MONITORING HAWAII'S MARINE PROTECTED AREAS

EXAMINING SPATIAL AND TEMPORAL TRENDS USING A SEASCAPE APPROACH

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Monitoring Hawaii's Marine Protected Areas: Examining Spatial and Temporal Trends Using a Seascape Approach

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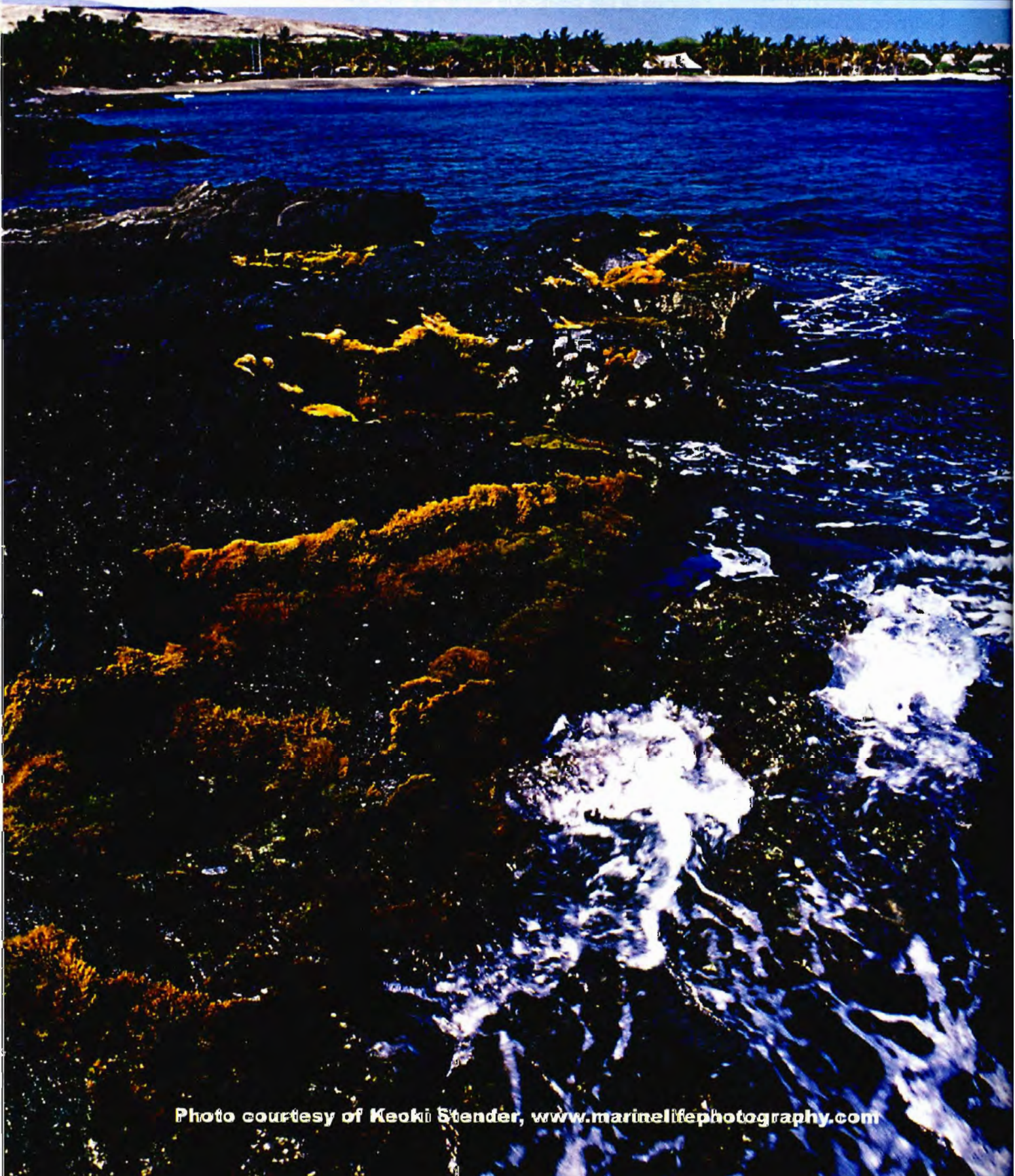

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Executive Summary

Hawaii's coastal marine resources have declined dramatically over the past 100 years due to multiple anthropogenic stressors including overfishing, coastal development, pollution, overuse, invasive species and climate change. It is now becoming evident that ecosystem-based management, in the form of marine protected areas (MPAs), is necessary to conserve biodiversity, maintain viable fisheries, and deliver a broad suite of ecosystem services. Over the past four decades, Hawaii has developed a system of MPAs to conserve and replenish marine resources around the state. These Marine Life Conservation Districts (MLCDs) 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/NOS/NCCOS/Center for Coastal Monitoring and Assessment's Biogeography Branch used digital benthic habitat maps coupled with comprehensive ecological studies between 2002 and 2004 to evaluate the efficacy of all existing MLCDs using a spatially-explicit stratified random sampling design. The results from this work have shown that areas fully protected from fishing had higher fish biomass, larger overall fish size, and higher biodiversity than adjacent areas of similar habitat quality. Other key findings demonstrated that top predators and other important fisheries species were more abundant and larger in the MPAs, illustrating the effectiveness of these closures in conserving these populations. Habitat complexity, protected area size and habitat diversity were the major factors in determining effectiveness among MPAs.

In order to more effectively evaluate these MLCDs, a seascape ecology approach was subsequently applied to characterize ecosystem patterns at scales that are commensurate with marine resources and their users. Furthermore, a monitoring program in four representative MLCDs (Hanauma Bay and Pupukea, Oahu; Honolua-Mokuleia Bay, Maui, and Kealakekua Bay, Hawaii Island) was established and these sites were sampled annually between 2006-2008. These study sites were chosen because they are characterized by a wide range of habitats types, representative wave exposures, varying levels of resource protection and human use. NOAA's 2007 benthic habitat maps, which utilize a more robust classification scheme, were also integrated to apply a stratified random sampling design and to support a seascape ecology approach in order to characterize and quantify the seascape within each MLCD and adjacent area open to fishing. General benthic habitat types were similar inside and outside MLCDs (Friedlander et al. 2007b) although coral cover tended to be higher inside. Therefore, the focus of this study was to examine trends over time in each of these management regimes. This approach allowed for the identification of seascape characteristics that support robust and effective MPAs in the state of Hawaii. The major findings of the study are highlighted below:

Benthic Assemblage Characteristics Among Study Sites and Over Time:

- Coral species richness and cover was greater inside the Hanauma, Pupukea and Honolua-Mokuleia Bay MLCDs compared to adjacent open areas and the rank order of these metrics among the four MLCDs did not change over the study period.
- Coral cover generally increased over time in Hanauma, Pupukea and Honolua-Mokuleia Bay MLCDs and did not change within Kealakekua MLCD.
- Macroalgae cover was generally greater outside the MLCDs and increased over time, particularly adjacent to the Hanauma Bay MLCD (Maunalua Bay, Oahu), Honolua Bay MLCD (west Maui) and Kealakekua Bay MLCD (south Kona, Hawaii Island).

Seascape Characteristics Among Study Sites:

- Seascape metrics derived from the 2007 NOAA benthic habitat maps were used to characterize the spatial structure and composition of habitat in the MLCDs, as well as the spatial configuration of the protected area boundary. These metrics included Shannon's habitat diversity and evenness indices, patch fractal dimensions, MLCD perimeter and area and MLCD perimeter/area ratio.

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- Several LiDAR-derived seascape metrics (e.g., depth, rugosity, slope) were developed for each MLCD to better describe the three dimensional seascape structure within each protected area.
- The quantification of both two (e.g. habitat diversity) and three dimensional (e.g. habitat complexity) structure of the seascape in the MLCDs allowed for the characterization of seascape attributes that support a successful protected area and may inform future marine spatial planning efforts.
- Changes to the size and spatial configuration of the Pupukea MLCD since 2003 have greatly increased the habitat quality and ecosystem health within this protected area.

Fish Assemblage Characteristics Among Study Sites and Over Time:

- Rank order of MLCDs by fish assemblage characteristic (species richness, numerical abundance, biomass and diversity) remained the same between the 2002-2004 sampling period and the 2006-2008 sampling period.
- Fish biomass increased in three of the four MLCDs from the initial sampling period. There was a 14% increase in Pupukea, a 7% increase in Kealakekua and a 5% increase in Honolua Bay. Biomass in Hanauma Bay did not change appreciably during this same period.
- Fish biomass declined by 39% outside the Pupukea MLCD on Oahu but increased by 32% outside Hanauma Bay on the south shore of Oahu, although the absolute increase (+0.05 t ha^{-1}) was small.
- Apex predator biomass increased in the Pupukea MLCD and in the Hanauma Bay MLCD as a result of increasing numbers and sizes of bluefin trevally jacks (omilu, *Caranx melamypgus*). Herbivore biomass increased by 17% within the Pupukea MLCD and this increase was driven mainly by large parrotfishes that are primary fisheries target species.

Combining seascape-scale habitat stratification with *in situ* ecological data allowed for the development of a statistically robust monitoring program of living marine resources (e.g., fishes, corals and other invertebrates, algae) within and adjacent to four representative marine protected areas in Hawaii. The results clearly show that areas with good habitat quality and management conserve fish populations within their boundaries while areas without protection are in poorer ecological health and continue to decline over time. These temporal patterns support the findings of the initial assessment conducted by Friedlander and colleagues (Friedlander et al. 2006, 2007a, 2007b) and increase confidence in the effectiveness of marine protected areas as a management tool for the conservation of nearshore marine resources in Hawaii.

Remotely sensed data allowed the examination of these MLCDs at spatial scales that are more appropriate for management and provide valuable information on seascape metrics (e.g. rugosity, slope, depth, habitat type) that are relevant to the design of future MPAs. Marine protected areas are spatially discrete forms of management and georeferenced data on seascape metrics can be integrated using a spatial framework to ensure MPA design scenarios are incorporating an appropriate range in depth, habitat complexity, and a mosaic of interconnected habitat types.

The findings from this study greatly contribute to the understanding of marine protected area design and function in Hawaii and can be useful in the development of comprehensive coastal and marine spatial planning.

Introduction

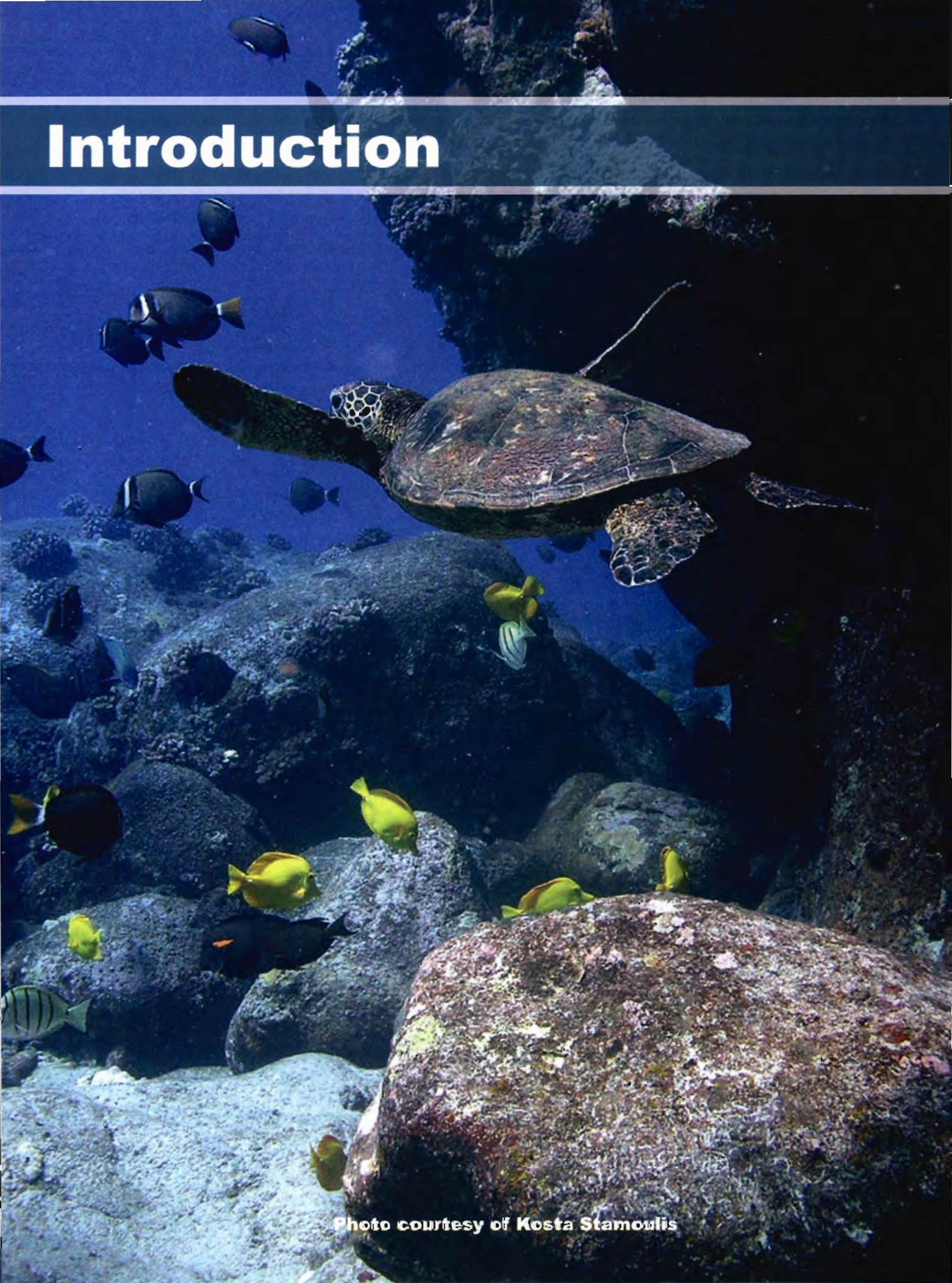

Photo courtesy of Kosta Stamoulis

Introduction

Background

Coral reef ecosystems are facing overexploitation and severe depletion on a global scale (Birkeland 2004, Bellwood et al. 2004, Pandolfi et al. 2005). Pollution, coastal development, and invasive species all impact coral reefs locally, and climate change now is having a global effect on corals and coral reef communities. Fishing, however, has historically exerted the most direct influence on most reefs and other marine ecosystems (Jennings and Kaiser 1998, Jackson et al. 2001). Increasing fishing pressure on coral reefs over the last few decades has not only led to declines in valued fish stocks, but have also resulted in major impacts to this fragile ecosystem as a whole.

Marine resources were important to the ancient Hawaiians for subsistence, culture, and survival. Today, 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. However, the 1.2 million residents and nearly seven million tourists each year have put increasing pressure on Hawaii's coral reefs, which have been valued at over US$10 billion (Figure 1; Cesar and van Beukering 2004, Friedlander et al. 2008a).

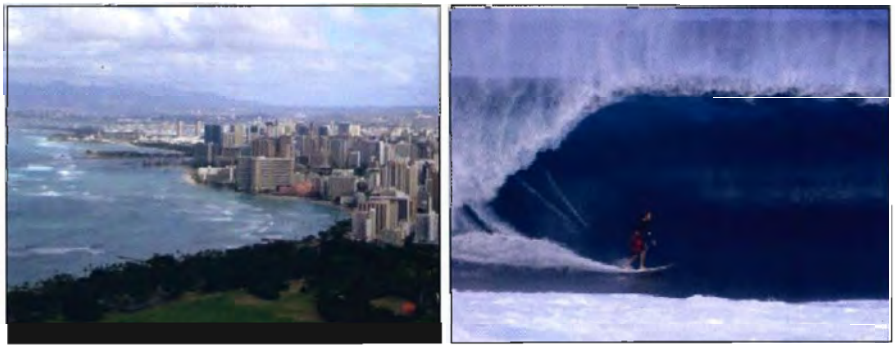

Figure 1. Honolulu's crowded coast (left). Photo: A. Clarke. Hawaii's coral reefs provide world famous surfing spots like the Banzai Pipeline on Oahu's north shore (right). Photo: J. Stahl.

The combination of increased fishing pressure and growing coastal populations has reduced the ability to achieve the management goal of sustainable fisheries. In the past, Hawaiians managed fisheries in a sustainable manner based on traditional ecological knowledge and restricted marine resources that were more vulnerable to over harvesting (Poepoe et al. 2007). Currently, the main Hawaiian Islands are faced with the problems of increasing anthropogenic impacts that are a result of a growing coastal population and tourism (Friedlander et al. 2008a,b). The effects of fishing are evident at the level of individual stocks, as well as throughout the entire ecosystem (Friedlander and DeMartini 2002, Williams et al. 2008). In order to preserve marine biodiversity, ecosystem function, and the goods and services provided by resilient systems, marine reserves have been increasingly recommended as part of an ecosystem-based approach to management. Benefits derived from marine reserves include the enhancement of fisheries, insurance against management failures, the protection of essential fish habitat, and increased recruitment of fishes to adjacent open areas (Lubchenco et al. 2003, Browman and Stergiou 2004).

Objectives

The focus of this study was to develop and implement a monitoring program of living marine resources (e.g., fishes, corals and other invertebrates, algae) within and adjacent to four representative MLCDs, develop metrics of seascape using remotely sensed data, and organize these data in a GIS to better understand ecosystem processes at the seascape scale.

Specifically:

- Examine temporal variation in fish assemblages and benthic habitat cover across a range of habitat types and management strata to determine trends and variability over time.
- Develop metrics from remotely sensed data (e.g., LiDAR, benthic habitat maps) that provide seascape-level characterization of the benthic environment.

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- Integrate remotely sensed data with ecological data into GIS to better understand ecosystem processes at broader spatial scales.
- Determine efficacy of marine protected areas using a seascape ecology approach.

Seascape Ecology Approach

Effective management of species and assemblages of concern requires accurate, spatially explicit information that characterizes and quantifies the seascape that supports the resources. Landscape ecology has been widely applied in the terrestrial environment to understand ecological patterns and processes, and this information is often used to inform conservation planning and resource management actions (Turner 2005). A landscape ecology approach can be integrated within a geospatial framework using Geographic Information Systems (GIS) and remote sensing to identify the spatial association of reef fishes with the seascape. Information on the seascape, derived from remote sensing methods (e.g., LiDAR, benthic habitat maps), can provide valuable and spatially discrete ecological criteria that can be integrated in GIS, along with social and economic considerations, and ultimately provide support for marine spatial planning applications (Pittman et al. 2007a,b, Wedding et al. 2008, Wedding and Friedlander 2008, Monaco et al. 2005). This integrated approach aids in defining the forces that shape broad-scale community structure, and addresses specific questions about particular groups of economically and ecologically important species at the regional scale that management decisions are typically implemented across the state of Hawaii.

Benthic habitat type is a major determinant of fish assemblage structure and can be used as a surrogate to explain the distribution of fishes across the seascape (Figure 2). Benthic habitat maps provide fundamental information that can be used to guide marine conservation and management actions such as marine protected area (MPA) design, and evaluation (Friedlander et al. 2008 a,b). These maps allow a better understanding of the seascape, ecosystem function, and species habitat utilization patterns in a coastal area (Christensen et al. 2003, Friedlander et al. 2003, Pittman et al. 2007a). This work evaluated four marine protected areas in Hawaii by utilizing NOAA's Biogeography Branch benthic habitat maps in order to utilize a seascape approach. Further, these maps were used to characterize and quantify the seascape within each marine protected area to assist in understanding the important attributes of the seascape that support high abundance, diversity and biomass.

Figure 2. A school of white cheek surgeonfish swim over typical Hawaiian reef structure. Photo: K. Stamoulis.

Hawaii Marine Protected Areas

Hawaii established its first MPAs over 30 years ago and since that time numerous protected areas have been established with varying levels of protection, ranging from complete 'no-take' areas to areas that have allowed a wide variety of activities to occur within their boundaries (Figure 3). The state of Hawaii, Division of Aquatic Resources has developed Marine Life Conservation Districts (MLCDs) to conserve and replenish marine resources around the state. Between 2002 and 2004, NOAA/NOS/NCCOS/Center for Coastal Monitoring and Assessment's Biogeography Branch conducted a comprehensive evaluation of all MLCDs in the state (Friedlander et al. 2006, 2007a, 2007b). Results from this comprehensive assessment showed MLCDs protected from fishing, with high habitat complexity and good habitat quality (e.g., high coral cover and low macroal-

gae cover), had higher values for most fish assemblage characteristics. To more effectively assess the efficacy of these protected areas, a monitoring program in four representative MLCDs (Hanauma Bay, Honolua-Mokuleia Bay, Kealakekua Bay and Pupukea) was established and these sites were sampled annually between 2006 and 2008. These four sites were chosen because they were representative of the diverse habitat types, wave exposures, and benthic environments across a broad geographic area of the main Hawaiian Islands.

Figure 3. Hanauma Bay Marine Life Conservation District (MLCD) was designated as the first "no-take" marine protected area (MPA) in Hawaii in 1967 and encompasses approximately 41 ha. This area receives over one million visitors per year and is the most visited MPA in the world. Photo: L. Wedding.

Methods

Photo courtesy of Keoki Stender, www.marinelifephotography.com

Study Sites

The study areas are located in the main Hawaiian Islands at Pupukea and Hanauma Bay on the island of Oahu; Honolua-Mokuleia Bay, Maui; and Kealakekua Bay, Hawaii (Figure 4 and Table 1). These study sites were chosen because they are characterized by a wide range of habitats types, representative wave exposures, varying levels of resource protection, and human use. Each site has an MPA, referred to as MLCDs in Hawaii, and an adjacent area of comparable habitat that is open to resource extraction. This provides an opportunity to examine the relationship between relatively intact fish assemblages (MPAs), and their associated habitat, as well as the ability to compare the strength of the fish-habitat relationships in adjacent open access areas.

