address Land-based Pollution Threats to Coral Reefs is watershed-based. The LAS was developed to incorporate the holistic management aspects of traditional Hawaiian land and natural resource management at the watershed or "ahupuaa" level. The LAS partners with community stakeholders to focus on demonstration projects in three ahupuaa in the main Hawaiian Islands: Honolua, Maui; Kawela to Kapualei, Molokai; and Hanalei, Kauai. The overall goal of the LAS is to improve coastal water quality and coral ecosystem function and health by reducing land-based pollution. This is being achieved through the implementation of projects that: 1) Reduce pollutant load to surface water and groundwater through site-specific actions and best management practices; 2) Improve understanding of the links between land-based pollution and coral reef health through focused scientific research and monitoring; and 3) Increase awareness of pollution prevention and control measures statewide. The LAS has had several small successful projects implemented over the past three years and is now being revised to incorporate new information and to consider additional watersheds where community involvement is strong.

Aquatic Invasive Species Local Action Strategy (AIS-LAS)

The purpose of the Hawaii's *AIS-LAS* is to act as a tool in which to help enhance the coordination of current management efforts, identify remaining problems areas and gaps, and recommend additional actions which are needed to effectively address AIS issues in Hawaii that affect coral reefs. The focus of the AIS LAS is the identification of feasible, cost-effective management practices to be implemented by state, federal, county, nongovernmental, private, and volunteer entities for the environmentally sound prevention and control of aquatic invasive species in a coordinated fashion. It is based on the comprehensive AIS Management Plan that was written in 2002 to bring together all stakeholders to address both marine and freshwater aquatic invasive species. Funding comes from several sources to undertake activities such as the "Habitattitude" campaign – a program to educate the public about the problems that released aquarium pets and plants can cause, as well as research and technology grants studying toxic dinoflagellates in ballast water.

Recreational Impacts to Reefs Local Action Strategy (RIR-LAS)
Hawaii's Local Action Strategy to address recreational impacts to reefs focuses on minimizing the impacts of recreational activities that have the potential to directly and indirectly impact reef ecosystem health such as breakage from physical contact, alterations in marine life behavior and degradation of surrounding water quality. The goal of the RIR-LAS is: "to determine the impacts of marine recreation activities on Hawaii's coral reef ecosystems and develop innovative management techniques that increase the environmental sustainability of those activities." Under the overarching goal, projects are organized into three objectives including: data, management and outreach. Currently the priorities are focusing on installation and use of day-use mooring buoys, human use assessment tool development and social carrying capacity research, tour operator stewardship training, supporting community stewardship efforts in high use coastal sites and developing outreach materials for distribution to users at point of rental orientation.

Coral Reef Fisheries Local Action Strategy
Hawaii's coral reef fisheries local action strategy has focused efforts on supporting community-based management activities at selected sites, understanding the life history characteristics of key reef fish species, determining the predator/prey relationships of introduced snappers and groupers to native reef fishes and providing support for enforcement. This LAS is also being revised to focus on a few key management needs.

Climate Change and Marine Disease Local Action Strategy
This is Hawaii's newest local action strategy, which was completed in late 2005. Preliminary efforts are focused on developing training materials for managers on coral disease and developing a rapid response protocol for bleaching and disease events.

Hawaii Invasive Species Council (HISC)
The state of Hawaii continues to address aquatic invasive species issues through a variety of means. HISC was created by the state legislature and appointed by the Governor to address both terrestrial and aquatic invasive species issues. HISC continues to fund the Aquatic Invasive Species Response Team at DAR, which has recently begun a program of hull inspections for all vessels traveling to the NWHI Monument to prevent or reduce the introduction of AIS from the Main Hawaiian Islands to the Monument. In addition, HISC has provided funding which address public outreach on targeted aquatic invasive species. HISC and other funders also supported the development of a Supersucker Jr. a more mobile version of the Supersucker discussed under threats. HISC and the DLNR/DAR also worked with the Hawaii Superferry (a new inter-island transportation option that started service in 2007) on planning ways to minimize the risk of inter-island spread of AIS.

Recent Regulations
Governor Lingle approved amendments to regulations restricting the use of lay nets and prohibiting their use in certain waters in the spring of 2006. Included are requirements for lay net registration, limits on dimensions and soak times, requirements for attendance and inspection, and prohibitions on use in streams and stream mouths. Lay net use is also prohibited around the entire island of Maui, and in certain waters off Oahu, including Kaneohe and Kailua Bays, and along three miles of the south shore between Koko Head and Pearl Harbor. Also in 2006, new laws and regulations were enacted which establish an "Ewa limu (seaweed) management area", where taking of plants is prohibited, as well as another that prohibits the taking or killing of female spiny lobsters, Kona crabs and Samoan crabs.

Community-Based Management Initiatives
The level of community stewardship involvement in marine resource management has increased markedly in the past few years. More and more communities are creating community groups to assist in caring for, monitoring and protecting high use sites throughout the state. In some sites this community planning and active participation in management is in response to growing concerns about levels of use, in others it is in response to perceived changes to lifestyle. There is currently a network of over 28 communities that meets twice a year to discuss concerns and compare notes on what they are each doing to care for the reef resources in their backyard. DAR worked with the Community Conservation Network to develop Caring for Coastal and Marine Communities: A Guidebook for Community Stewardship, to provide communities with the tools and a set of standard methods that could be employed to co-manage these resources.

