EVALUATION OF NEARSHORE CORAL REEF CONDITION AND IDENTIFICATION OF INDICATORS IN THE MAIN HAWAIIAN ISLANDS

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We certify that we have read this dissertation and that, in our opinion, it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Geography.

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ABSTRACT

The primary objective of this research is to identify indicators that can accurately predict decline in the condition of Hawaiian coral reef communities and aid in the assessment of identification of the forcing functions involved. This large-scale assessment, including all eight islands, covers the greatest spatial scale in the Main Hawaiian Islands to date. The major results of this research include the development of an extensive baseline database for future research and comparisons, the description of Hawaiian coral reef communities on a large scale, and the identification of key factors influential in explaining spatial patterns of biotic populations and their linkages to impaired conditions.

Although it was determined that no single factor had a correlation strong enough to substitute as a direct measure of coral cover, a combination of both natural (topographic relief, depth and wave energy) and anthropogenic (human population and stream distance) factors are most influential in explaining the variability in coral community structure.

A similar pattern exists for fishes, where both natural (topographic relief, coral diversity, coralline algae, precipitation, and latitude) and anthropogenic (human population and organics) variables heavily influence fish communities. With substrate rugosity most highly correlated with fish population parameters, identifying areas of high spatial complexity can provide a simple measure to assist managers in designing and implementing marine reserves and proposing fishing regulations.

Sediment composition and grain-size can be indicators of environmental stress. Although wave energy is the most important factor in structuring Hawaiian coral reef communities, when fine sediment overwhelms the system it becomes the dominant forcing function on community structure.

A statistical model was developed and tested to rank reef condition.

TABLE OF CONTENTS

Page

Page

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

LIST OF APPENDICES

Appendix Page

CHAPTER 1 INTRODUCTION

A recent international report estimates that 27% of the coral reefs worldwide are irreparably impaired with an additional 14% decline projected in the near future (IUCN 2002). Currently, over 60% of the world's population resides within 100 km of the coastline. A further population increase in the coastal region of 25% is expected by the year 2020 (Global Environment Outlook 3 2002). This population expansion, with its associated increase in activity and impact in marine environments, will place increasing pressure on coral reef communities; and coral reefs are known to be vulnerable to coastal land use practices and over-exploitation of marine resources (UNESCO 1985).

For example, the coral reefs in the Main Hawaiian Islands (MHI) have experienced anthropogenic impacts related to an increase in population and tourism (Gulko 1998). Yet, it is extremely difficult to estimate the extent of environmental damage, the rates of biotic decline, and the consequences of impacts on resources. Due to extremely high variability, complex interactions and non-comparable data, Hawai‘i's coral reefs have not been thoroughly evaluated on a statewide scale. The Coral Reef Assessment and Monitoring Program (CRAMP) and the Rapid Assessment Technique (RAT) project are evaluating both temporal changes and spatial differences on this large scale. CRAMP monitoring in Hawai‘i which began in 1998, will continue to assess changes over time in coral reefs.

1.1 Objectives

The primary objective of this research is as follows:

- To identify biological and physical factors that accurately describe the condition of Hawaiian coral reef communities with respect to natural and anthropogenic forcing functions.

To meet these objectives, it is necessary to identify relevant criteria for classifying Hawaiian coral reef ecotypes, establish and define reference standards for undisturbed sites and determine how different components of the community respond to various impacts. The major goals of this research are as follows:

- To describe spatial variation in Hawaiian coral reef communities in relation to natural and anthropogenic factors.
- To describe "natural habitat" criteria and establish baseline data for reference sites.
- To identify reference sites for each habitat class to be used as standards against which impacted regions can be evaluated and anthropogenic effects determined.
- To identify specific factors, groups of factors, indicator species or assemblages of organisms that can provide early warning signs of coral reef decline.
- To develop a statistical model to predict biological community condition. A first approximation is based on physical

variables that stratify biological populations (wave regime and depth). Further model refinement will be based on biological and environmental factors subsequently measured at each site. Such a model will allow prediction of reef condition at sites not previously visited and serves as a valid test of the model's predictive ability.

1.2 Hypotheses

Under pristine conditions, a range of values can be determined for parameters such as fish abundance, diversity and coral cover. Significant departure from these values would signal environmental problems. Relatively few variables can be used to define the community. The following hypotheses will be evaluated in this project:

1. For biological parameters, quantitative measures of only three groups of reef organisms (coral, macroalgae and reef fish) are sufficient to define the condition of Hawaiian coral reefs.
2. For habitat-scale physical parameters, the five quantitative measures of substrate, rugosity, depth, wave regime and bulk sediment deposit composition can define Hawaiian coral reef condition.
3. At a local scale, factors such as distance to perennial streams and proximity of human population are sufficient to define the condition of Hawaiian coral reefs.

4. The degree of impact from anthropogenic activity can be quantified by the degree of alteration of key environmental parameters of coral reef communities from their natural states.
5. The degree of over-fishing for specific coral reef communities can be determined through comparison of abundance and biomass data for select fish species.

1.3 Impacts to Coral Reefs

Both natural (Stoddart 1963, 1965; Highsmith et al. 1980; Grigg 1998) and anthropogenic (Smith et al. 1973; Stoddart 1981; UNESCO 1985; Tilmant 1987; Glenn and Doty 1989; Hatcher 1989; Eldredge 1994; Laws and Allen 1996) threats to coral reefs have been well-documented. These threats are discussed briefly below.