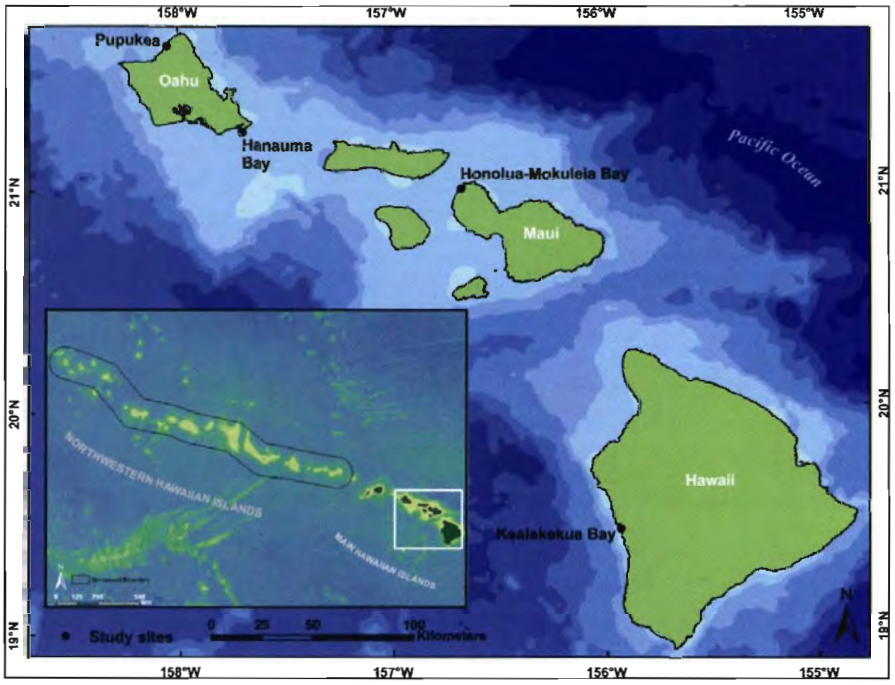

Figure 4. Map of the Hawaiian Islands and study locations.

Table 1. Summary of Marine Life Conservation Districts at four study sites in the main Hawaiian Islands.

Marine Life Conservation District	Island	Established	Area (km^2)	Use	Protection from fishing	Permitted activities
Pupukea	Oahu	1983* (2003)	0.71	moderate	moderate	pole-and-line from shore; harvest of seaweed (seasonal)**
Hanauma Bay	Oahu	1967	0.41	high	high	complete no-take
Honolua-Mokuleia Bay	Maui	1978	0.19	moderate	high	complete no-take
Kealakekua Bay	Hawaii	1969	1.24	high	moderate	hook and line; throw net; harvest of seaweed (seasonal)** and crustaceans in 60% of the total area

"Use" represents the level of use that was classified by the state of Hawaii, Department of Land and Natural Resources, Division of Aquatic Resources (DAR 1992). Protection from fishing is based on the qualitative ranking of Division of Aquatic Resources (DAR) regulations.
*Pupukea Marine Life Conservation District (MLCD) boundary was expanded and rules were modified in 2003.
***Selar crumenophthalmus* (November-December) and *Decapterus* spp. (August-September)

Benthic Habitat Mapping

NOAA acquired and visually interpreted orthorectified satellite imagery for selected near-shore waters and parts of the main Hawaiian Islands. An important step in producing benthic habitat maps was the development of a habitat classification scheme. Thirty-two distict benthic habitat types (e.g., four major and 14 detailed geomorphological structure classes; eight major and three detailed biological cover types) within 13 attribution zones were digitally mapped in GIS using heads-up visual interpretation of orthorectified satellite imagery (Tables 2, 3 and 4).

The classification scheme was influenced by many factors including requests from the management community, the National Ocean Service's coral reef mapping experience, existing classification schemes, and quantitative habitat data for the area. The hierarchical scheme allows users to expand or collapse the thematic detail of the resulting map to suit their needs. For instance, additional hierarchical categories can be added into a GIS system by users with more detailed knowledge or data for specific areas. For example, habitat polygons

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Table 2. Description of attribute "Zone" in the 2007 NOAA benthic habitat classification scheme. Source: Battista et al. 2007.

Zone	Description	Typical Habitats
Shoreline intertidal	Area between the mean high water line and the lowest spring tide level.	Sand, seagrass, rocks, reef and mangroves.
Vertical wall	Near-vertical slope between the shore and the shelf. Not usually distinguishable in remotely sensed imagery.	Rock, boulder, algae and coral
Lagoon	Shallow, between shore and intertidal zone, only present when reef crest is present.	Sand, seagrass, algae, hard bottom, patch reefs
Back reef	Between edge of reef crest and lagoon floor. Only present when a reef crest and lagoon exists.	Sand, rubble, seagrass, algae patch reef
Reef flat	Shallow, between intertidal zone and reef crest. Not usually present if a lagoon is present.	Sand, rubble, seagrass, algae, patch reef
Reef crest	Flattened emergent or nearly emerged segment of reef between back reef and fore reef.	Rubble, aggregated coral
Fore reef	Between edges of reef crest sloping deeper to the edge of the shelf platform. Also, features not forming emergent reef with a slope greater than the shelf.	Spur and groove
Bank/Shelf	A flattened platform extending seaward from the fore reef to the insular shelf escarpment that drops to deeper water.	Sand, patch reefs, algae, pavement, sand channels
Bank/Shelf Escarpment	Edge of shelf where depth increases rapidly to oceanic water.	Sand, spur and groove
Channel	Naturally occurring channels can cut across other zones.	Sand, mud, pavement
Dredged	Natural geomorphology disrupted or altered by excavation or dredging.	Mud, sand
Unknown	Zone, cover, and structure un-interpretable due to turbidity, cloud cover, water depth or other interference.	
Land	Terrestrial features above the spring high tide line.	

Table 3. Description of attribute "Geomorphic Structure" in the 2007 NOAA benthic habitat classification scheme. Source: Battista et al. 2007.

Geomorphic Structure		Description
Unconsolidated sediment	Sand	Coarse sediment typically found in exposed areas
	Mud	Fine sediment, associated with river discharge and sheltered areas
Coral Reef and Hard bottom	Spur and groove	Alternating sand and high relief coral formations, oriented perpendicular to shore
	Patch reef	Isolated coral formations with no organized structural axis
	Individual patch reef	Distinctive single patch that are larger or equal to the minimum mapping unit
	Aggregate patch reef	Clustered patches that are too small or too close together to map separately
	Aggregate reef	High relief lacking sand channels of spur and groove
	Scattered coral/rock in unconsolidated sediment	Sand or seagrass bottom with small rocks and coral heads too small to delineate individually
	Pavement	Flat, low-relief, solid carbonate rock with biological cover dense enough to obscure surface
	Rock/boulder	Solid carbonate blocks, boulders, or volcanic rock.
	Reef rubble	Dead, unstable coral rubble often colonized by biological cover
	Pavement with sand channels	Alternating low-relief sand/surge channels oriented perpendicular to shore.
Other Delineations	Artificial	Man-made, including: wrecks, piers, submerged jetties, fish ponds, and shoreline created by dredge spoil
	Land	Terrestrial features above the spring high tide line
Unknown	--	Zone, cover, and structure un-interpretable due to turbidity, cloud cover, water depth or other interference.

Table 4. Description of attribute "Biological Cover" in the 2007 NOAA benthic habitat classification scheme. The minimum mapping unit (MMU) is 1 acre. Source: Battista et al. 2007.

Biological Cover		
Live Coral	Substrates colonized by live reef building corals and other organisms with at least 10% live coral cover.	
	Continuous coral	Live coral covering > 90% of the substrate. May include areas < 90% coral cover if < 10% of the total area is too small to be mapped independently (< 1 MMU).
	Patchy coral	Discontinuous live coral with breaks in coverage (< 1 MMU) to be mapped as continuous coral. Live coral cover 50% > 90% of the bottom.
	Sparse coral	Discontinuous live coral with breaks in coverage (< 1 MMU) to be mapped as continuous coral. Live coral cover 10% > 50% of the bottom.
Seagrass	Habitat with 10% or more of seagrass.	
	Continuous seagrass	Seagrass > 90% of the substrate. May include blowouts < 10% of the total area that are too small to be mapped independently (< 1 MMU).
	Patchy seagrass	Discontinuous seagrass community with breaks in coverage (< 1 MMU) to be mapped as continuous seagrass. Cover 50% > 90% of the bottom.
	Sparse seagrass	Discontinuous seagrass community with breaks in coverage (< 1 MMU) to be mapped as continuous seagrass. Cover 10% > 50% of the bottom.
Macroalgae	Substrates with > 10 % coverage of any combination of numerous species of red, green, or brown macroalgae.	
	Continuous macroalgae	Macroalgae covering > 90 % of the substrate. May include areas < 10% of the total area that < 1 MMU.
	Patchy macroalgae	Discontinuous macroalgae with breaks in coverage (< 1 MMU) to be mapped as continuous macroalgae. Cover 50% > 90% of the bottom.
	Sparse macroalgae	Discontinuous macroalgae with breaks in coverage that are too diffuse or irregular, or result in isolated patches of macroalgae that are too small (smaller than the MMU) to be mapped as continuous macroalgae. Overall cover is estimated at 10% > 50% of the bottom.
Encrusting/ Coralline Algae	> 10% coverage of any combination of encrusting or coralline algae.	
	Continuous corraline algae	Coralline algae covering > 90% of the substrate. May include areas < 10% of the total area that are < 1 MMU.
	Patch corraline algae	Discontinuous coralline algae with breaks in coverage (< 1 MMU) to be mapped as continuous coralline algae. Cover 50% > 90% of the bottom.
	Sparse corraline algae	Discontinuous coralline algae with breaks in coverage (< 1 MMU) to be mapped as continuous coralline algae. Cover 10% > 50% of the bottom.
Turf Algae	A community of low lying species of marine algae composed of algal divisions dominated by filamentous species lacking upright fleshy macroalgal thali.	
	Continuous turf	Turf algae > 90 %of the substrate. May include areas < 10 % of the total area that are< 1 MMU.
	Patchy turf	Discontinuous Turf algae with breaks in coverage (< 1 MMU) to be mapped as continuous Turf algae. Cover50% > 90% of the bottom.
	Sparse turf	Discontinuous Turf algae with breaks in coverage (< 1 MMU) to be mapped as continuous Turf algae. Cover 10% < 50% of the bottom.
Emergent vegetation	Emergent habitat composed primarily of *Rhizophora mangle* (red mangrove) and *Hibiscus* sp (hau) trees.	
	Continuous vegetation	Emergent vegetation > 90 % of the substrate. May include areas < 10% of the total area that are < 1 MMU.
	Patchy vegetation	Discontinuous Emergent vegetation with breaks in coverage (< 1 MMU) to be mapped as continuous Emergent vegetation. Cover 50% < 90% of the bottom.
	Sparse vegetation	Discontinuous Emergent vegetation with breaks in coverage (< 1 MMU) to be mapped as continuous Emergent vegetation. Cover 10% > 50% of the bottom.
Uncolonized	Substrates not covered with a min. of 10% of any of the above biological cover types. This habitat is usually on sand or mud structures.	
Unknown	Zone, Cover, and Structure uninterpretable due to turbidity, cloud cover, water depth, or other interference.	

smaller than the minimum mapping unit (the minimum mapping unit, or MMU, is 1 acre for NOAA maps) can be delineated, such as individual patch reefs, or habitat polygons delineated as colonized pavement using this scheme could be further attributed with health information (e.g., bleached, percent live cover) or species composition. For more information, visit http://ccma.nos.noaa.gov/products/biogeography/hawaii_cd_07/htm/overview.html.

The hierarchical scheme was modified throughout the development process based upon feedback provided by workshop participants and other contributors. Additional modifications were made during the mapping process to ensure that each category definition reflected the intended habitats and zones encountered in the field as accurately as possible. For instance, the separation of biological cover and geomorphological structure in the present scheme represents a significant evolution of previous versions of the classification schemes developed for mapping of the Caribbean in 1999 and of the Hawaiian Islands in 2000. The major product of this effort is a series of GIS-based benthic habitat maps that are characterized by a high degree of spatial and thematic accuracy (Figures 5 and 6; Battista et al. 2007, Coyne et al. 2003).

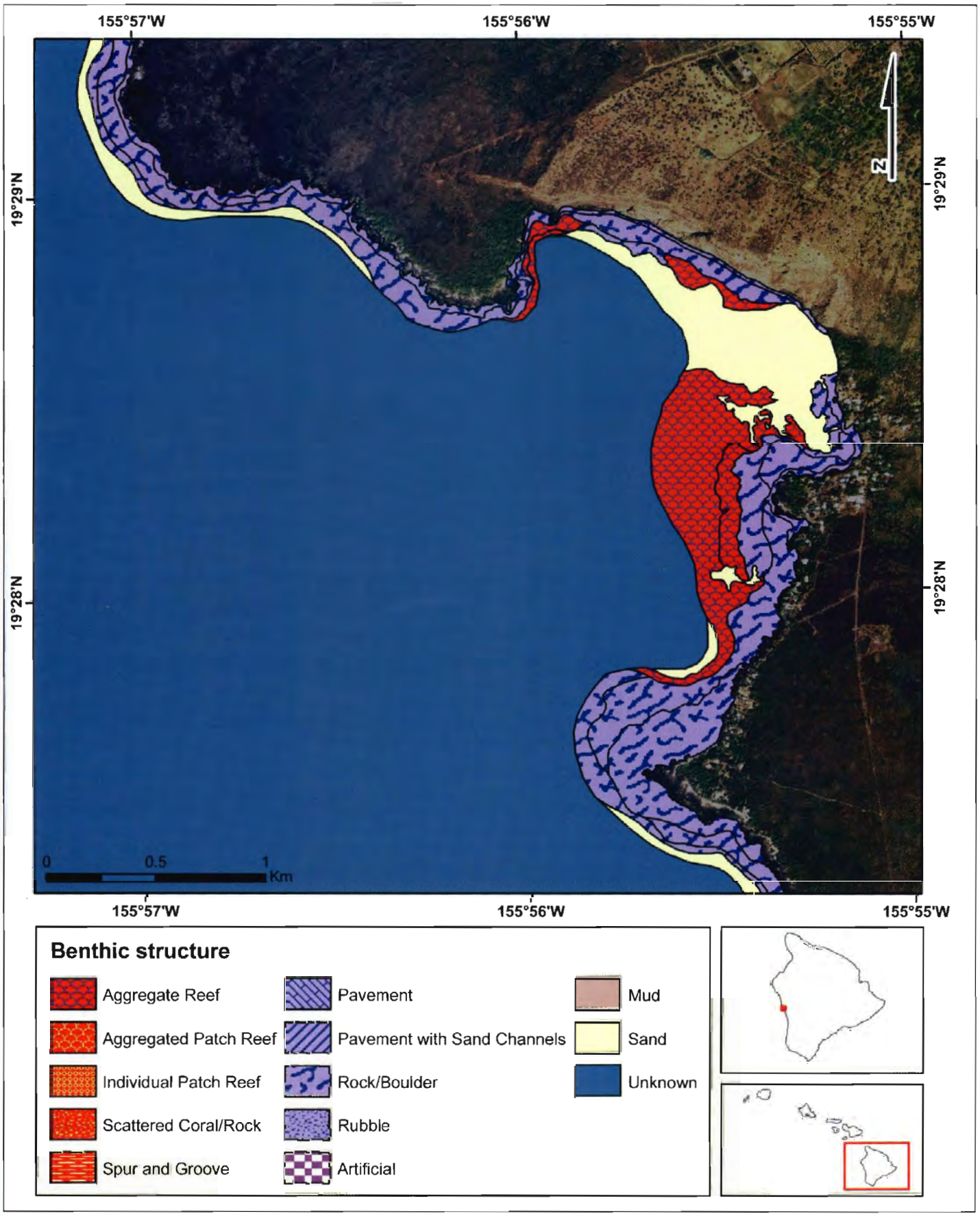

Figure 5. Example of NOAA's Biogeography Branch benthic habitat map of geomorphic structure in Kealakekua Bay, Hawaii.

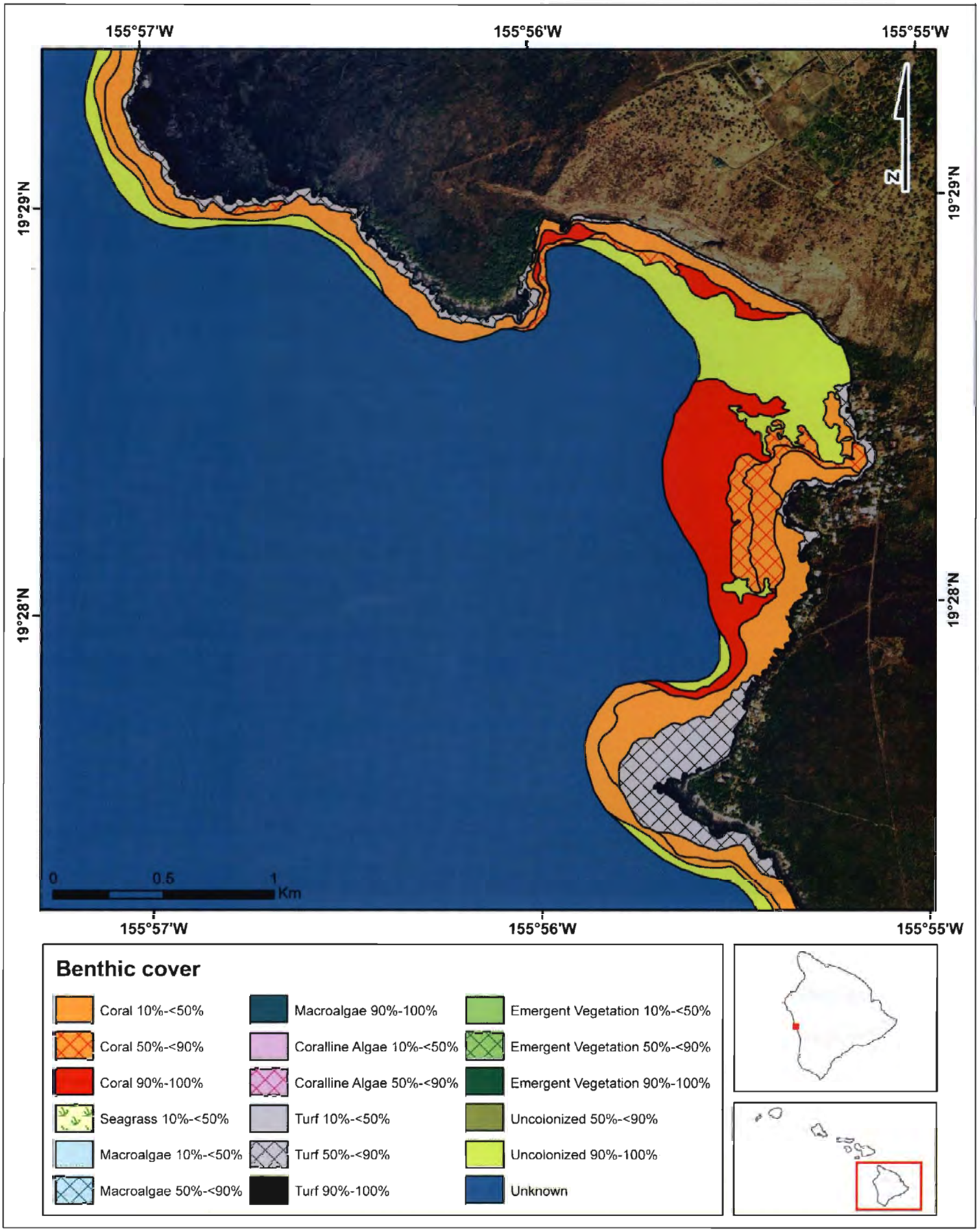

Figure 6. Example of NOAA's Biogeography Branch benthic habitat map of biological cover in Kealakekua Bay, Hawaii.

Bathymetric LiDAR Data

The U.S. Army Corps of Engineers Scanning Hydrographic Operational Airborne LiDAR Survey (SHOALS) system is an airborne LiDAR bathymeter utilized to remotely collect topographic and bathymetric measurements using infrared (1,064 nm) and blue-green (532 nm) scanning laser pulses (Figure 7). SHOALS LiDAR data was collected in Hawaii between 1999 and 2000. The sensor provides a vertical accuracy of ± 20 cm and a horizontal resolution of ± 1.5 meters. The minimum depth range is typically 0 - 1 meter, with a maximum depth range of approximately 40 meters, and a spatial resolution of 4 meters (Irish and Lillycrop 1999; Figures 7, 8 and 9).

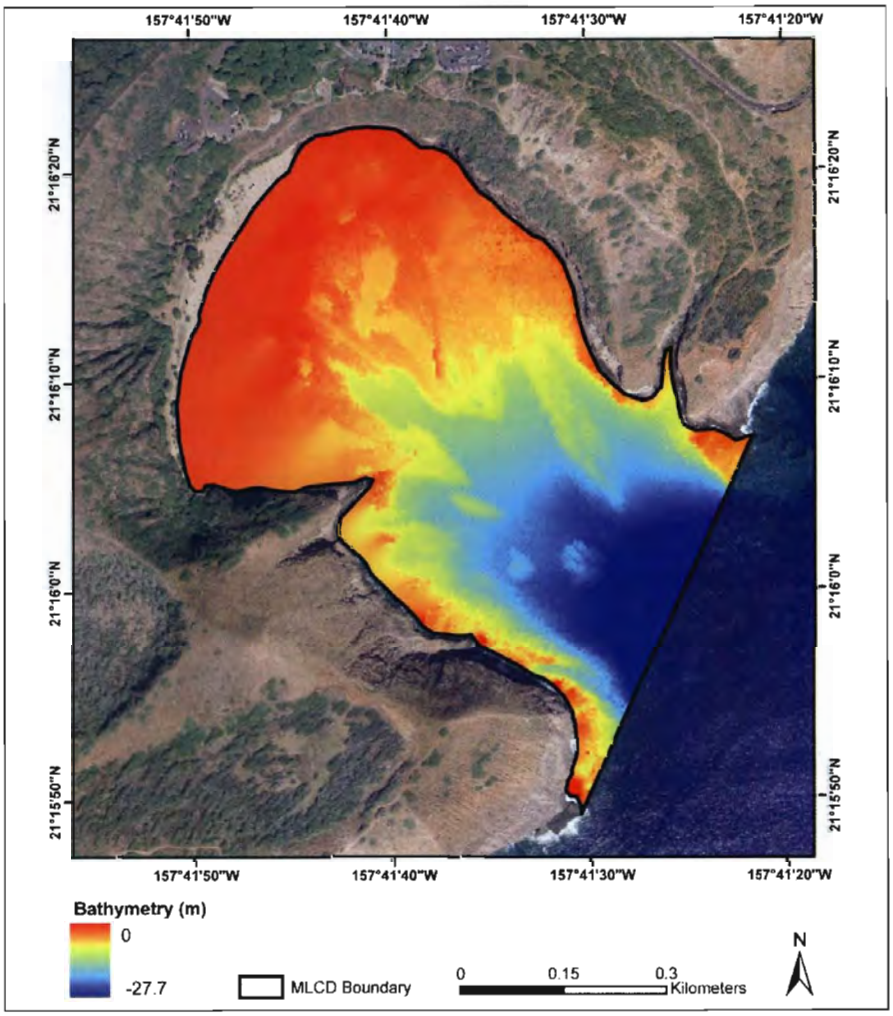

Figure 7. Bathymetric grid derived from LiDAR data at Hanauma Bay, Oahu.