OVERALL CONCLUSIONS AND RECOMMENDATIONS

Food, recreation, culture, commerce, aesthetics, and shoreline protection are just a few of the ecosystem services provided by Hawaii's coral reefs. These reefs also have extremely high biodiversity and conservation value due to large proportion of species found nowhere else on earth. Hawaii's coral reefs, which have been valued at over U.S. $10 billion, are an important component of the economy and form the backbone for many of our leisure pursuits and way of life. However, the 1.2 million residents (over 70% of which live on Oahu) and over seven million tourists each year have put increasing pressure on Hawaii's coral reefs. A number of urban areas and popular tourist destinations have suffered from land-based sources of pollution, significant fishing pressure, recreational overuse, and alien species. Despite these anthropogenic stressors, many of Hawaii's coral reefs, particularly in remote areas, are still in fair to good condition.

The effects of fishing are evident at the level of individual stocks, as well as throughout the entire ecosystem. Enforcement remains a challenge statewide. Compliance with existing regulations is lacking and further complicated by minimal prosecution of natural resource violations which are not considered serious offences by the judiciary. Information on basic life-history parameters exists for few species and, current regulations fail to protect many species from harvest before first reproduction, much less consider the implications of sex changing species or the importance of larger and older individuals to total reproductive output. The non-commercial catch is enormous and a much greater emphasis needs to be placed on assessing these fisheries and how best to manage them. The integration of mapping and monitoring of coral reef ecosystems and reef fish habitat utilization patterns has assisted managers in making informed decisions about MPA design and effectiveness, as well as helping to define essential fish habitat and ecosystem function for ecosystem-based fisheries management decision making. The effects of intensive fishing pressure must be mitigated and stocks and ecosystems rebuilt through a series of coordinated measures including: additional restrictions on overly efficient gear types such as gillnets and SCUBA fishing (particularly at night), bag limits, and larger area closures.

Water quality in the MHI is generally very good and the majority of the coastal waters and upland surface waters are in good condition. However, in past years storm water runoff during high rain events into urban streams has caused a significant number of beach closures for human health and safety reasons. Nutrient inputs from sewage systems in need of upgrades into selected systems is of highest concern on the heavily developed and urbanized coasts of Oahu and Maui. Hawaii's groundwater quality is considered excellent overall and chemical contaminant concentrations detected in public groundwater/drinking water sources are normally below state and federal drinking water standards. Coastal waters (including nearshore coral reefs) that are impaired by pollutants are primarily harbors, semi-enclosed bays, and protected shorelines, where mixing is reduced and resident time of pollutants is long compared to exposed coasts. The most widely distributed coastal pollutants are nutrients, sediments and *Enterococcus*. However sediment discharge is probably the leading land-based pollutant causing alteration of reef community structure in the MHI. As coastal development continues to expand in the MHI, focus should be given to the implementation, maintenance, and enforcement of best management practices that reduce sediment runoff and prevent further damage to coral reefs. Holistic management approaches that consider the entire watershed from ridge to reef should also be encouraged and adopted wherever possible.

The continued invasion and degradation of new habitats by alien algae remains one of the most pressing threats to reefs in Hawaii. Preliminary research indicates that the suite of control methods developed by the HIMAG group can be an effective means of restoring affected reef habitats, but full-scale and full-time implementation of these methods (e.g., the Super Suckers) has not yet been achieved. Better information on the current distribution of alien algal species and the habitat requirements of these species is necessary to develop a comprehensive, state-wide management plan for addressing this threat. It is also clear that more investment in prevention activities must also be a priority. The fact remains the most cost effective method for managing invasive species is to prevent invasions.

One of the biggest obstacles to effective management is the lack of data on the status and trends of many important resources and ecosystem components. In addition, the scientific information available is not effectively translated to the public and policy makers. Due to its large research community, Hawaii is well poised to lead the way in effective management of insular coral reef ecosystems but currently lacks a coordinated focus. A comprehensive large-scale research initiative that includes state, federal, academic, non-profits, NGOs, and others partners would integrate existing research and management into a more holistic ecosystem-based approach that would greatly benefit Hawaii and serve as a model for other locations. A step towards this goal is the Hawaiian Archipelago Marine Ecosystem Research Plan, which strives to understand the entire archipelago's marine physical and biological environments, their dynamics and their interactions with human beings as a single connected system leading toward improved resource management. This ten year, multi-agency, collaborative program is proposed to advance ecosystem science and resource management in Hawaii through a better understand of the ecological function and natural states of resistance and resilience and compare these to the anthropogenic impacts experienced in the MHI.

A better knowledge of the spatial dynamics of Hawaii's reefs and the impacts to it are needed. GIS efforts to map existing data, identify gaps and develop predictive models require a greater level of support than currently exits. These tools need to also be provided to the managers through capacity building, training and funding for basic hardware and software. With adequate funding, these tools can then be used to identify where anthropogenic impacts are most likely to occur as well as determine sites of high biodiversity potential that are not currently protected and determine means to protect these sites. This broad-scale seascape approach will also provide information relevant to predictive species mapping and marine reserve design.

Community-based management has been effective in a number of locations in Hawaii and the expansion of these efforts will ensure that key socioeconomic and cultural concerns are well integrated in research and management. Programs like Makai Watch provide local communities the opportunity to become directly involved in the protection of their local coastal resources and should be expanded and integrated into the management decision-making process. A better understanding of the socio/cultural and biological importance of a site is critical to effective assessment of management strategies. Locally-managed marine areas that incorporate traditional concepts of customary marine tenure have been effective in many Pacific Islands. Including elements of these established and recognized practices into a contemporary framework will increase the legitimacy of management decisions and makes compliance with rules and regulations easier.

Hopefully, conserving entire ecosystems and variety of all habitats will be the focus of management in the coming years. A more holistic approach to place-based management will require comprehensive ocean zoning if we are to resolve the mismatches between spatial and temporal scales of governance and ecosystems. To achieve ecosystem-based management, a spatially explicit approach will be required to better understanding the patterns and processes that regulate ecosystem function and to ensure the sustainability and benefits of the entire ecosystem to society.

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