Sampling Locations

A field team consisting of two divers navigated to waypoints using GPS, they then marked the location with a lead weight and float and accurately established the location using GPS measurements. Direction of each transect was determined randomly along the isobath of that point except in cases where that direction caused the transect to traverse multiple habitats. In those situations, transects were run within a habitat polygon at a similar isobath strata. Divers descend together; with diver 1 carrying a 25 m transect line and rugosity chain and diver 2 carrying a digital camera and a 1 square-meter quadrat. Diver 1 began a 25 x 5 m fish transect starting at the marked waypoint and moved along the depth contour. As the fish count diver started his/her count, he or she visualized out to the end of the transect line and enumerated all individuals that were potentially leaving the census area. This partially accounts for the behavior that targeted species acquire in areas that are frequented by spearfishers. The fish count method is described in detail below. As diver 1 laid out transect line, diver 2 conducted benthic surveys within the quadrat. Once diver 1 completed the fish transect, he/she conducted rugosity measurements as described below.

Figure 8. Aerial imagery of Hanauma Bay, Oahu overlaid on LiDAR-derived digital elevation model.

Methods

Fish Sampling Methodology

Fish assemblages at each location were assessed using standard underwater visual belt transect survey methods (Brock, 1954; Brock, 1982). A diver swam each 25m x 5m transect at a constant speed (approximately 15 min/transect) and identified to the lowest possible taxon, all fishes visible within 2.5 m to either side of the centerline (125 m^2 transect area). Nomenclature followed Randall (1996). Total length (TL) of fish was estimated to the nearest centimeter. Length estimates of fishes from visual censuses were converted to weight using the following length-weight conversion: $W = a \bullet SL^{\beta}$ where the parameters a and β are constants for the allometric growth equation and SL is standard length in mm and W is weight in grams. Total length was converted to standard length (SL) by multiplying standard length to total length-fitting parameters obtained from FishBase (www.fishbase.org). Length-weight fitting parameters were available for 150 species commonly observed on visual fish transects in Hawaii (Hawaii Cooperative Fishery Research Unit, unpublished data). This was supplemented by using information from other published and web-based sources. In the cases where length-weight information did not exist for a given species, the parameters from similar bodied congeners were used. All biomass estimates were converted to metric tons per hectare (t/ha) to facilitate comparisons with other studies in Hawaii. Finally, fish taxa were categorized into three trophic categories (herbivores, secondary consumers and apex predators) according to various published sources and FishBase (www.fishbase.org).

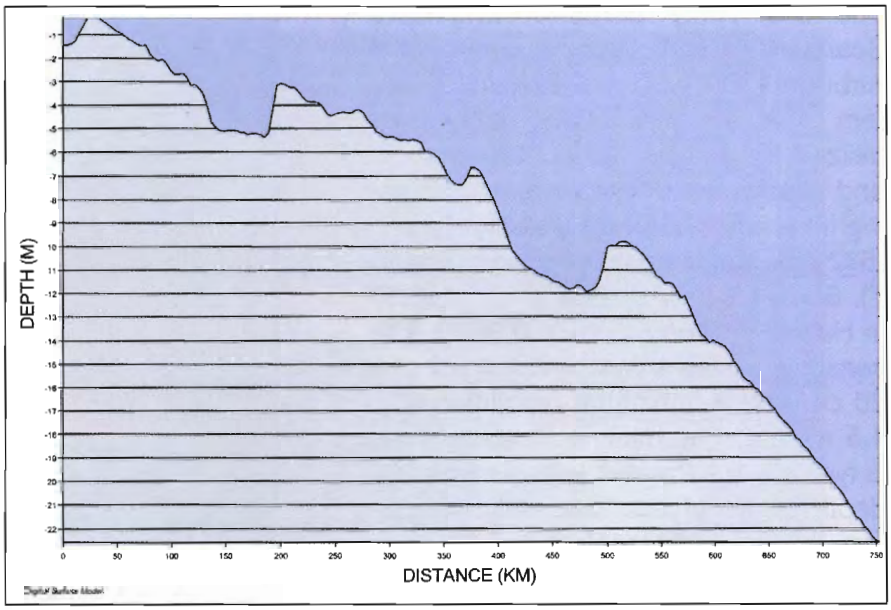

Figure 9. Bathymetric profile of Hanauma Bay, Oahu derived from LiDAR data.

Fish Sample Size Optimization Analysis

Optimal sample size was determined for number of species and number of individuals per transect among the four major habitat types surveyed in the study area (Table 5, Figures 10 and 11). A technique developed by Bros and Cowell (1987) using the standard error of the mean to resolve statistical power was used to determine the number of samples needed using number of species and number of individuals. This method uses a Monte Carlo simulation procedure to generate a range of sample sizes versus power. The sample size at which further increase in sample size does not substantially increase power (decreasing standard error of the mean) is taken as the minimum suitable number of samples. For number of species per transect, high and low standard error of the mean began to level off and converge at ca. four samples in the colonized hardbottom habitat and unconsolidated sediment habitat and ca. eight samples for the macroalgae and uncolonized hardbottom habitats. For number of individuals per transect, high and low standard error of the mean began to converge at six samples in the unconsolidated sediment habitat and nine samples in the macroalgae habitat. Given these results, nine to 10 samples per habitat appeared to be adequate to control the standard error of the mean for number of individuals and number of species per transect.

Table 5. Summary of sampling allocation of transects by location and management regime with a total sample size of n=329 per year.

	Pupukea	Hanauma Bay	Honolua-Mokuleia Bay	Kealakekua Bay	Total
MLCD	35	33	37	34	139
FRA				29	29
Open areas	38	47	63	13	161
Total	73	80	100	76	329

* MLCD = Marine Life Conservation District; FRA = Fisheries Replenishment Area; Open = Area open to resource extraction.

Benthic Survey Techniques

The four MLCDs and the surrounding benthic habitat were surveyed using the *in situ* planar point intercept quadrat method (Reed 1980). Each 25 m fish transect was stratified into 5 x 5 m segments with quadrat placement randomly allocated within each segment. The quadrat grid was 1m^2 in area and consisted of 1 inch PVC tubing fitted with nylon line spaced 10 centimeters apart to form a square grid with 81 intersections. A subset of 25 randomly selected intersections were marked and used for substrate identification. The rationale for the subset was that 25 points sufficiently represented the habitat with acceptable error and optimized sampling time (Friedlander et al. 2006). Each intersection was identified using substrate categories of sand, coralline algae, turf algae, macroalgae, *Halimeda* spp and coral. Coral and macroinvertebrates were identified down to species using Veron (2000) and Hoover (2002) respectively. The macroinvertebrates category incorporated echinoderms and other large invertebrates (e.g., zooanthids, octocorals) that occupied significant portions of the substrate. Macroinvertebrates were also included in the results for comparative purposes, but the methodology limited conclusions about distribution and abundance for this group of organisms. Limitations of *in situ* methodology precluded taxonomic resolution of algae down to the species level so algae were identified to genera using Littler and Littler (2003). 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.

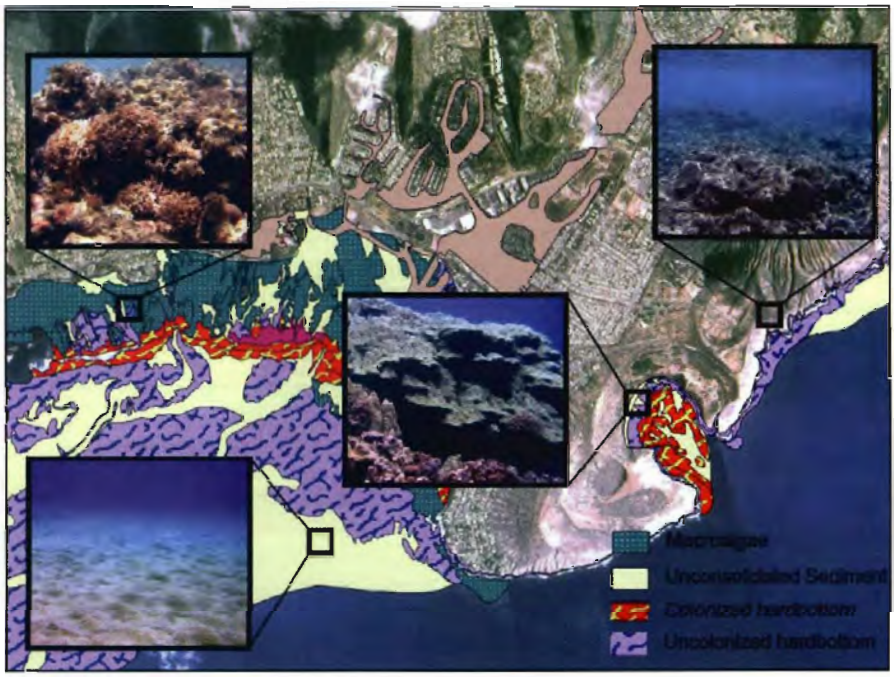

Figure 10. Four major habitats using NOAA benthic habitat maps to inform a stratified random sampling approach types (Maunalua Bay and Hanauma Bay, Oahu).

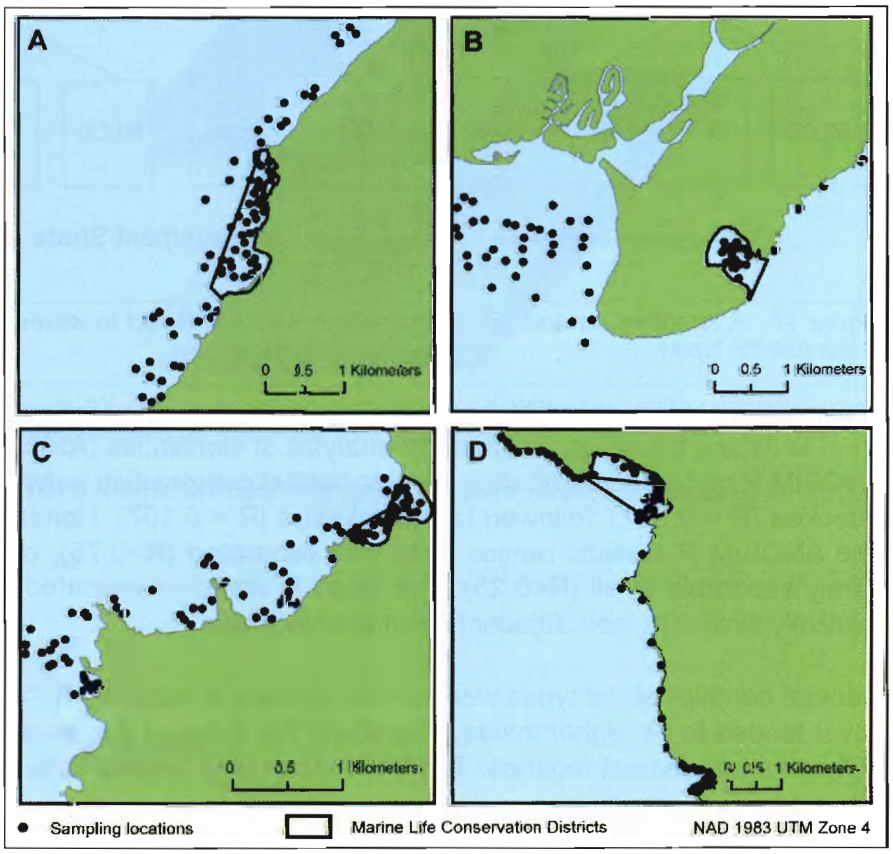

Figure 11. GPS points of sampling locations at (A) Pupukea (B) Hanauma Bay (C) Honolua-Mokuleia and (D) Kealakekua Bay MLCDs in the main Hawaiian Islands.

Methods

Rugosity Methods

To measure reef rugosity or surface relief, a chain of small links (1.3 cm per link) was draped along the full length of the centerline of each transect (Risk 1972). Care was taken to ensure that the chain followed the contour of all natural fixed surfaces directly below the transect centerline. A ratio of distance along the reef surface contour to linear horizontal distance gave an index of spatial relief or rugosity.

Sample Design

A stratified random sampling design was employed (Figure 12). Habitat polygons were attributed into four major habitat types (colonized hard bottom, uncolonized hard bottom, macroalgae and sand). Within each major habitat type, sampling was further stratified by management regime (MLCD; fisheries management area, or FMA; and open access). All sampling locations were randomly generated in ArcGIS (Figure 13).

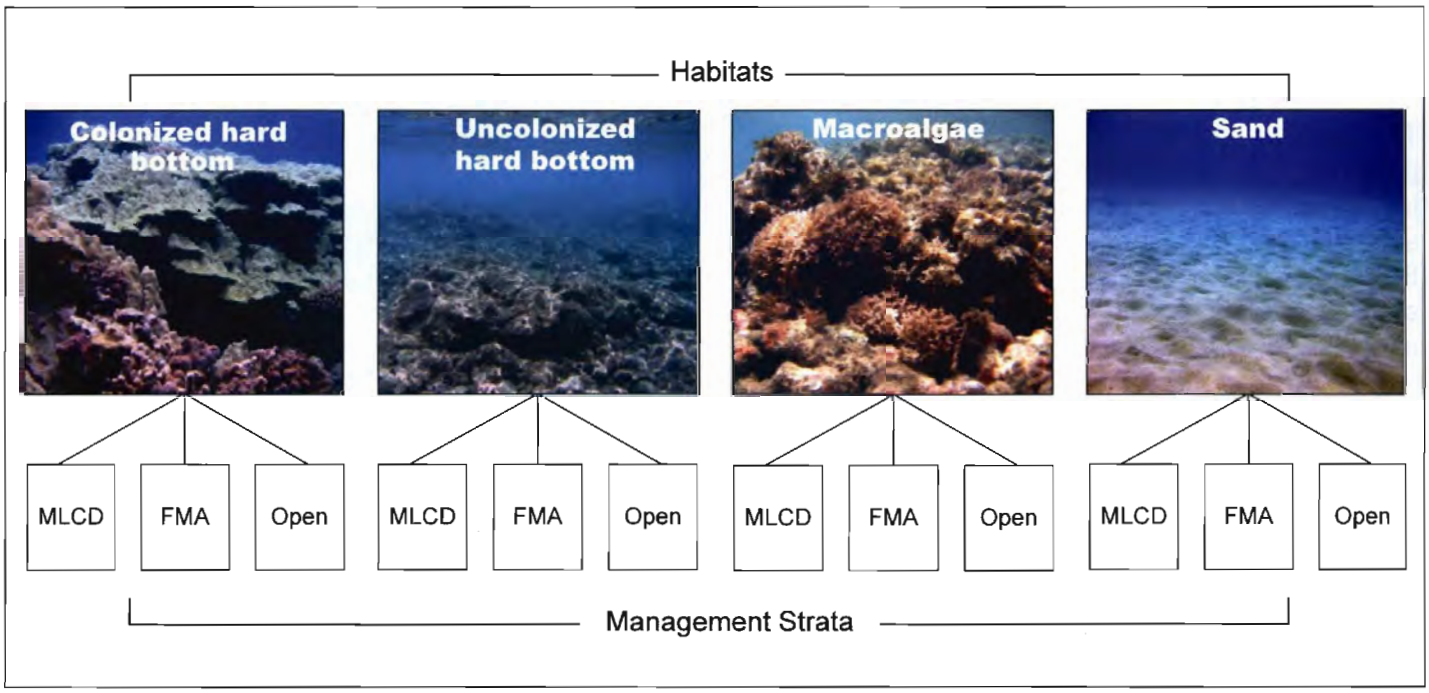

Figure 12. A stratified random sampling design was employed to assess MLCDs, FMAs and areas open to fishing by major habitat types.

The overall benthic assemblages were generally similar between the MLCDs and the corresponding areas open to fishing based on multivariate analysis of similarities (ANOSIM; Friedlander et al. 2007). The pairwise ANOSIM R test value comparing benthic habitat composition between MLCDs and open areas was highest in Pupukea (R = 0.327), followed by Kealakekua (R = 0.107), Hanauma (R = 0.040) and Honolua (R = 0.002). The ANOSIM R statistic ranges from well separated (R>0.75), overlapping but clearly different (R>0.5), or barely separable at all (R<0.25). The small R statistics indicated that these benthic assemblages were still relatively similar to their adjacent open access areas.

General benthic habitat types were similar inside and outside MLCDs (Friedlander et al. 2007b) although coral cover tended to be higher inside. Therefore, the focus of this study was to examine trends over time in each of these management regimes. The trends over time tended to be consistent with the level of protection (e.g. MLCD).

Data Analysis

For fish assemblage characteristics, the number of individuals and biomass were ln(x+1) transformed for statistical analysis. Numbers of individuals were converted to number/m^2 and biomass was converted to t/ha for comparisons with other studies throughout the state. Comparisons of fish species richness, biomass, and diversity among management strata were conducted using a Nested Analysis of Variance (ANOVA) us-

ing only the habitat types common to all management strata. Significant differences between pairs were examined using the Tukey-Kramer HSD (honestly significant difference) test for ANOVAs ($\alpha = 0.05$).

Species diversity was calculated from the Shannon-Weaver Diversity Index (Ludwig and Reynolds 1988): $H'=S\ (p_i \ln p_i)$, where p_i is the proportion of all individuals counted that were of species i. An index of relative dominance (IRD) for each fish taxa was created by multiplying the percent frequency of occurrence of the taxa on each transect by the relative percent number of that taxa (Greenfield and Johnson 1990).

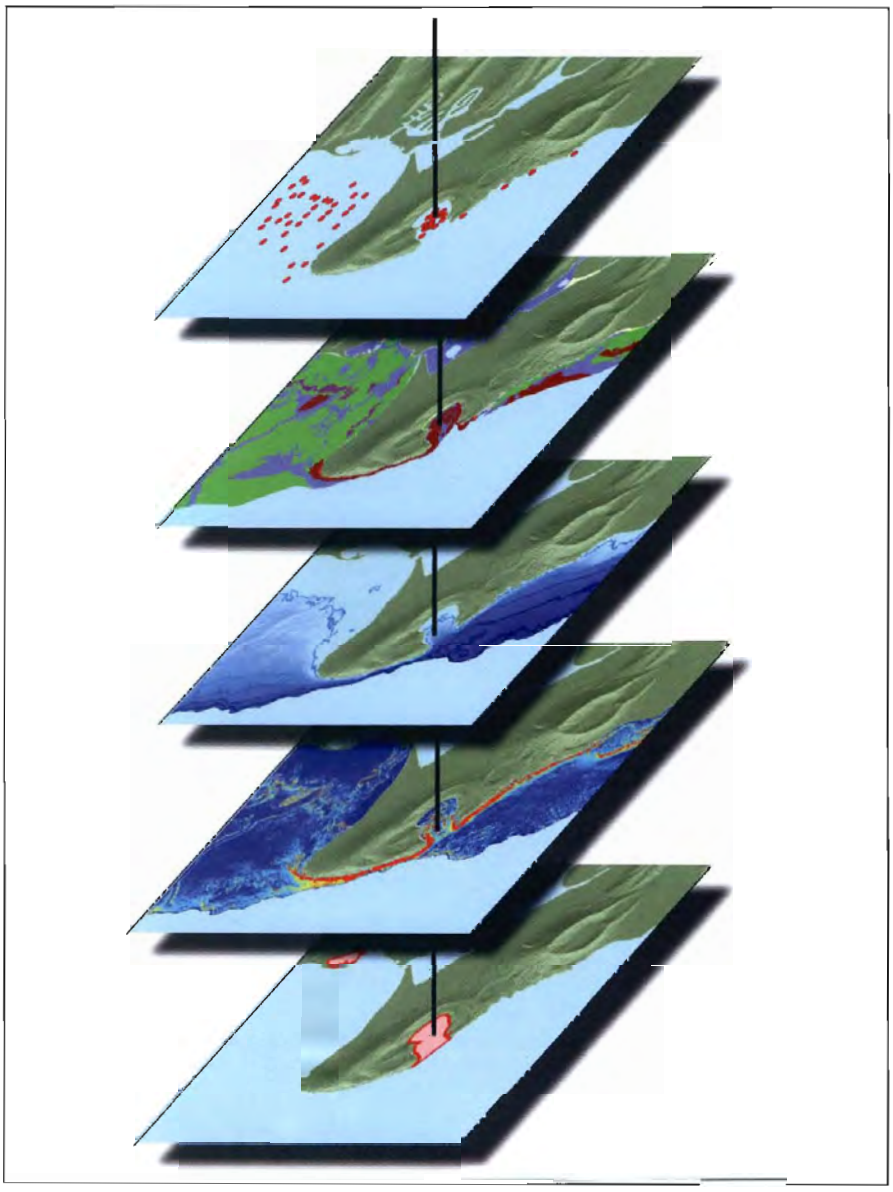

Figure 13. GIS layers used to quantify and characterize the seascape cover were compiled for each site by management regime.

Quantifying Seascape Metrics

Bathymetric grids were created from the LiDAR data for each study area by interpolation using Inverse Distance Weighting in ArcGIS Spatial Analyst (ESRI) at a grid cell size of 4 meters. Slope was derived from the gridded (4 m cell size) LiDAR bathymetry using the ArcGIS Spatial Analyst extension, where the raster cell values represented the maximum rate of change in elevation between neighboring cells and were calculated in degrees. Rugosity was derived from the gridded (4 m cell size) LiDAR bathymetry using the 'Benthic Terrain Modeler for ArcGIS', where the raster cell values reflected the ratio of the seascape surface area to the planimetric area determined in a neighborhood analysis (Jenness 2004, Lundblad et al. 2006).

Results

Photo courtesy of Keoki Stender, www.marinelifephotography.com

PUPUKEA MLCD AND NORTH SHORE OAHU

The north shore Oahu study area extended from Sunset Beach to Kawailoa Beach (ca. 6.5 km^2) and included the Pupukea MLCD (Figure 40).

Sample Allocation

A total of 80 samples were collected in 2004 and 2006, in 2007 and 2008 only hardbottom habitat was sampled (n=51; Figure 41 and Table 13). The two levels of sampling stratification included major habitat types (CHB, MAC, UCH and sand) and fisheries management regime (open access and MLCD). Macroalgae habitat was not present at the one-acre minimum mapping unit within the MLCD, and CHB habitat was likewise not present in the open area at the one-acre minimum mapping unit.

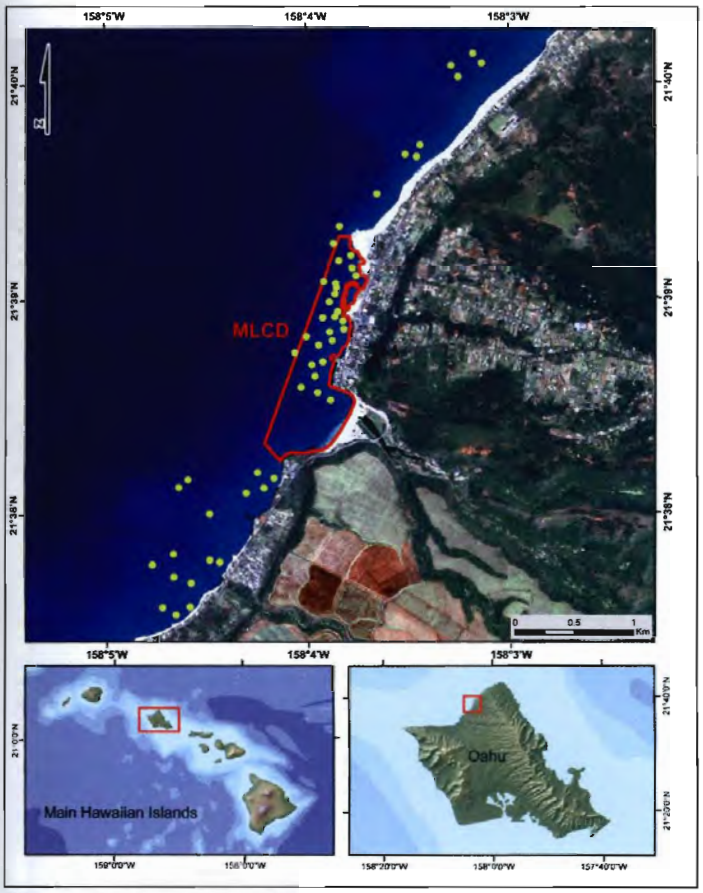

Figure 40. Overview of Pupukea MLCD and adjacent areas with sampling locations.

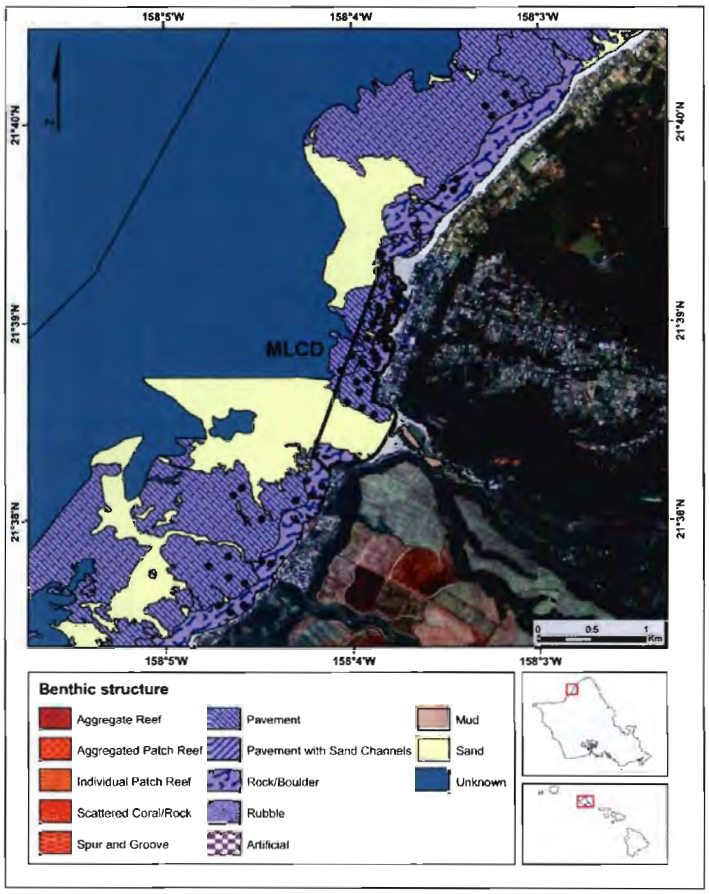

Figure 41. Sampling locations and benthic structure for the Pupukea MLCD and adjacent areas.

Table 13. Sample allocation at Pupukea MLCD by habitat (2002-2008).

	MLCD	CHB	UCH	UCS	Open	MAC	UCH	UCS	Total
2003	35	9	15	11	38	12	15	11	73
2006	35	9	15	11	38	12	15	11	73
2007	24	9	15		27	12	15		51
2008	24	9	15		27	12	15		51
Total	118	36	60	22	130	48	60	22	

* MLCD = Marine Life Conservation District; CHB = Colonized hard bottom; UCH = Uncolonized hard bottom; UCS = Unconsolidated sediment; Open = Area open to resource extraction; MAC = Macroalgae.

Results

Characterization of Spatial Patterns of the Seascape and MLCD Configuration

The total seascape area within the Pupukea MLCD was 0.11 km² in 1983 and was expanded to 0.71 km² in 2003, with the perimeter to area ratio decreasing from 27.9 to 7.34 and the fractal dimension also increasing from 1.35 to 1.79. (Tables 14 and 15, Figure 42). Based on the NOAA Biogeography Branch benthic habitat maps the habitat diversity, represented by Shannon's diversity index and Shannon's evenness index was 0.91 and 0.65 respectively in 1983 and 1.45 and 0.81 respectively in 2003 (Table 14). Bathymetric grids were created from the LiDAR data within Hanauma Bay MLCD that represented an approximate depth range of 0 – 12.07 meters ($\bar{x}$ = 3.59) in 1983 and in increased to include a depth range up to 16.98 ($\bar{x}$ = 8.09) in 2003. The average slope ($\bar{x}$ = 8.55) and average rugosity ($\bar{x}$ = 1.02) both increased slightly between the 1983 and 2003 boundary respectively (Table 16 and Figure 43).

Table 14. Summary of seascape metrics derived from 2007 NOAA Biogeography Branch benthic habitat maps.

	1983 Boundary MLCD*	2003 Boundary MLCD*
Shannon's diversity index	0.91	1.45
Shannon's evenness index	0.65	0.81
Mean patch fractal dimension	1.35	1.79

* MLCD = Marine Life Conservation District.

Table 15. Summary of marine reserve boundary analysis for Pupukea MLCD.

	1983 Boundary MLCD*	2003 Boundary MLCD*
Reserve perimeter (km)	2.97	5.21
Reserve area (km²)	0.11	0.71
Perimeter to area ratio	27.9	7.34

* MLCD = Marine Life Conservation District.

Figure 42. Aerial imagery of Pupukea MLCD with original (1983) and extended boundaries (2000).

Table 16. Summary of seascape structure derived from LiDAR bathymetric grids for Pupukea MLCD.

	Depth			Rugosity			Slope (percent)		
	Average	Standard deviation	Depth range	Average	Standard deviation	Rugosity range	Average	Standard deviation	Deviation range
1983 Boundary MLCD*	3.59	2.62	0-12.07	1.02	0.04	1-1.52	8.55	9.65	0.02-94.04
2003 Boundary MLCD*	8.09	4.23	0-16.98	1.02	0.04	1-1.52	9.28	10.63	0.01 - 94.04

* MLCD = Marine Life Conservation District.

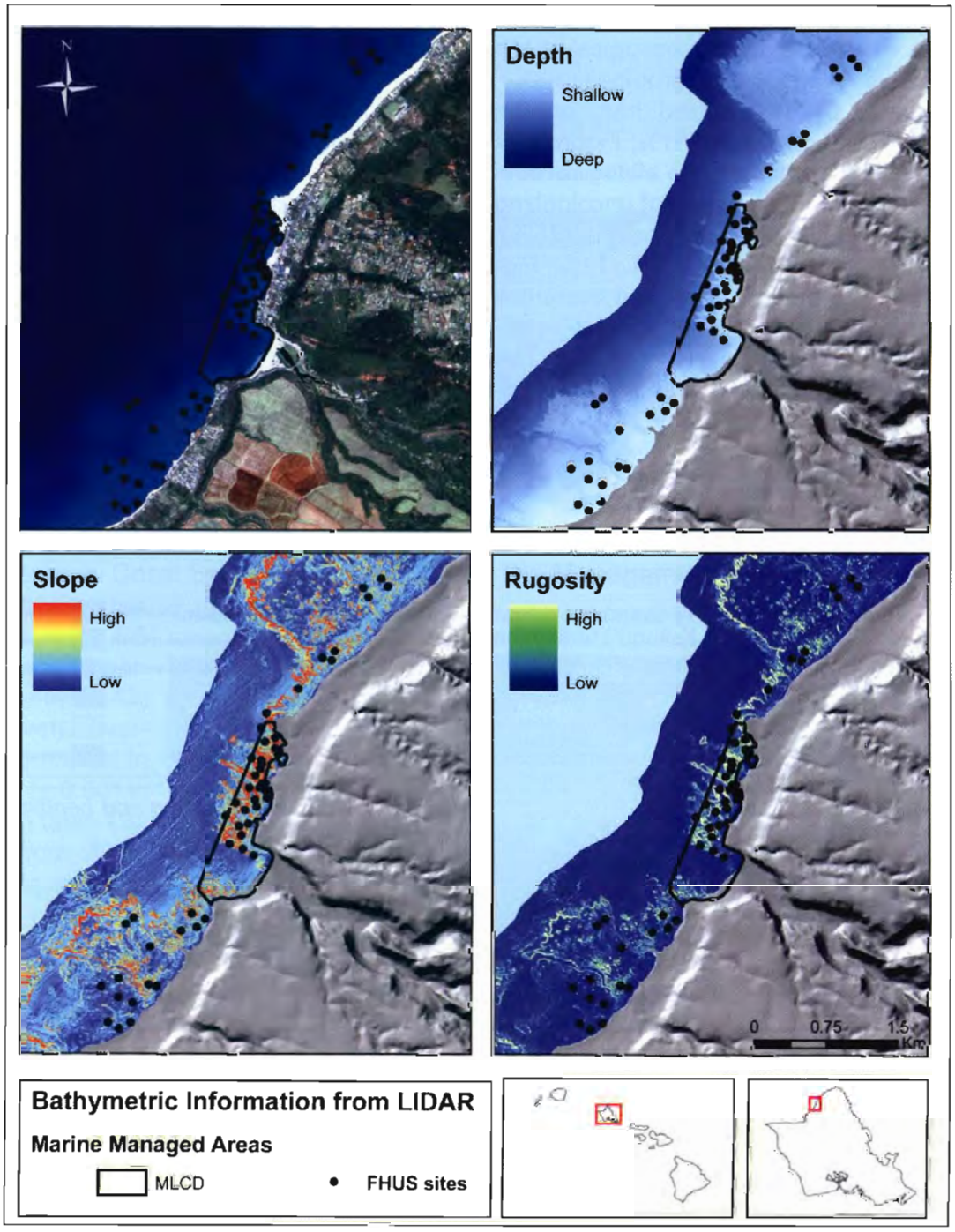

Figure 43. Aerial imagery of Pupukea and surrounding study region with other panels describing seascape characteristics (e.g. depth, slope, rugosity) derived from bathymetric LiDAR data.

Results

Evaluation of MLCD Boundary Expansion Using a Seascape Perspective

The total area within the Pupukea MLCD increased by 646% after the expansion of the boundaries (Table 15). Prior to expansion, the MLCD was dominated by rock/boulder habitat (74%). After boundary expansion, the geomorphic structure consisted of a mix of pavement (37%), sand (33%) and rock/boulder (26%). Before expansion the biological cover was dominated by macroalgae (63%), followed by uncolonized hard bottom (24%), and turf algae (11%; Figure 44). Following expansion, the biological cover consisted of a mixture of uncolonized hard bottom (33%), macroalgae (25%), turf algae (25%) and coral (12%; Figure 44). Habitat diversity and evenness increased by 59% and 25%, respectively, after boundary expansion. The mean perimeter-area ratio among habitat polygons increased by 24% and the mean patch fractal dimension increased by 33%. The total perimeter-area ratio decreased by 66%.

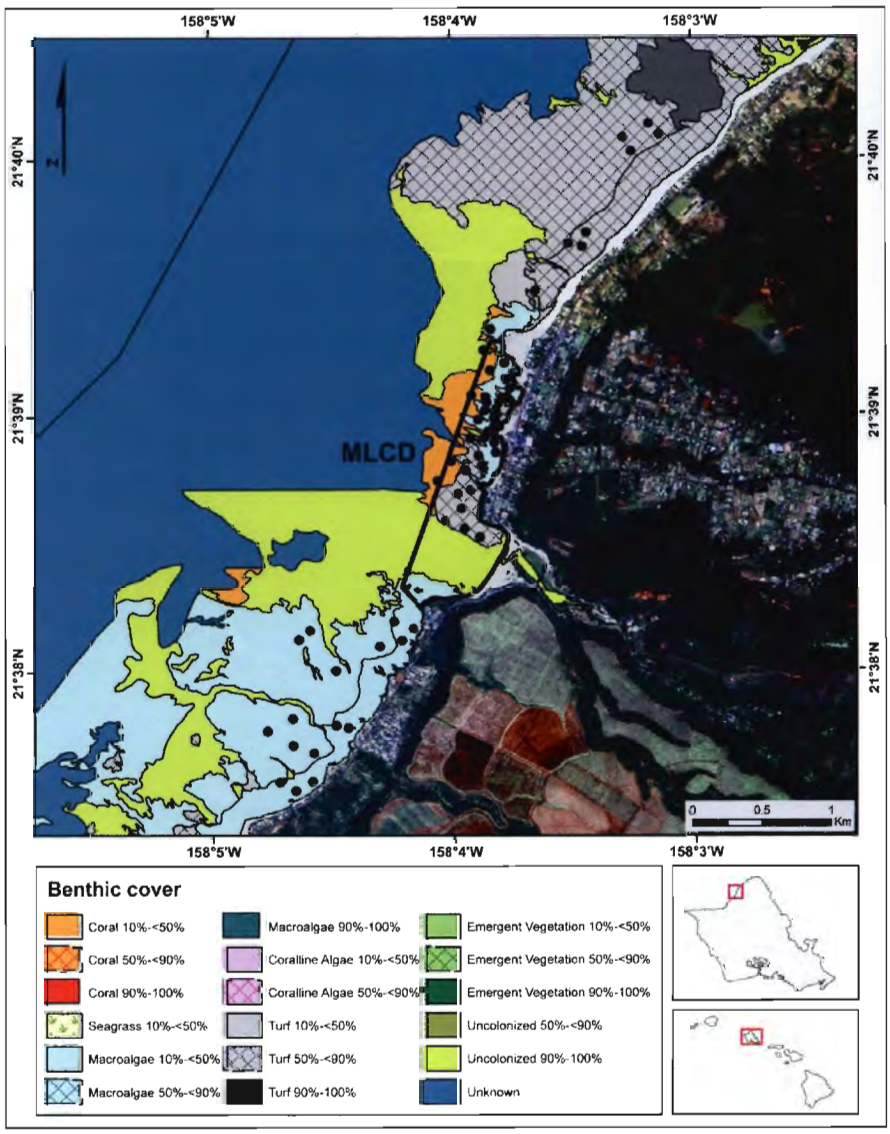

Figure 44: Sampling locations and benthic cover for the Pupukea MLCD and adjacent areas.

Large-scale Benthic Cover

Benthic coverage for the Pupukea MLCD was derived from the NOAA benthic habitat maps with coral reef and hard bottom major structure accounting for 64% of the total habitat within the MLCD, followed by unconsolidated sediment (33%). The coral reef and hard bottom structure consisted mostly of pavement (37%), rock/boulder (26%), and with only 1% of scattered coral and rock. The remaining portion of the MLCD was characterized by sand (33%; Table 17). Biological cover was dominated by macroalgae 10-50% (26%). The remaining portion of the biological cover in the MLCD consisted of uncolonized (33%) and turf (26%; Table 18).

Table 17. Geomorphic structure for the Pupukea MLCD derived from NOAA benthic habitat maps.

Major Structure	Detailed Structure	Area (km^2)	Percentage
Coral Reef and Hardbottom	Pavement	0.26	37%
Coral Reef and Hardbottom	Rock/Boulder	0.18	26%
Coral Reef and Hardbottom	Scattered Coral/Rock	0.00	<1%
Other Delineations	Land	0.03	4%
Unconsolidated Sediment	Sand	0.24	33%
Unknown	Unknown	0.00	<1%

Table 18. Biological cover for the Pupukea MLCD derived from NOAA benthic habitat maps.

Major Cover	Percent Cover	Area (km^2)	Percentage
Coral	10% - 50%	0.09	12%
Macroalgae	10% - 50%	0.18	26%
Turf	10% - 50%	0.003	<1%
Turf	50% - 90%	0.18	25%
Unclassified		0.03	4%
Uncolonized	90%-100%	0.24	33%
Unknown	Unknown	0.002	<1%

Spatial and Temporal Patterns in Coral Species Richness within the Management Regimes

Average coral species richness per transect in Pupkea MLCD was 1.6 times greater than the adjacent open area with a grand mean of 4.45(± 0.43) and 2.79 (± 0.49), respectively. Average species richness in CHB habitat in the MLCD ranged from 4.56 (± 0.50) in 2003 to 5.89 (± 0.35) in 2006 (Table 19). Patterns in coral richness from 2003-2007 increased slightly inside and outside of the MLCD (Figure 45). Patterns of change over time among management and habitat regimes were generally consistent over time with coral richness in the MLCD CHB habitat being the greatest overall, with all categories increasing in 2006. CHB habitat was not present outside of the MLCD (Figure 46). Coral richness outside of the MLCD was nearly equal among habitats in 2003 and 2006, although richness was slightly greater in the UCH habitat compared to the MAC habitat in 2007 (Figure 47a).

Table 19. Comparison of coral species richness in major habitats and among different management regimes at Pupukea MLCD.

	2003		2006		2007	
	Mean	SE	Mean	SE	Mean	SE
MLCD						
CHB	4.56	0.50	5.89	0.35	4.56	0.50
UCH	2.60	0.38	5.47	0.39	3.67	0.46
Open						
MAC	1.83	0.32	3.67	0.51	2.42	0.50
UCH	1.87	0.46	3.47	0.53	3.53	0.60

* MLCD = Marine Life Conservation District; CHB = Colonized hard bottom; UCH = Uncolonized hard bottom; Open = Area open to resource extraction; MAC = Macroalgae.

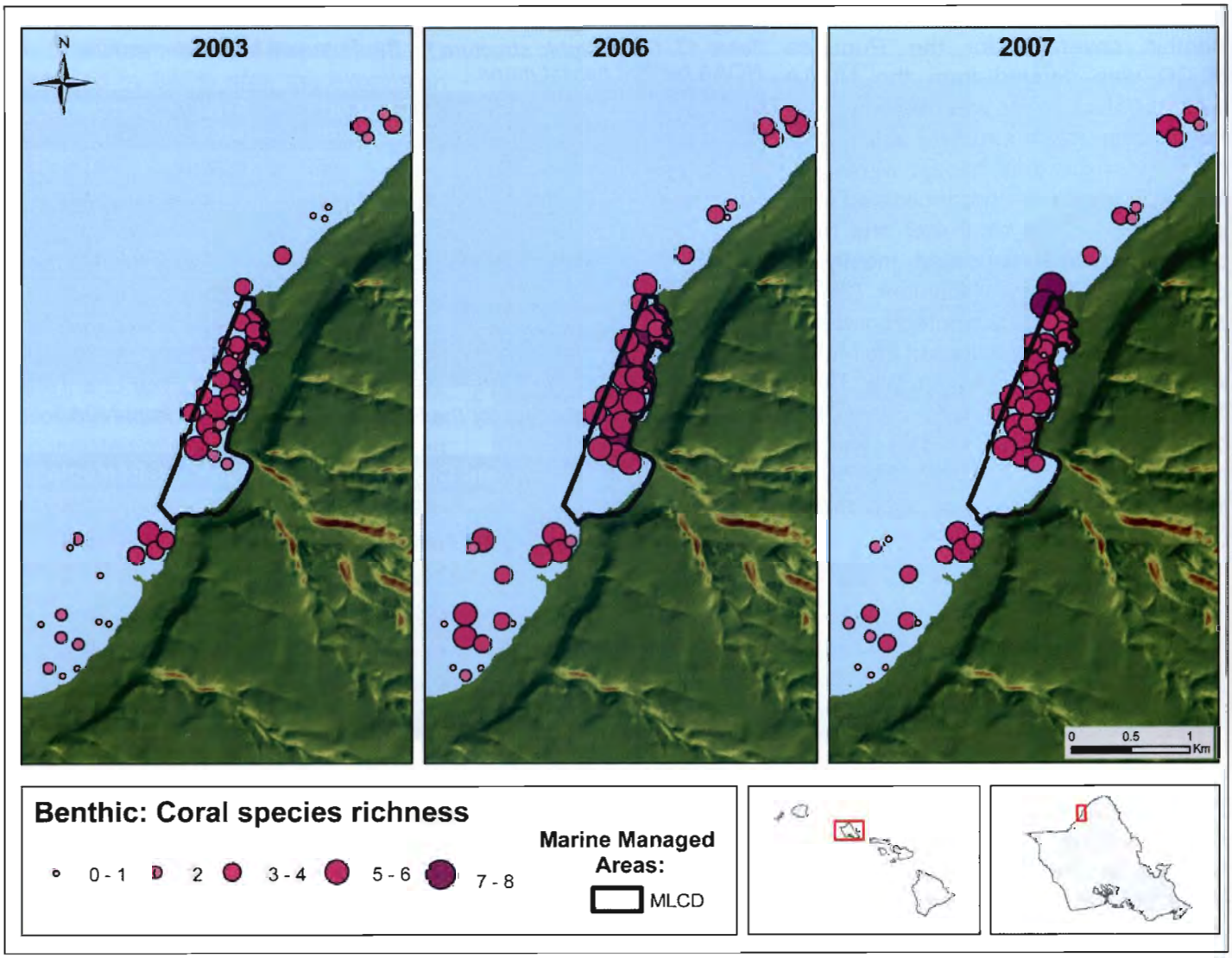

Figure 45. Coral species richness by individual transects for north shore Oahu study area including Pupukea Bay MLCD from 2003-2007.

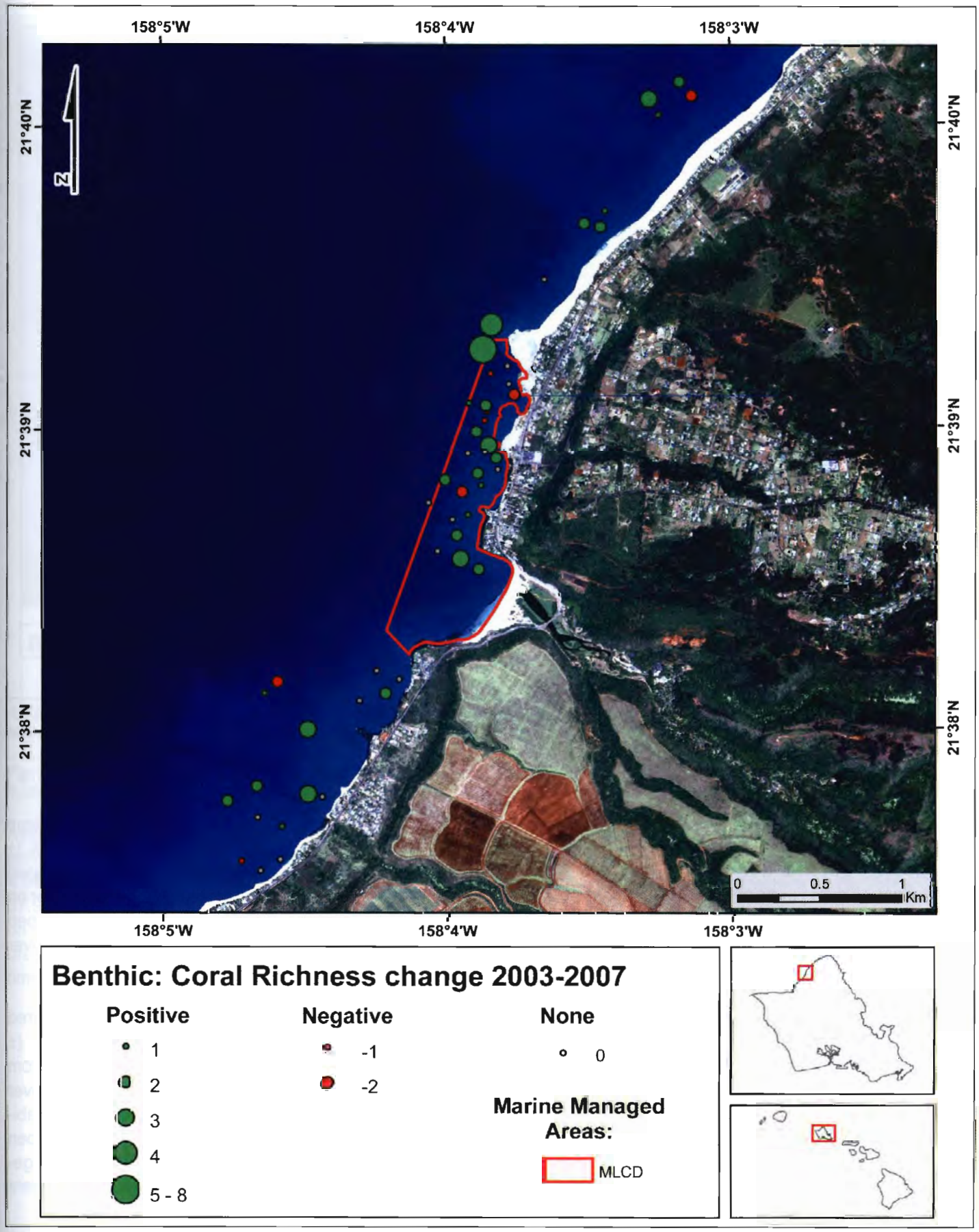

Figure 46. Change in coral species richness from 2003-2007 for the Pupukea MLCD and adjacent areas.

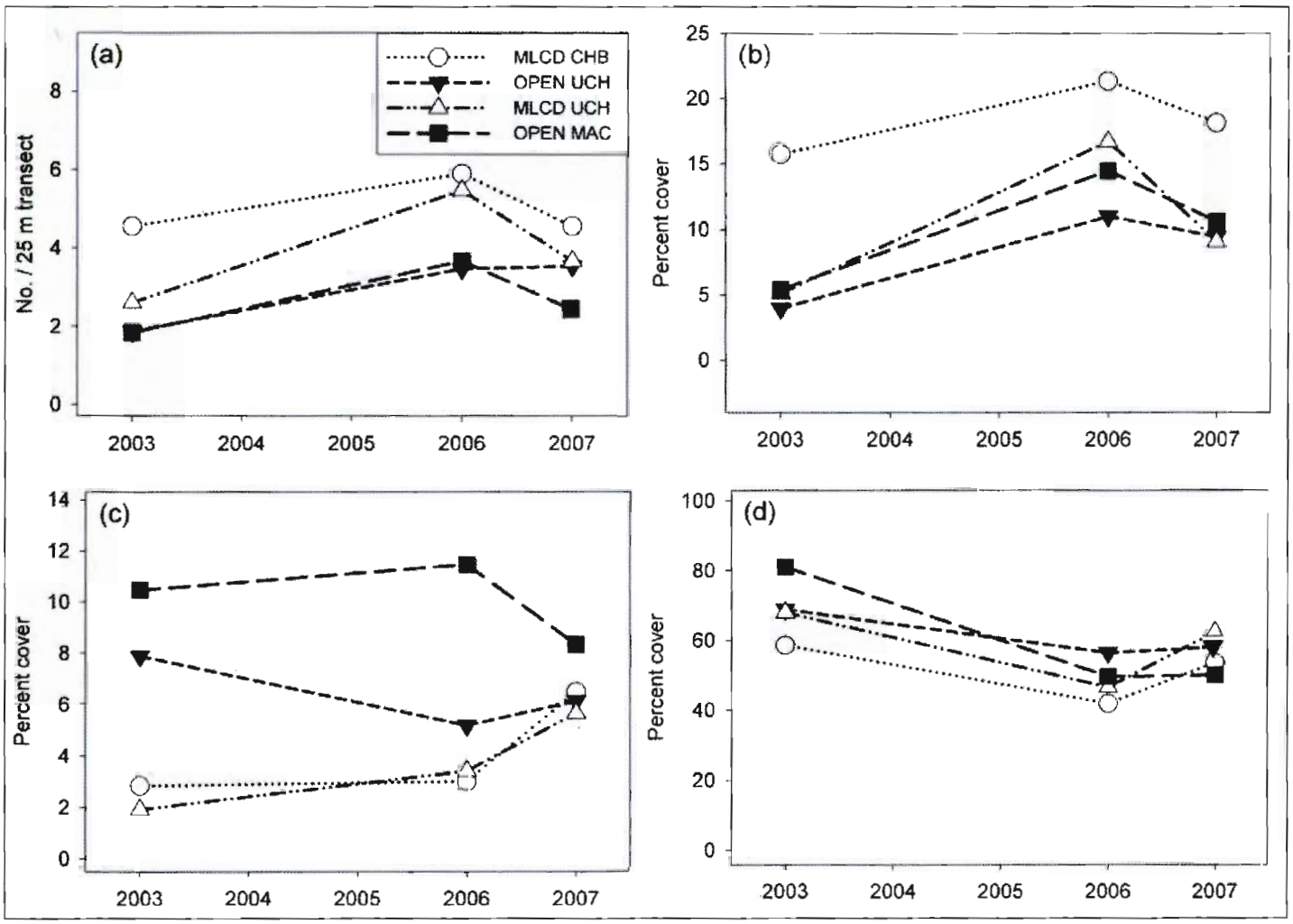

Figure 47. Temporal change in benthic communities at Pupukea MLCD and surrounding areas by habitat type from 2003-2007. (a) Mean species richness by year (b) Mean percent cover of coral (c) Mean percent cover of macroalgae (d) Mean percent cover of turf algae.

Spatial and Temporal Patterns in Benthic Cover within the Management Regimes

Average percent coral cover over the sampling period was greater in Pupukea MLCD ($\bar{x}$ =10.21) compared to the adjacent area ($\bar{x}$ =7.09). Average percent coral cover per transect in the MLCD ranged from 6.24% (± 1.30) in 2003 to 12.64% (± 1.79) in 2006. This compared to the adjacent open area where coral cover ranged from 3.26% (± 0.71) in 2003 to 9.95% (± 1.58) in 2007 (Figure 48). Patterns of percent change of coral cover on transects between 2004-2007 show an overall increase both inside Pupukea MLCD and in the adjacent open areas (Figure 49). Patterns of change among management and habitat regimes were generally consistent over time with MLCD CHB covering the greatest percentage in all years (Figure 47b).

Average percent macroalgal cover over the sampling period was greater in the open area ($\bar{x}$ =6.32) compared to the MLCD ($\bar{x}$ =2.94). Average percent macroalgal cover per transect in the MLCD ranged from 1.55% (± 0.30) in 2003 to 5.97% (± 1.15) in 2007. This compared to the adjacent open area where cover ranged from 5.66% (± 1.13) in 2006 to 7.11% (± 1.25) in 2007 (Figure 50). Patterns of percent change of macroalgal cover on transects between 2004-2007 show a general increase to the north of Pupukea MLCD in hard bottom habitat with small decreases in adjacent open areas (Figure 51). Macroalgae is generally much greater in the open areas compared the MLCD, and higher on hard bottom habitats when examined over time among management and habitat regimes. Macroalgal cover is similar for both habitat types in the MLCD and follow consistent trends over time (Figure 47c).

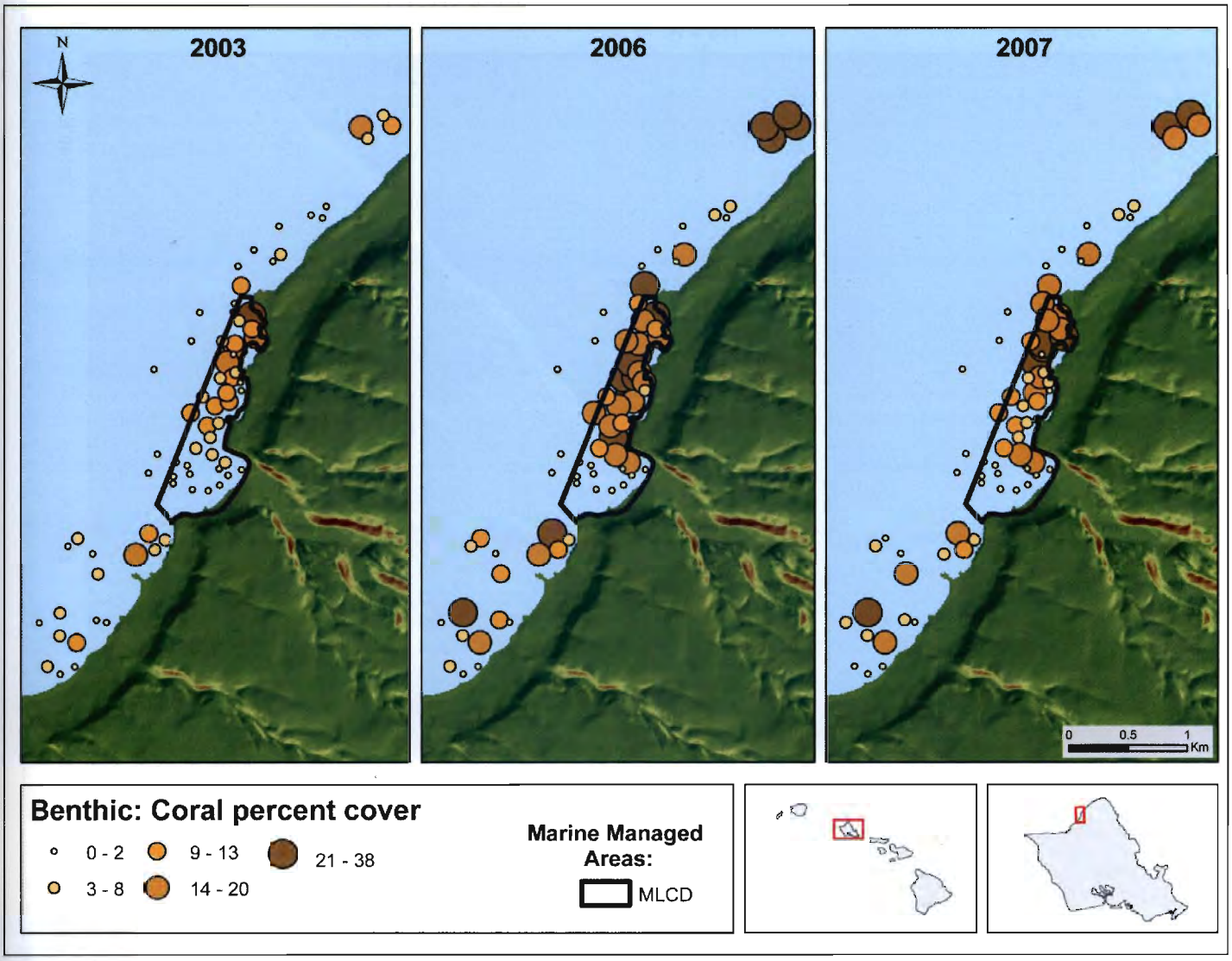

Figure 48. Mean percent coral cover by individual transects for north shore Oahu study area including Pupukea MLCD from 2003-2007.

Average percent turf cover over the sampling period was slightly greater in the open area ($\bar{x}$ =47.74) compared to the MLCD ($\bar{x}$ =43.00). Average percent turf cover per transect in the MLCD ranged from 30.70% (± 4.01) in 2006 to 59.10% (± 2.03) in 2007. This compared to the adjacent open area where cover ranged from 37.92% (± 4.38) in 2006 to 54.43% (± 2.62) in 2007 (Figure 52). Spatial patterns of percent change of turf cover on transects between 2004-2007 show a general decrease in turf cover inside and outside of the MLCD (Figure 53). Patterns of change over time among management and habitat regimes were generally consistent over time with all categories being relatively similar and decreasing slightly over the sampling period (Figure 47d).

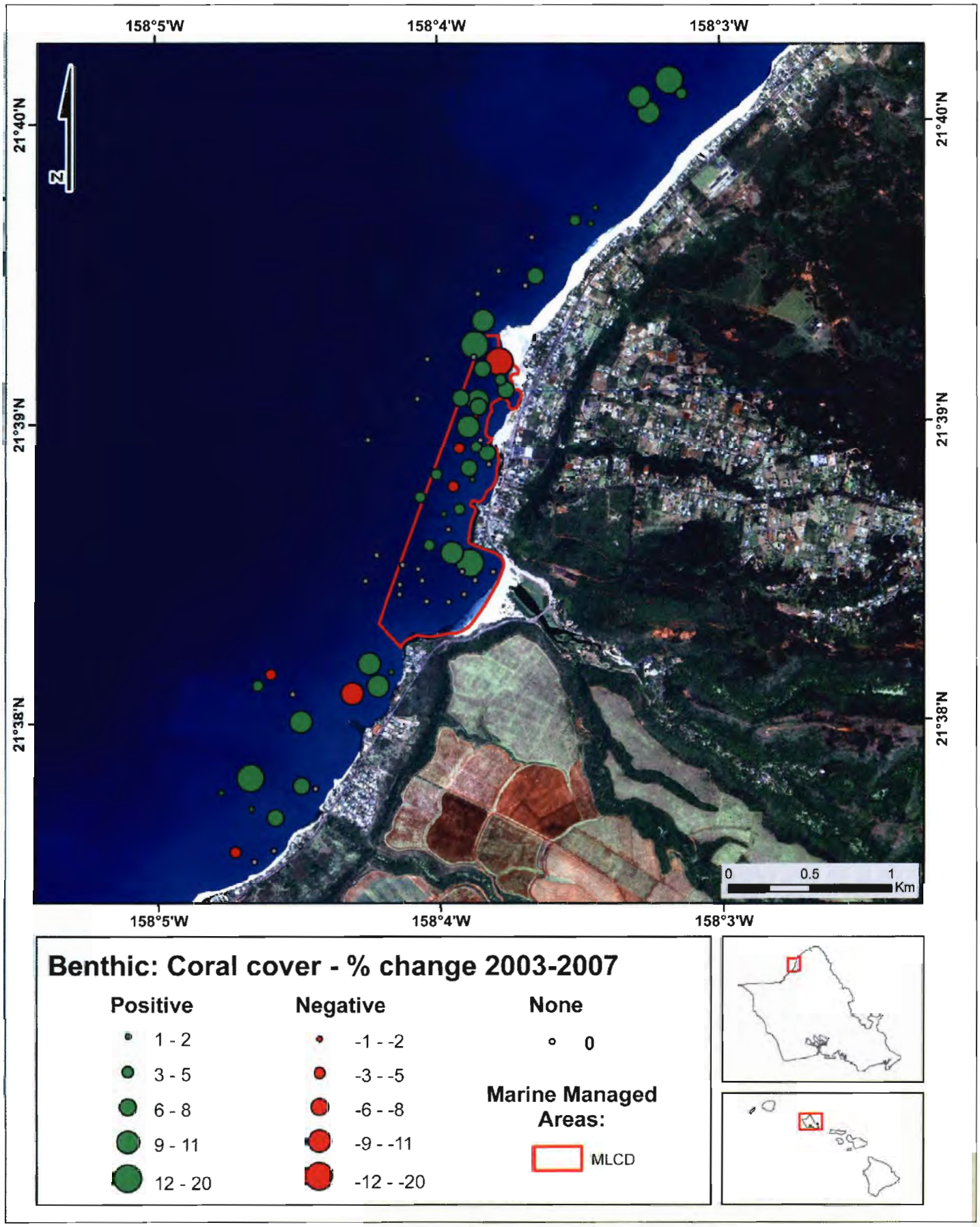

Figure 49. Change in mean coral cover from 2003-2007 for the Pupukea MLCD and adjacent areas.

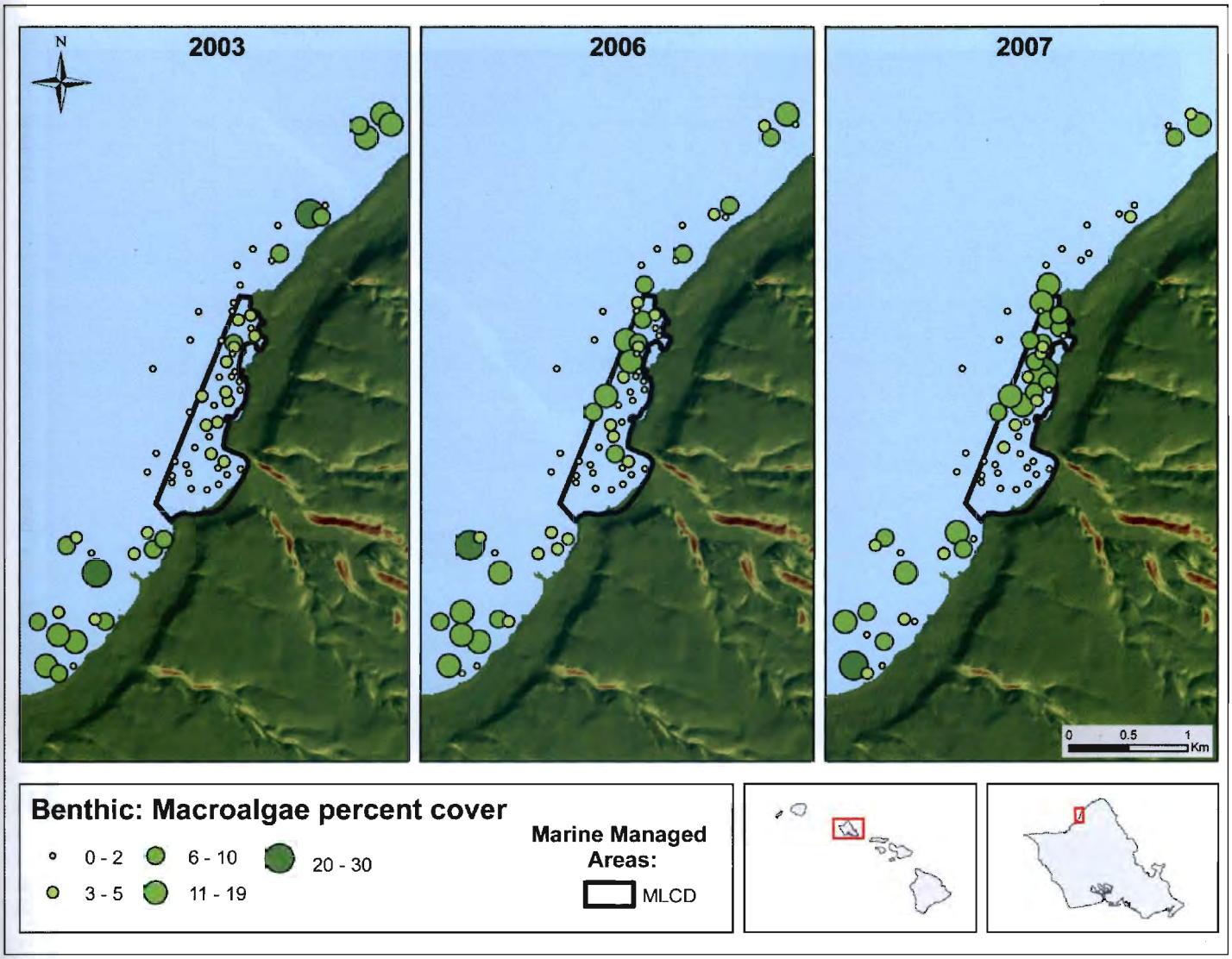

Figure 50. Mean percent macroalgal cover by individual transects for north shore Oahu study area including Pupukea MLCD from 2003-2007.

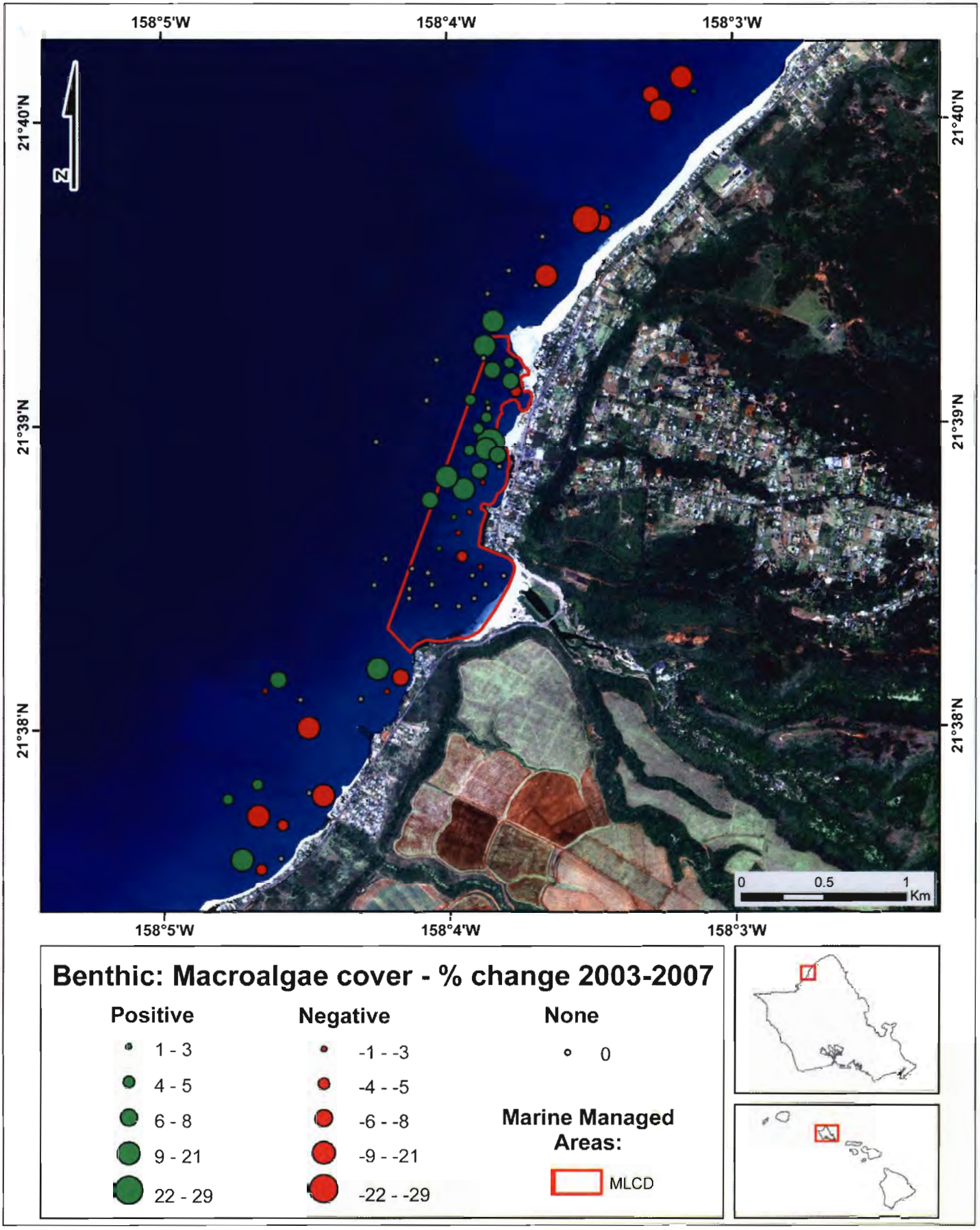

Figure 51. Change in mean macroalgal cover from 2003-2007 for the Pupkea MLCD and adjacent areas.

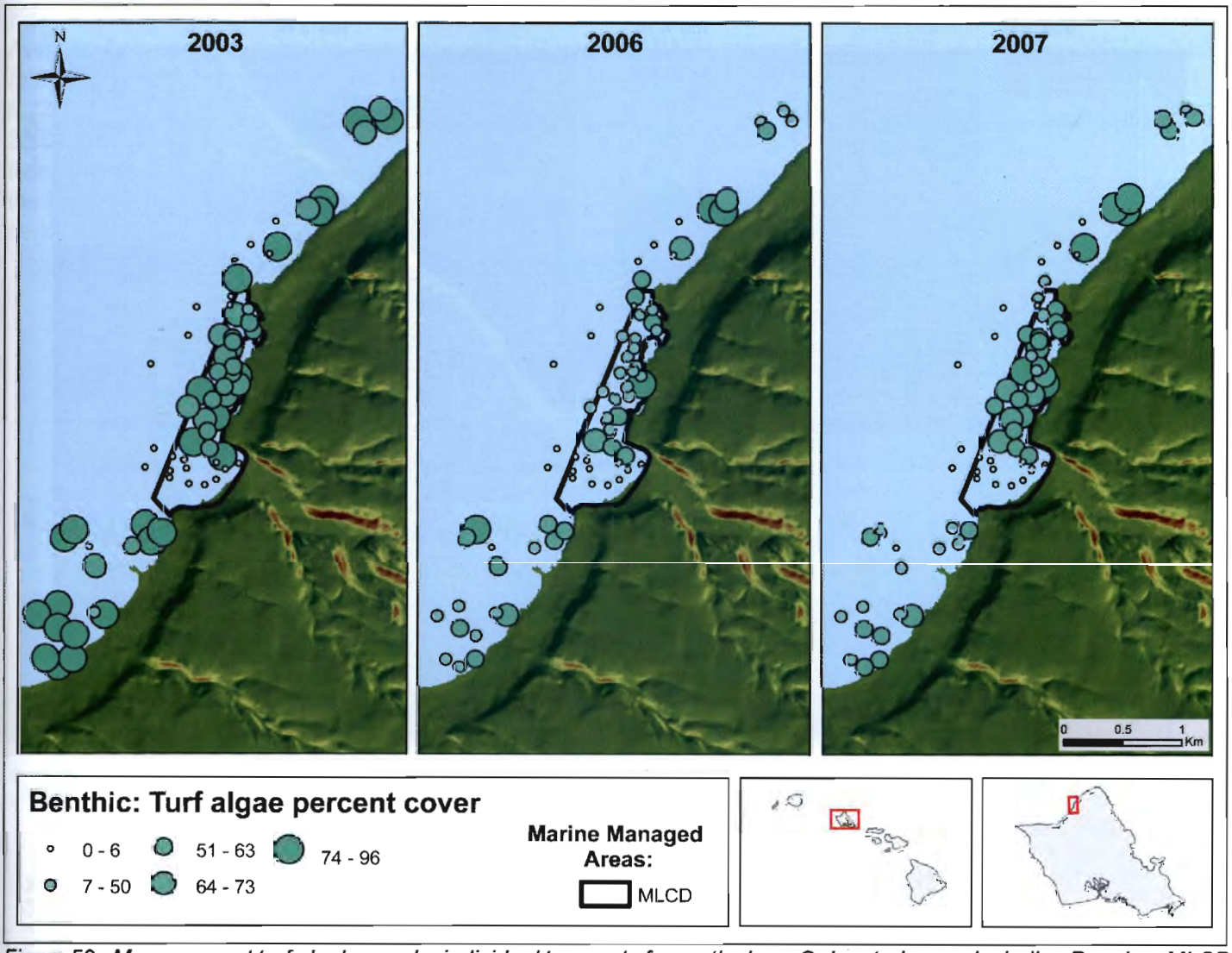

Figure 52. Mean percent turf algal cover by individual transects for north shore Oahu study area including Pupukea MLCD from 2004-2007.

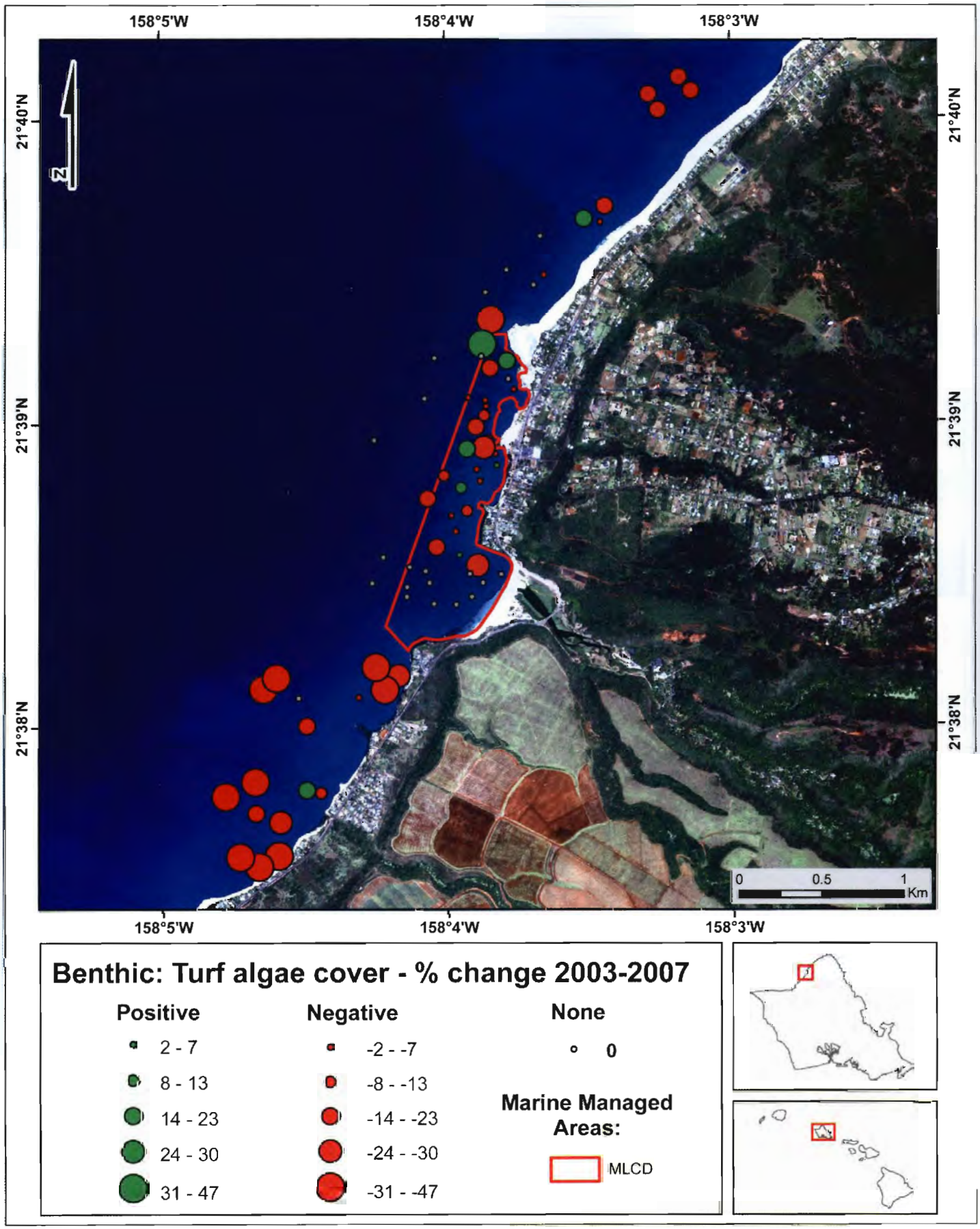

Figure 53. Change in mean turf algal cover from 2003-2007 for the Pupkea MLCD and adjacent areas.

Fish Assemblage Characteristics Among Habitat Types and Between Management Regimes

Average fish species richness per transect in Pupukea MLCD ranged from 19.96 (± 5.45) in 2007 to 21.33 (± 5.58) in 2003 (Figure 54). This compared to the adjacent open area where richness ranged from 14.51 (± 6.22) in 2007 to 15.89 (± 6.28) in 2003. Richness averaged 3.04 (± 7.23) fewer species in the MLCD between 2003 and 2008 while richness declined by 0.96 (± 6.43) species on average in the open area during this same time period (Figure 55). The lowest overall richness was observed in the open MAC ($\bar{x}$ = 13.94 ± 1.04) and the highest was in the MLCD CHB ($\bar{x}$ = 22.56 ± 2.54). Richness remained consistent over the six year study period within the open area and declined slightly in the MLCD (Figure 56a).

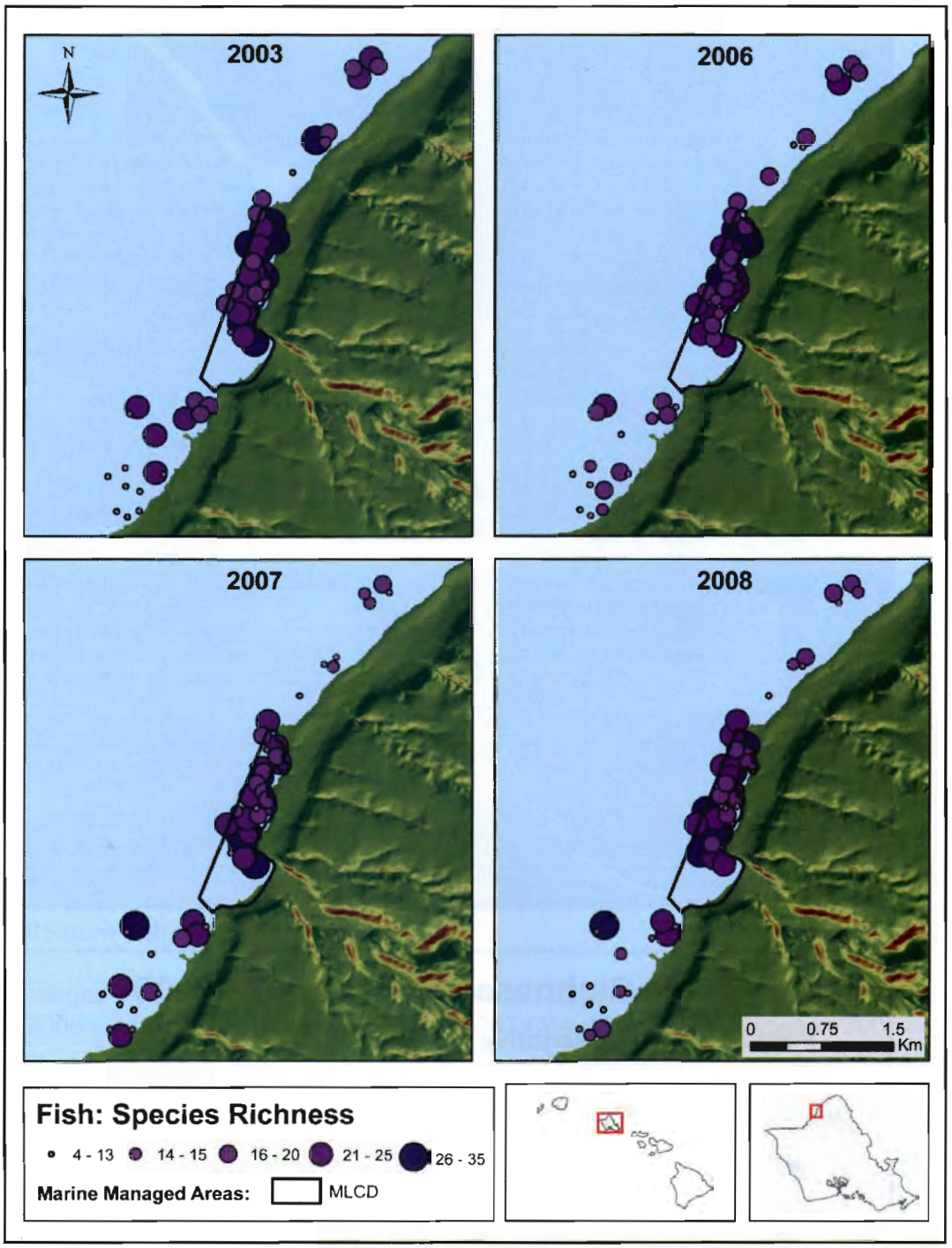

Figure 54. Fish species richness by individual transect for north shore Oahu study area including Pupukea from 2003-2008.

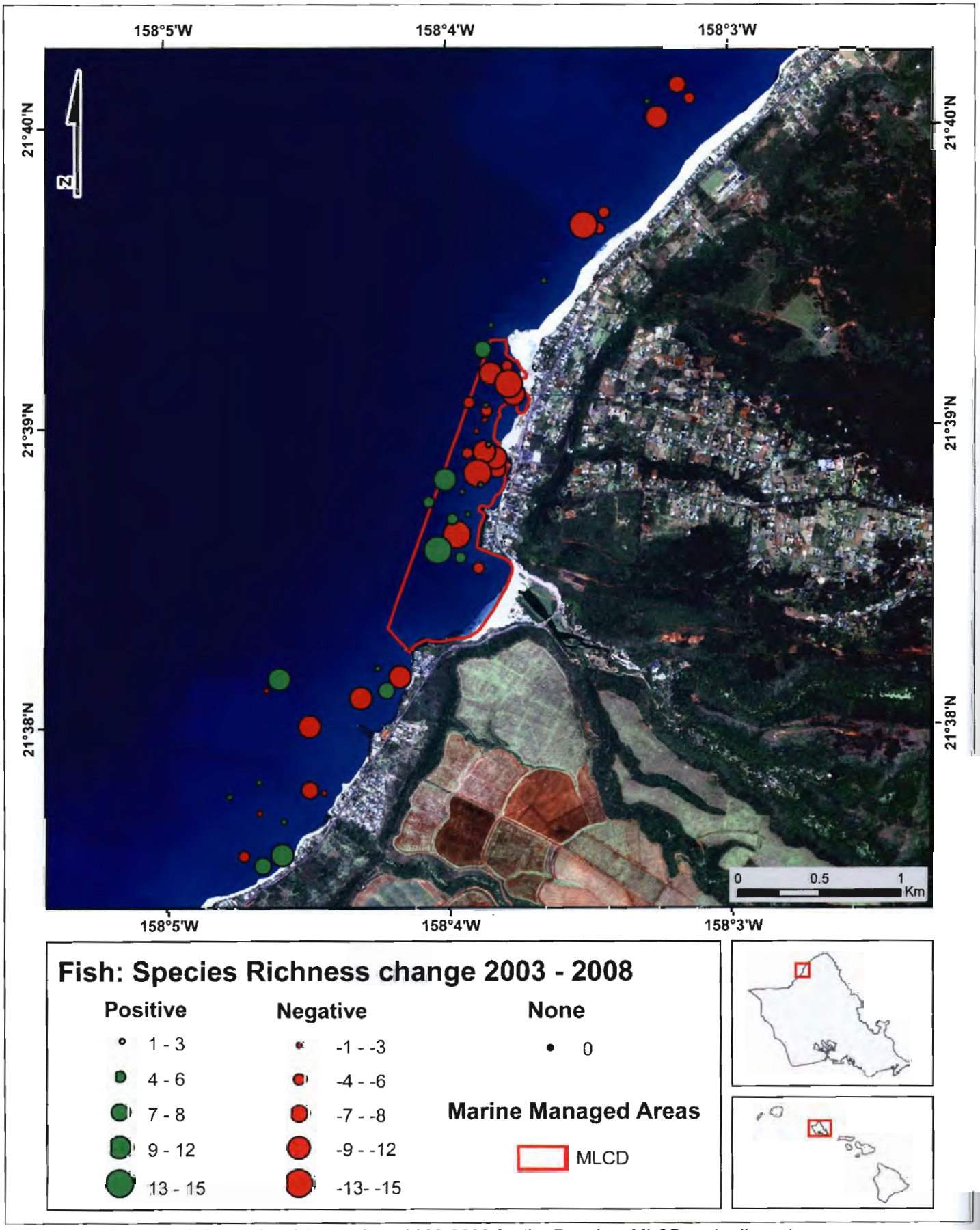

Figure 55. Change in fish species richness from 2003-2008 for the Pupukea MLCD and adjacent areas.

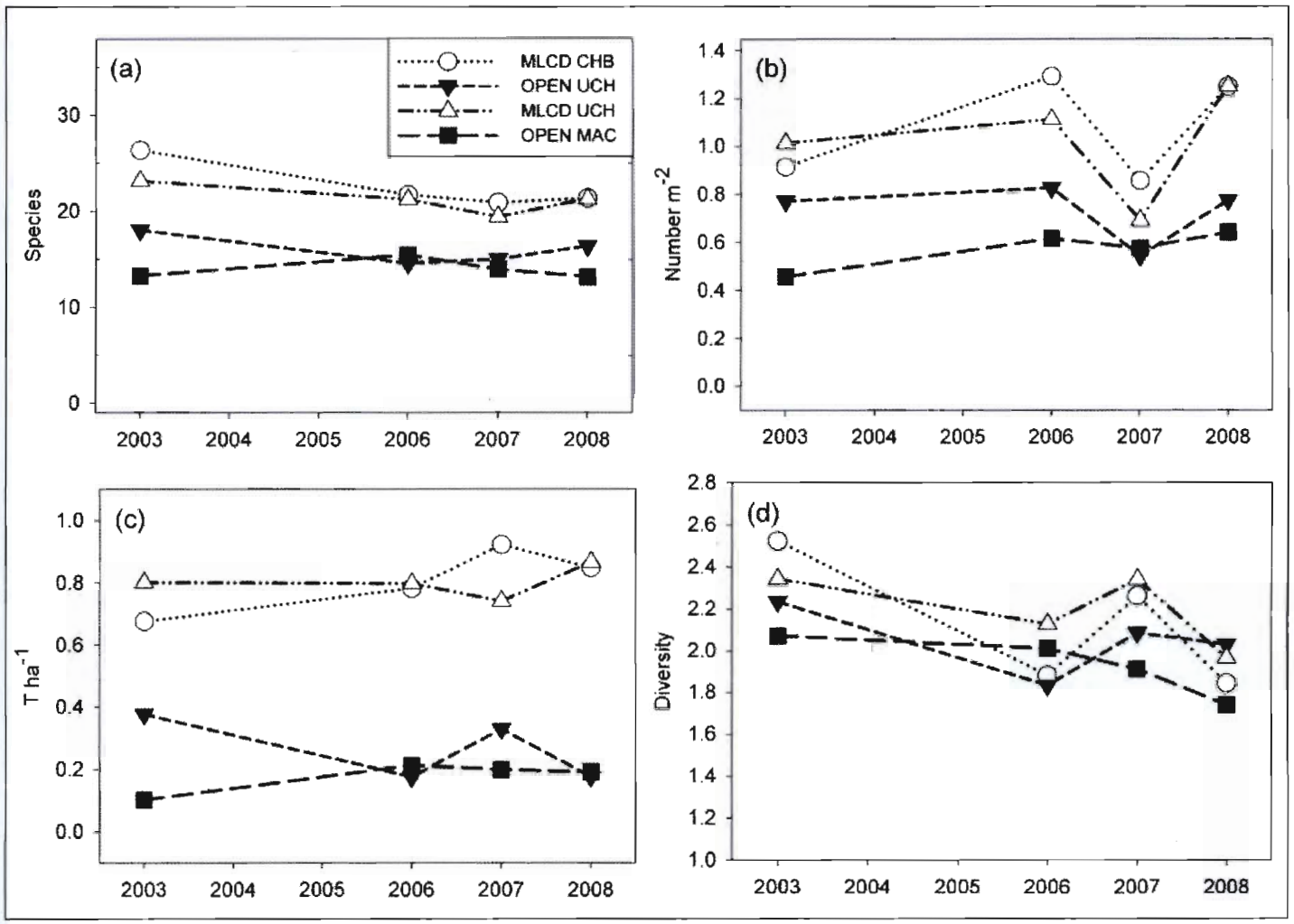

Figure 56. Temporal change in fish assemblages at Pupukea MLCD and surrounding areas by habitat type from 2003-2008. (a) Species Richness (b) Numerical Abundance (c) Biomass (d) Diversity.

Average number of individuals m² in the MLCD ranged from 0.75 (± 0.45) in 2007 to 1.18 (± 0.53) in 2006 (Figure 57). The highest average number of individuals per m² in the open area was recorded in 2006 ($\bar{x}$ = 0.73 ± 0.43) and the lowest occurred in 2007 ($\bar{x}$ = 0.56 ± 0.39). Average number of individuals increased by 0.28 m^{-2} (± 0.62) in the MLCD and 0.08 (± 0.52) in the open area between 2003 and 2008 (Figure 58). The lowest overall numerical abundance was observed in the open MAC ($\bar{x}$ = 0.57 ± 0.08) and the highest was in the MLCD CHB ($\bar{x}$ = 1.08 ± 0.22). Trends were fairly consistent over time except for a large decrease across all habitat types in 2007 due to a reduced number of small planktivores during that year, primarily blackfin chromis and oval chromis (*Chromis ovalis*; Figure 56b).

Biomass (t ha^{-1}) in the MLCD ranged from 0.75 (± 0.54) in 2003 to 0.86 (± 0.62) in 2008 (Figure 59). In the open area, biomass was lowest in 2008 ($\bar{x}$ = 0.18 ± 0.18) and highest in 2007 ($\bar{x}$ = 0.27 ± 0.39). Between 2003 and 2008, biomass in the MLCD increased by 0.11 (± 0.57) but decreased in the open area (= 0.07 ± 0.40) during that same time period (Figure 60). Biomass was lowest in the open MAC ($\bar{x}$ = 0.18 ± 0.05) and highest in the MLCD CHB ($\bar{x}$ = 0.81 ± 0.10). Within the open area, biomass declined within UCH and varied little within MAC (Figure 56c). In the MLCD, the increase in biomass was most pronounced in CHB.

The highest diversity within the MLCD was observed in 2003 ($\bar{x}$ = 2.41 ± 0.40) and lowest in 2008 ($\bar{x}$ = 1.92 ± 0.48; Figure 61). In the open area, diversity ranged from 1.90 (± 0.44) in 2008 to 2.16 (± 0.41) in 2003. Diversity decreased by 0.49 (± 0.45) in the MLCD and 0.26 (± 0.51) in the open area between 2003 and 2008 (Figure 62). Diversity declined sharply between 2003 and 2006 across all habitat types and management strata (Figure 56d).

Results

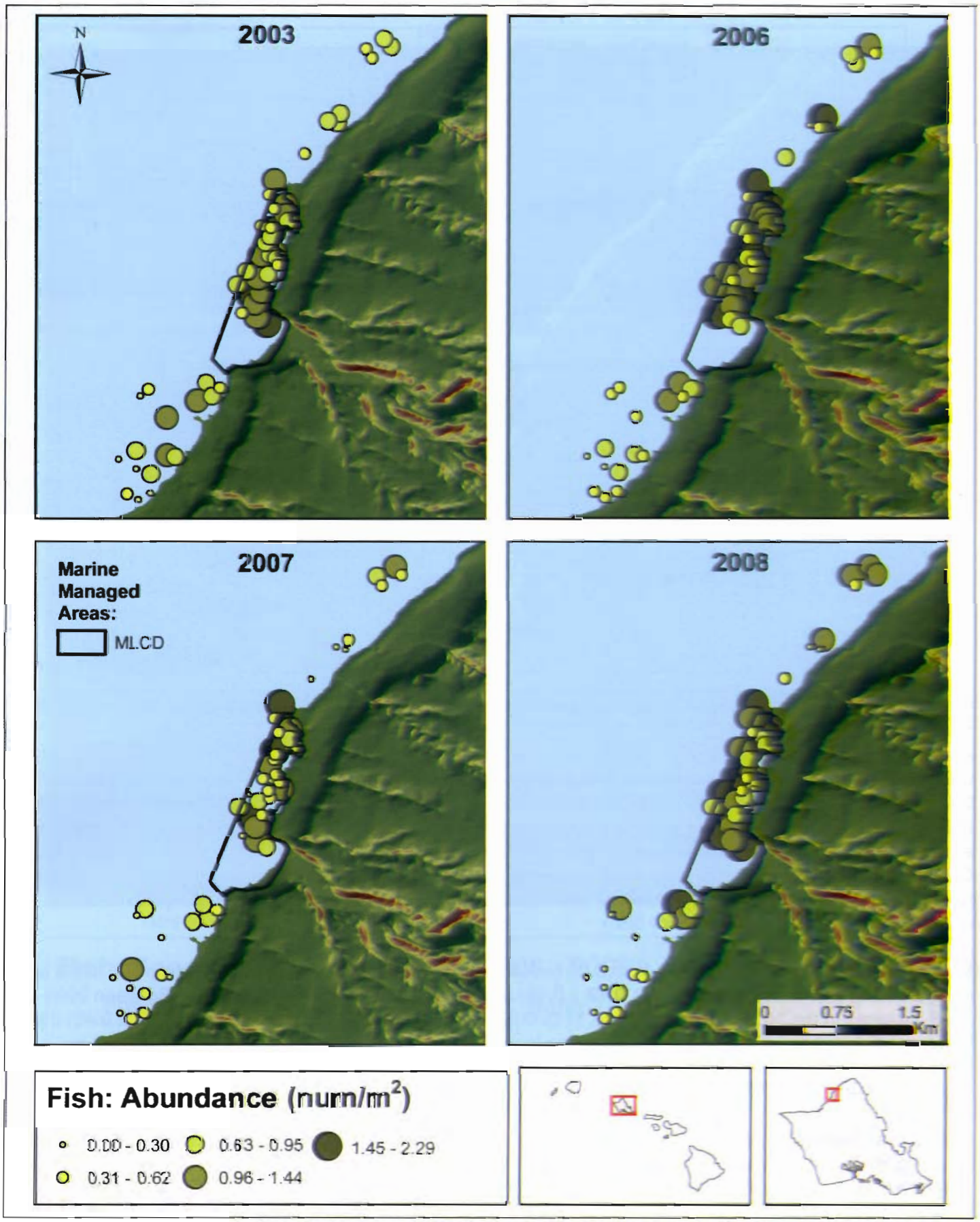

Figure 57. Fish abundance by individual transect for north shore Oahu study area including Pupukea from 2003-2008.

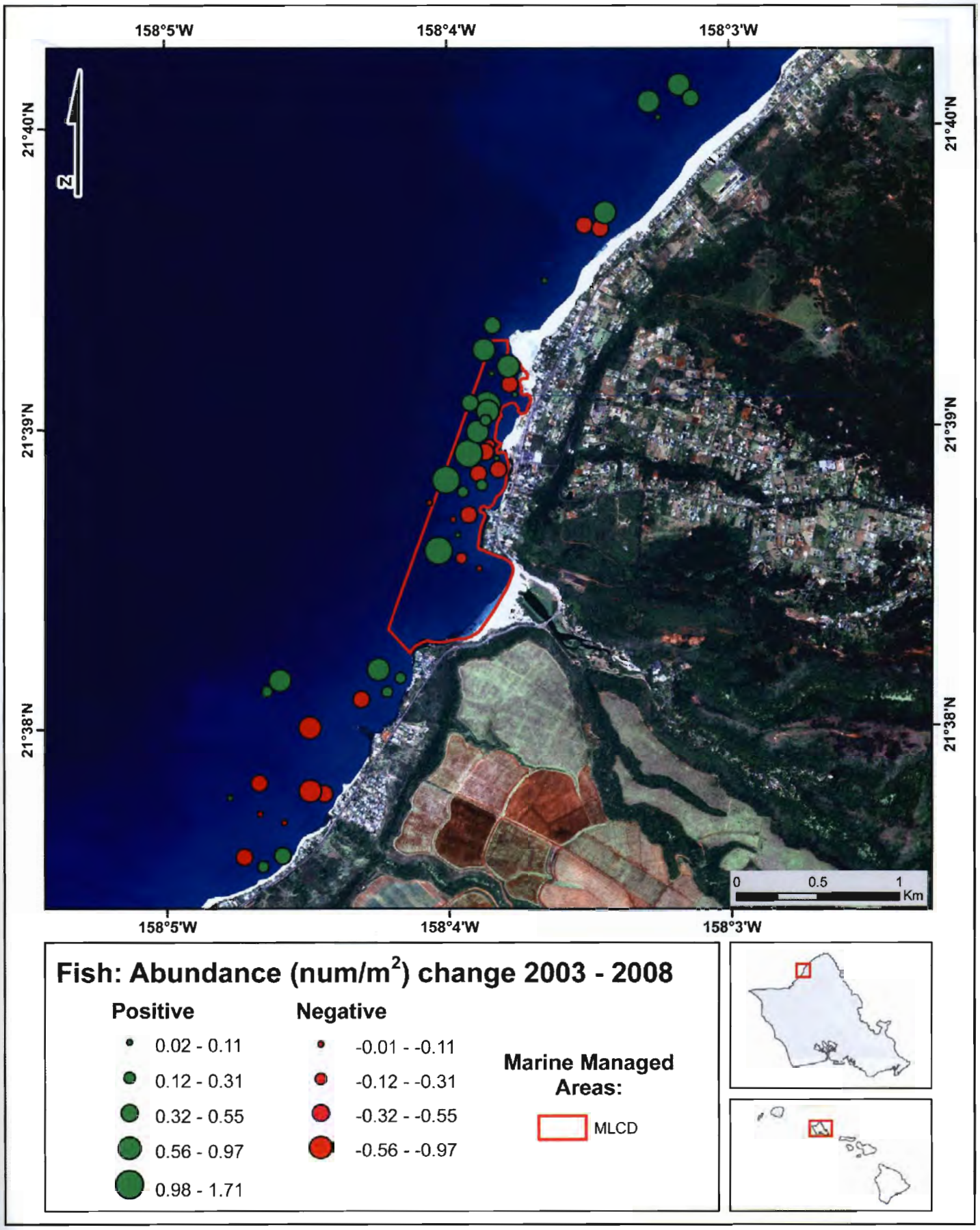

Figure 58. Change in fish abundance from 2003-2008 for the Pupukea MLCD and adjacent areas.

Results

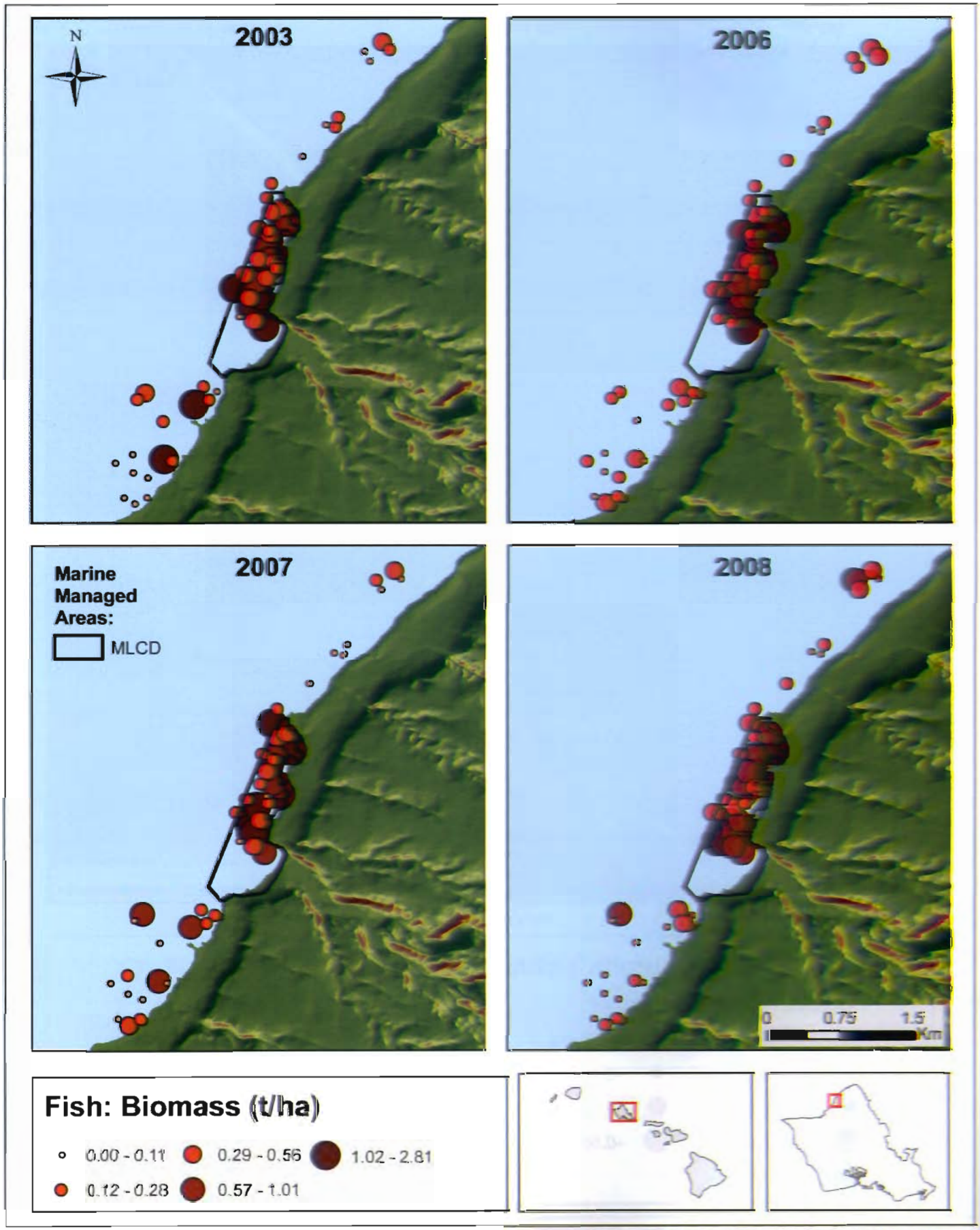

Figure 59. Fish biomass by individual transect for north shore Oahu study area including Pupukea from 2003-2008.

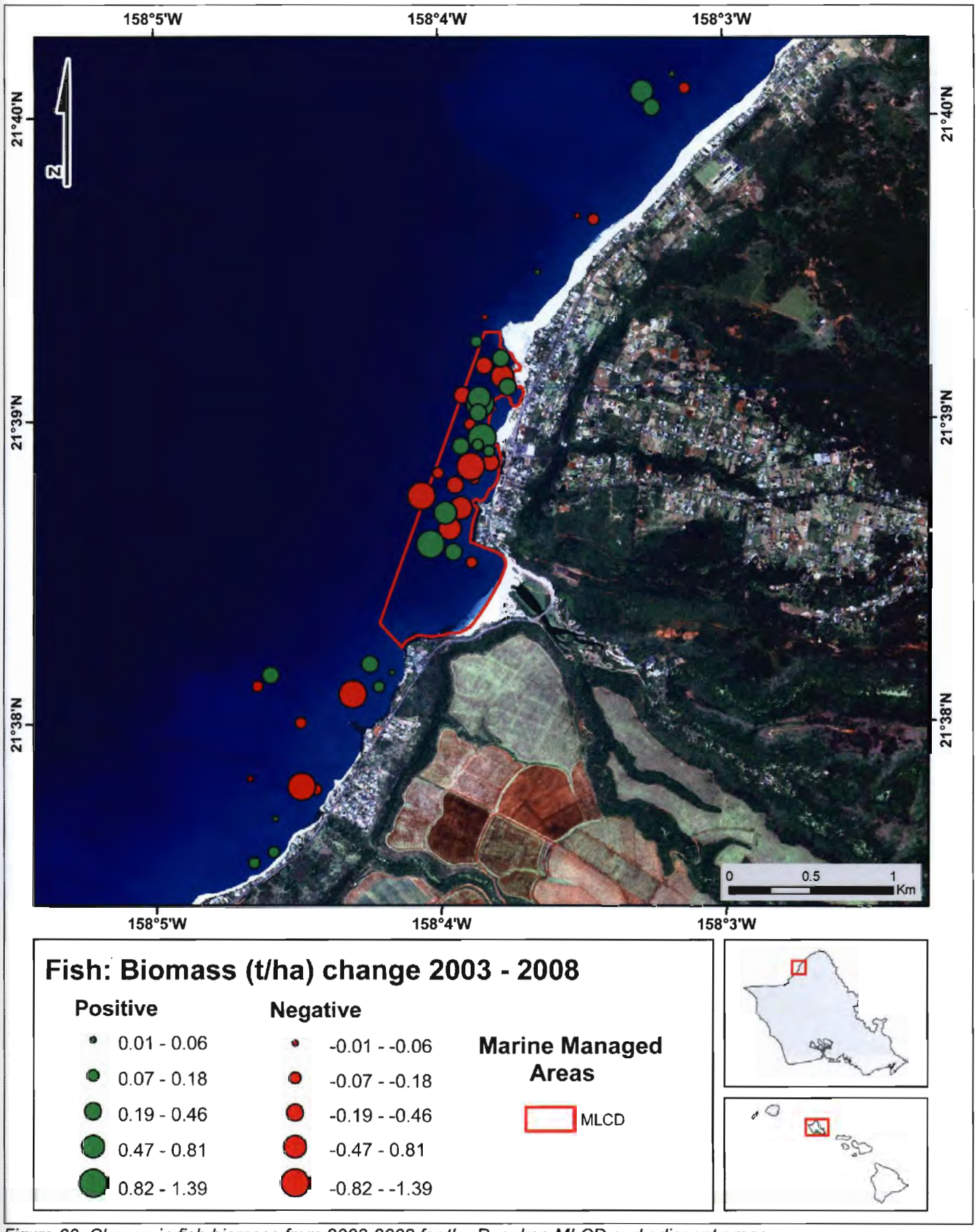

Figure 60. Change in fish biomass from 2003-2008 for the Pupukea MLCD and adjacent areas.

Results

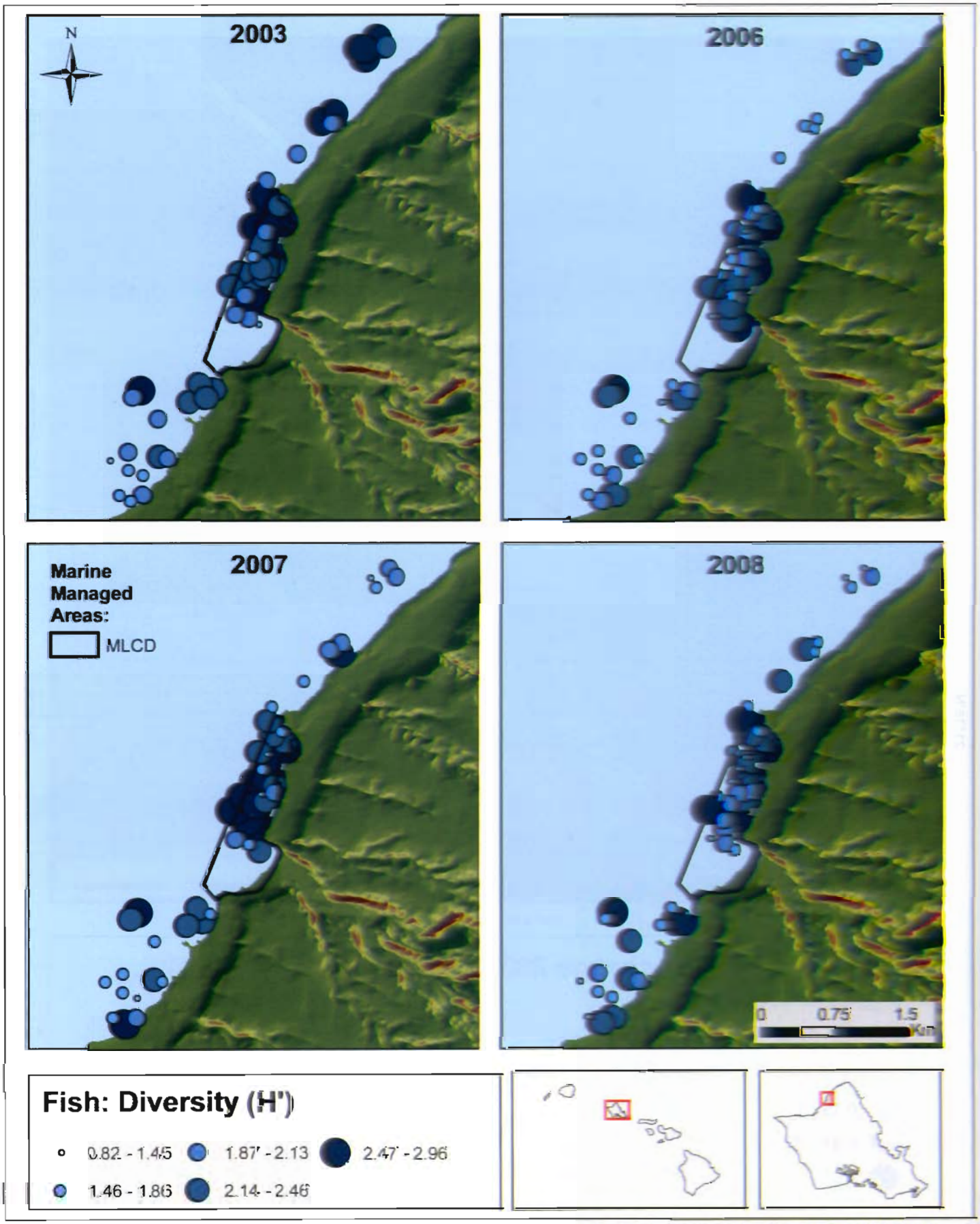

Figure 61. Fish diversity by individual transect for north shore Oahu study area including Pupukea from 2003-2008.

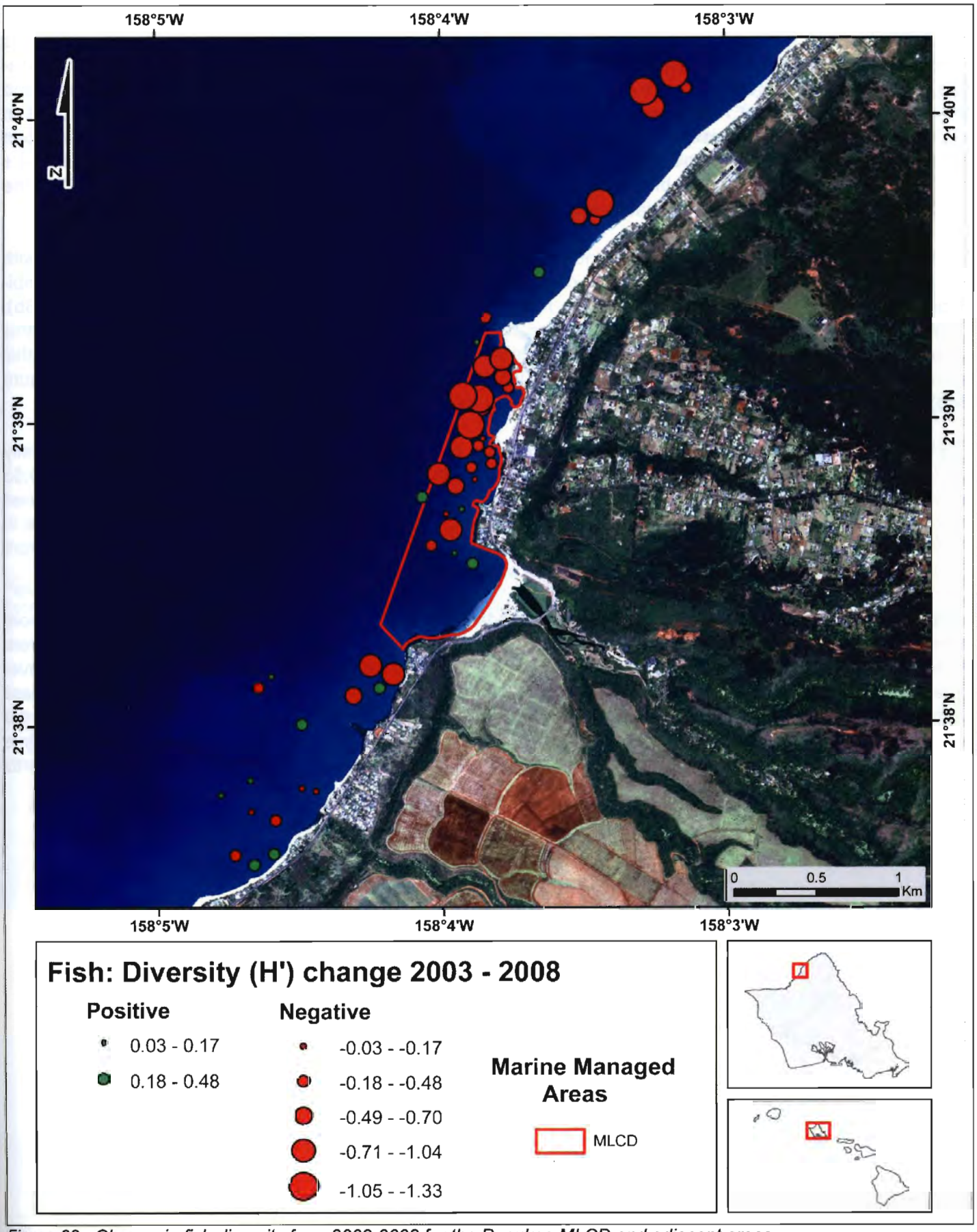

Figure 62. Change in fish diversity from 2003-2008 for the Pupukea MLCD and adjacent areas.

Results

Fish Trophic Structure Between Management Regimes and Among Habitats

Apex predators accounted for only 0.2% of the numerical abundance in Pupukea MLCD but were 3.3 times more abundance than in the adjacent open area where they accounted for 0.1% of the individuals in that location. Numbers of apex predators were low overall and varied greatly without trend among the management and habitat strata (Figure 63a). Apex predators accounted for 1.8% of the total biomass in the MLCD and 3.1% in the open area yet they comprised more than twice as much total biomass in the MLCD compared with the open area. Apex predator biomass was similar in the MLCD Open UCH ($\bar{x}$ = 0.014 ± 0.050) and CHB ($\bar{x}$ = 0.014 ± 0.028) habitats with slightly lower biomass in the open UCH ($\bar{x}$ = 0.012 ± 0.062). High biomass in 2007 in the MLCD and UCH habitats was associated with bluefin trevally (*Caranx melampygus*; Figure 64a).

Benthic carnivores comprised 30% of the numerical abundance in the MLCD and 48% in the open area with densities nearly equal. Numbers of benthic carnivores were similar among habitat and management combinations. Abundance declined across all strata from 2006 to 2007 but increased again in 2008 (Figure 63b). Benthic carnivores comprised 24% of the biomass in the MLCD and 43% in the open area. Biomass of benthic carnivores was nearly twice as high in the MLCD compared to the open area. The highest biomass of benthic carnivores was observed in the MLCD UCH ($\bar{x}$ = 0.22 ± 0.22) and this trend was consistent over time (Figure 64b). The other strata fluctuated without trend over the study period.

Planktivores accounted for 47% of the numerical density in the MLCD and 33% in the open area with density more than two times higher in the MLCD. Planktivore density was highest in the MLCD CHB habitat ($\bar{x}$ = 0.53 ± 0.52) and MLCD UCH ($\bar{x}$ = 0.46 ± 0.51) habitats. Abundance across all strata (except open MAC) declined from 2006 to 2007 but increased again in 2008 (Figure 63c). Planktivores comprised 5% of the biomass in the MLCD and 6% in the open area although biomass was nearly three times higher in the MLCD. Planktivore biomass varied without trend among management and habitat strata (Figure 64c).

Herbivores accounted for 23% of total numerical abundance in the MLCD and 19% in the open area. Herbivore biomass was more than two times higher in the MLCD compared to the open area. The highest densities were in the MLCD CHB ($\bar{x}$ = 0.26 ± 0.12) and UCH ($\bar{x}$ = 0.23 ± 0.18) habitats and showed modest declines over time (Figure 63d). Herbivores comprised 70% of the biomass in the MLCD and had five times greater biomass than the open area where herbivores accounted for 48% of the biomass. The highest densities were in the MLCD CHB ($\bar{x}$ = 0.63 ± 0.55) and UCH ($\bar{x}$ = 0.52 ± 0.52) habitats and showed a modest increase over time (Figure 64d). Most of this increase was due to the increase in number and size of the ember parrotfish (*Scarus rubroviolaceus*).

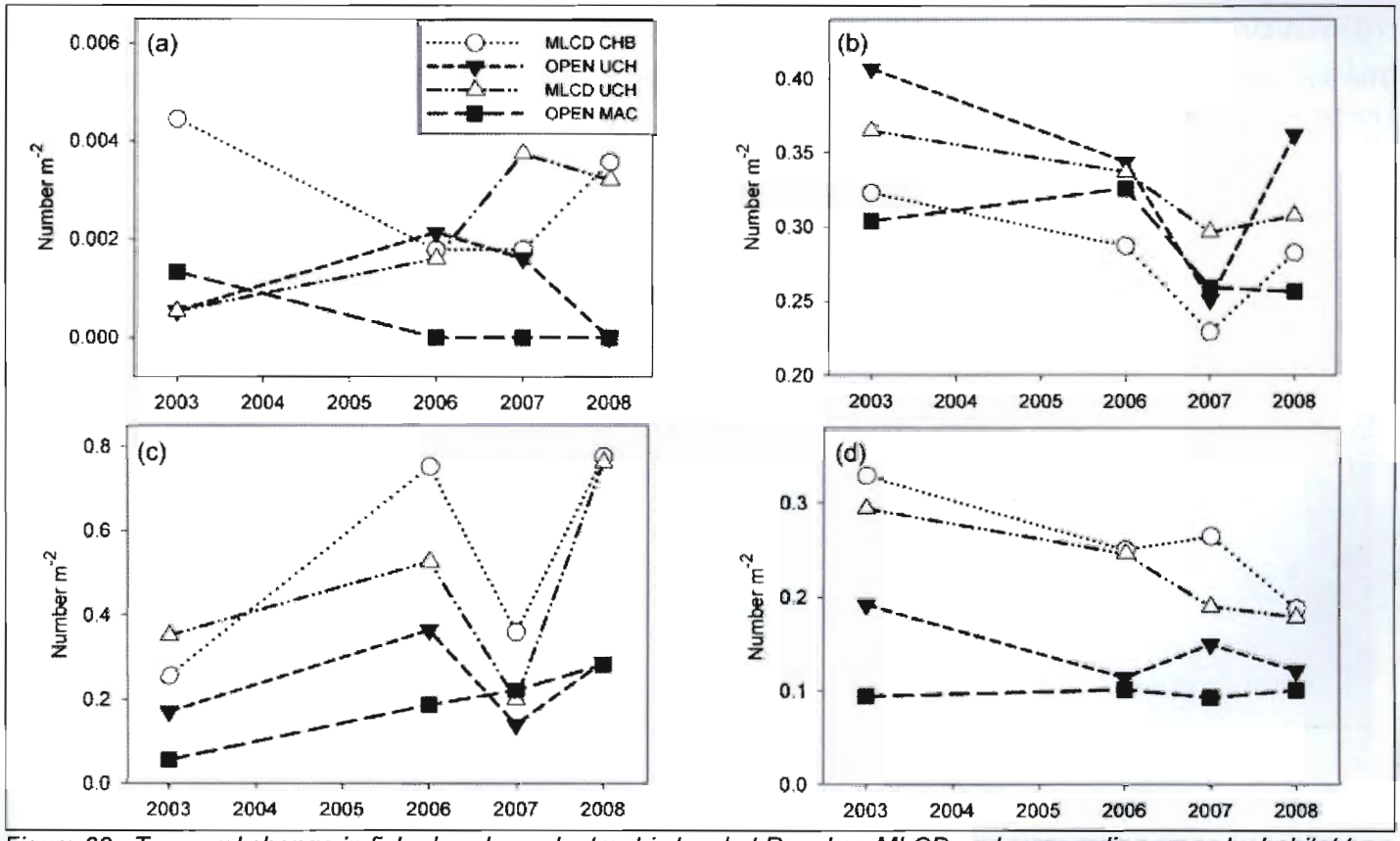

Figure 63. Temporal change in fish abundance by trophic level at Pupukea MLCD and surrounding areas by habitat type from 2004-2008. (a) Apex predators (b) Benthic invertivores (c) Planktivores (d) Herbivores.

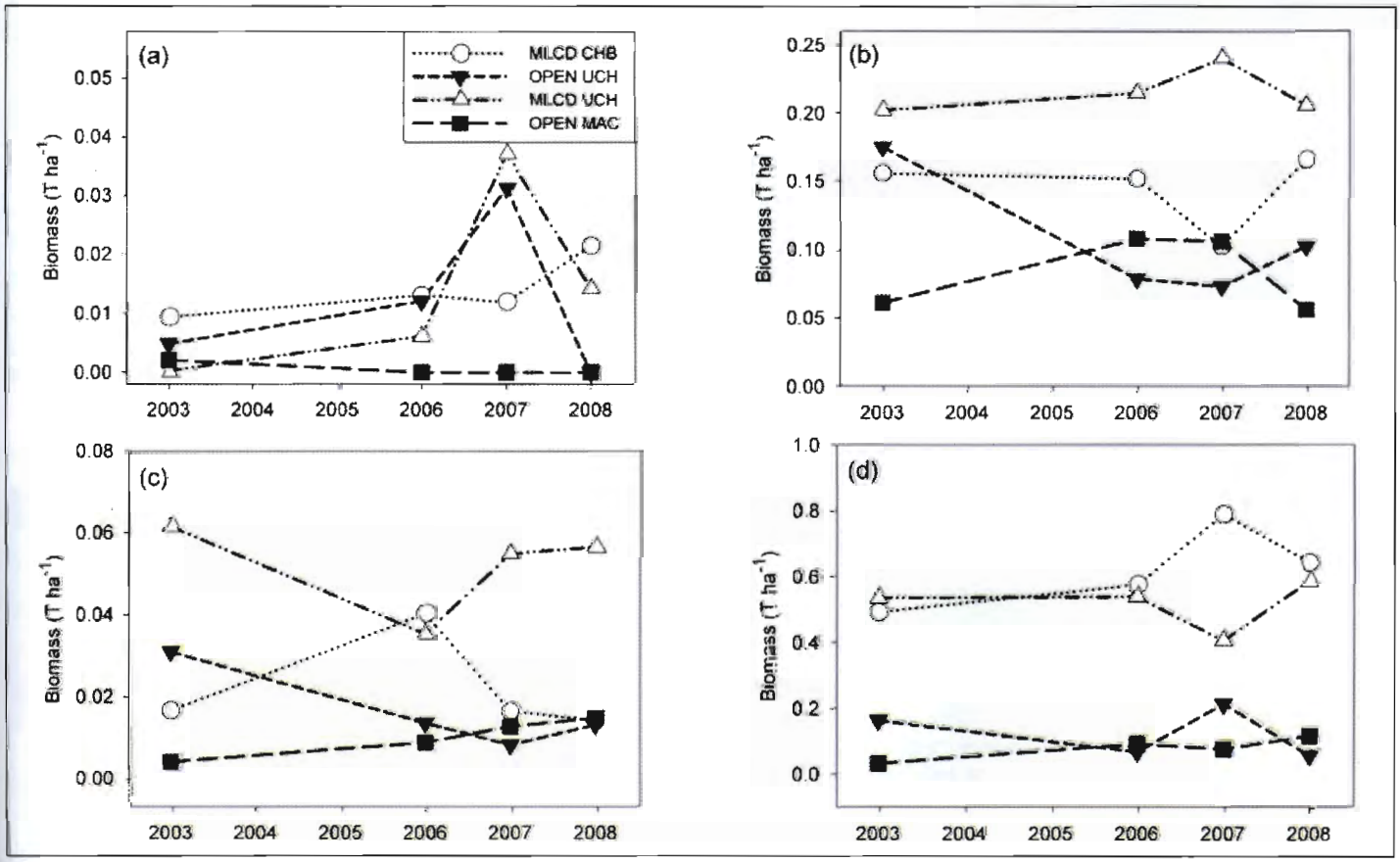

Figure 64. Temporal change in fish biomass by trophic level at Pupukea MLCD and surrounding areas by habitat type from 2004-2008. (a) Apex predators (b) Benthic invertivores (c) Planktivores (d) Herbivores.

Discussion

Photo courtesy of Keoki Stender, www.marinelifephotography.com

Discussion

The focus of this study was to 1) develop and implement a monitoring program of living marine resources (e.g., fishes, corals and other invertebrates, algae) within and adjacent to four representative MLCDs in Hawaii, 2) quantify the seascape using remotely sensed data to characterize the protected areas at a broader spatial scale, and 3) organize all of the associated spatial data sets in a GIS to better understand spatially-explicit ecosystem processes at the scale of the seascape.

Benthic Habitats

General benthic habitat types were similar inside and outside MLCDs (Friedlander et al. 2007b) although coral cover tended to be higher inside. Therefore, the focus of this study was to examine trends over time in each of these management regimes. The trends over time tended to be consistent with the level of protection (e.g. MLCD).

Coral species richness and coral cover were greater inside the Hanauma, Pupukea and Honolua-Mokuleia Bay MLCDs compared to adjacent open areas and the rank order in these metrics among these MLCDs did not change over the study period (Figure 114). Coral cover generally increased over time inside Hanauma, Pupukea and Honolua-Mokuleia Bay MLCDs and did not change within Kealakekua MLCD. These results highlight the benefits of protection from fishing to benthic communities.

Figure 114. MLCDs in Hawaii show a diverse mosaic of habitats such as this shallow, coral rich area. Photo: K. Stender, www.marinelifephotography.com

Macroalgae cover was generally greater outside the MLCDs and increased over time, particularly adjacent to the Hanauma Bay MLCD (Maunalua Bay, Oahu), Honolua Bay MLCD (west Maui) and Kealakekua Bay MLCD (south Kona, Hawaii Island). Areas adjacent to the Hanauma, Honolua and Kealakekua MLCDs all have varying degrees of human population and runoff associated with stream beds or freshwater springs that may facilitate increased macroalgae growth.

Seascape Metrics

Seascape metrics derived from NOAA benthic habitat maps were used to characterize the MLCDs. The NOAA benthic habitat maps released in 2007 were improved to include a hierarchical classification scheme and allowed for the quantification of seascape metrics based on zone, geomorphic structure, and biological cover classes. The seascape metrics used to characterize the MLCDs included: Shannon's habitat diversity and evenness indices, patch fractal dimensions, MLCD perimeter and area, and MLCD perimeter/area ratio. An increase in the area of the Pupukea MLCD from 0.11 km^2 in 1983 to 0.71 km^2 in 2003, due to changes in regulations, resulted in a broader diversity of habitats within the new reserve boundaries. Sand habitat was absent from the 1983 protected area and the geomorphic structure within the new boundary was characterized by large sand habitats adjacent to rock/boulder habitats. The inclusion of these sand habitats within the reserve provides a corridor between hard bottom habitats for mobile organisms and also provides important feeding habitats for a number of organisms. In addition, fish and other mobile organisms that transit these sandy habitats benefit from the protection from fishing that was not provided in the older boundary configuration. Hanauma Bay and Kealakekua Bay MLCDs had small perimeter to area ratios (P/A), which are preferable for marine reserve design since fish and mobile invertebrates are less likely to spill over into open access areas

where they are vulnerable to fishing pressure. This small P/A ratio also increases the core area within the protected area and reduces the amount of boundary perimeter that is available for fishing.

Several LiDAR-derived seascape metrics (e.g., depth, rugosity and slope) were quantified for each MLCD to better characterize the seascape within each protected area. In order for fisheries enhancement goals to be reached, marine protected areas should protect a range of structural complexities and habitat types in (Sladek-Nowlis and Friedlander, 2004). The Kealakekua Bay MLCD showed the highest overall seascape diversity among all protected areas. Hanauma Bay and Honolua-Mokuleia Bay MLCDs demonstrated comparable seascape-level diversity. Biological cover within the 1983 Pupukea MLCD was dominated mostly by macroalgae and turf algae in a shallow depth range, but following boundary expansion, biological cover showed a more representative diversity of cover types. Further, the boundary was expanded to included deeper habitats that were less impacted by wave disturbance, particularity during the winter months, and as a result the new boundary now protects approximately 8.5 hectares of coral habitat (10-50% coral cover) that was not included in the older design. With the inclusion of coral habitats, a greater depth range, and a broader diversity of habitats in the reserve, there was a greater diversity and biomass of fishes protected within this new reserve area (see discussion below). The application of landscape pattern analysis used in this study represents an effective way for scientists and resource managers to evaluate potential or current protected area design scenarios in the marine environment at spatial scales that are appropriate for conservation.

Fish Assemblages

Rank order of MLCDs for various fish assemblage characteristic (species richness, numerical abundance, biomass, and diversity) remained the same between the 2002-2004 sampling period and the 2006-2008 sampling period. Species richness and diversity did not change appreciably in any of the MLCDs over the monitoring period. Numerical abundance was highly variable and fluctuated without pattern among MLCDs and areas open to fishing.

Figure 115. Protected areas in Hawaii harbor large apex predators, like this jack. Photo: K. Stender, www.marinelifephotography.com

Biomass increased in three of the four MLCDs from the initial sampling period. There was a 14% increase in Pupukea, a 7% increase Kealakekua, and a 5% increase in Honolua Bay. Biomass within the Hanauma Bay MLCD declined by 5% during this same period. Hanauma Bay has been fully protected since 1967 and the small decline in biomass over the monitoring period is not statistically significant and is within the margin of sampling variability. Although overall biomass declined slightly, apex predator biomass in the Hanauma Bay MLCD increased as a result of increasing numbers and sizes of bluefin trevally jacks (omilu, *Caranx melamypgus;* Figure 115). A similar increase in apex predator biomass was observed in the Honolua Bay MLCD over the same time period. Herbivore biomass increased by 17% within the Pupukea MLCD and this increase was driven mainly by large parrotfishes that are prized fisheries species and likely responded to the increased protection provided by the expansion of the protected area in 2003. The significant increase in apex predator biomass within the Pupukea MLCD is also likely a result of the increase in protected area size.

Biomass declined by 39% outside the Pupukea MLCD and may reflect increased fishing pressure outside the MLCD over time. Biomass outside the Hanauma Bay MLCD increased by 32% although the absolute increase (+0.05 t ha^{-1}) was small. Because biomass was so low in this area, the presence of a few schools of larger fishes resulted in the large relative increase in biomass although the absolute biomass was still extremely low.

Management Implications

Combining seascape-scale habitat stratification with *in situ* ecological data allowed for the development of a statistically robust monitoring program of living marine resources (e.g., fishes, corals and other invertebrates, algae) within and adjacent to four representative MLCDs of marine protected areas in Hawaii. The results clearly show that areas with good habitat quality and management conserve fish populations and benthic communities within their boundaries while areas without protection are in poorer ecological health and continue to decline over time. The consistency of these patterns over time support the findings of the initial assessment conducted by Friedlander and colleagues (Friedlander et al. 2006, 2007a, 2007b) and increase confidence in the effectiveness of marine protected areas as a management tool for the conservation of nearshore marine resources in Hawaii.

Marine protected areas are spatially discrete forms of management and georeferenced data on seascape metrics can be integrated within a spatial framework to ensure MPA design scenarios are incorporating an appropriate range in depth, habitat complexity, and an interconnected mosaic of benthic habitat types. In this study, remotely sensed data allowed for the examination of MLCDs at spatial scales that are appropriate for management and provided valuable information on seascape metrics (e.g. rugosity, slope, depth, habitat type). Using a seascape approach controlled for differences in habitat by utilizing the NOAA benthic habitat maps and supported the development of a robust, spatially explicit monitoring program. This approach allows for the identification of spatial and temporal trends across the seascape to be highlighted and supports subsequent spatial planning and management actions. The findings from this study greatly contribute to the understanding of marine protected area design and function in Hawaii and are imperative to the development of comprehensive coastal and marine spatial planning.

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Photo courtesy of Keoki Stender, www.marinelifephotography.com

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