1.3.1 Rate of Disturbance

Coral reefs may be subjected to chronic prolonged perturbations (e.g., overfishing, sewage) or acute (e.g., hurricanes, anchor damage) disturbances which may be seasonal or temporary. Recovery is more difficult with chronic events where phase shifts may occur (Bertness et al. 2001). Environmental characteristics that interact to influence the severity of the impact include life history (susceptibility, size, shape, physiology), disturbance (intensity, duration, frequency and prior impact) and benthic parameters (type, substrate).

Disturbance can influence rates of succession, recovery, competition, longevity, growth, recruitment and settlement. On a larger community level, impacts can promote phase shifts, alien invasions, alterations of the environment or resource availability (Bertness et al. 2001).

1.3.2 Scale of Disturbance

Many of the factors influencing coral reef community structure have not been examined on large spatial scales greater than a few kilometers. Complex interactions and synergistic effects make it difficult to separate the impact of many different environmental factors. Analysis and interpretation of large datasets combining both biotic and abiotic factors can be extremely challenging. This research attempts to examine biotic and abiotic factors and link them to natural and anthropogenic impacts on a statewide spatial scale (600 km).

1.3.3 Natural Disturbance

Coral reef community structure is primarily controlled by natural forces (Highsmith et al. 1980). Natural forcing functions that can adversely affect reef ecosystems include climatic changes such as El Ninõ and global warming. Even slightly elevated temperatures of 1 to 2^{o}C above summer ambient temperatures induce coral bleaching. Subsequent coral mortality will occur if ambient temperatures are not restored (Coles and Jokiel 1977, 1978; Jokiel and Guinther 1978; Coles 1985).

Catastrophic, stochastic events, although rare, can produce highly influential forces on coral reefs (Stoddard 1963, 1965). These random, abiotic interactions can be as important as deterministic stresses. Their low frequency of occurrence makes predictability difficult. The sudden nature of events such as hurricanes, tsunamis and floods prevents avoidance responses or adaptive strategies (Jeffery 1990).

Other natural sources of impact include waves (Dollar 1982; Grigg 1983), disease (Peters 1997), volcanoes (Grigg and Maragos 1974) and predator population explosions (Mack and D'Antonio 1998).

Cumulative and synergistic effects from interacting stresses can combine to create devastating impacts on the system (Eakins et al. 1997).

1.3.4 Anthropogenic Disturbance

Grigg (1998) determined wave exposure to be the major forcing function on Hawaiian reefs. Where limited wave exposure exists, such as in protected shorelines, harbors, lagoons and bays, anthropogenic impacts can dominate (Grigg 1983). Extensive literature reviews of human impacts on coral reefs have been compiled (Stoddart 1981; UNESCO 1985; Tilmant 1987; Hatcher 1989).

The magnitude of anthropogenic impact along with their rates of change have greatly accelerated on both a temporal and spatial scale (Bjornstad and Grenfell 2001).

Pollution

Under both laboratory and field conditions, coral reefs can be affected negatively by thermal pollution (Coles and Jokiel 1977, 1978; Jokiel and Guinther 1978; Hudson 1981; Coles 1985), sewage pollutants (Smith et al. 1973; Hunter and Evans 1995; Laws and Allen 1996; Larned 1998), and oil pollution (Hatcher et al. 1989).

Trampling

A global increase in tourism has been associated with damaging effects to reefs from physical human contact (Woodland and Hooper 1977; Liddle and Kay 1987; Brosnan and Crumrine 1994; Brown and Taylor 1999; Rodgers 2001) and anchor damage from recreational vessels (UNESCO 1985).

Overfishing

An expansion of commercial and recreational fisheries with more effective and efficient methods has led to worldwide over-fishing (Friedlander and DeMartini 2002). Nearly 70% of fish stocks are considered to be below sustainable levels (Food and Agriculture Organization 1998). Both pelagic and coastal fish abundance have experienced extensive declines on a global scale.

Fishing pressure has also caused severe depletion of fish stocks on a local scale. In the MHI, overfishing has been documented as the main cause of decline (Shomura 1987). Many coastal fish populations have decreased to levels below the ability to replenish themselves (Friedlander and DeMartini 2002).

Coral and fish assemblages are highly correlated (Friedlander et al. 2003). High fish abundance is associated with complex reef systems. Coral communities are also structured by fish assemblages. In undisturbed reef ecosystems dominated by corals, herbivorous grazers remove the majority of algae (Carpenter 1986). However, in overfished regions, phase shifts to algal dominated reefs can result in reduced diversity and structural degradation. Corals can be overgrown by direct removal of herbivores, that limit algal growth, or indirectly through depletion of piscivorous fishes that restrict herbivorous populations (Conklin and Stimson 2004).

Sedimentation

Sedimentation of coral reefs is another major threat to the near-shore environment (Johannes 1975; Rogers 1990). Both natural and anthropogenic processes influence sediment loading in the ocean.

Although sediment loading has occurred throughout geologic time, it has been greatly accelerated by recent human activity. Reduction in vegetative cover is the primary cause of increased terrestrial erosion. Grazing animals, clearing of forests, poor agricultural practices, shoreline and inland construction, dredging, and mining can influence the biological integrity of coral reefs.

A shift in community structure can occur with increased stress from sedimentation. The dominant coral-algae-invertebrate associations can rapidly change to a benthic environment dominated by algae, filter feeders, and detritivores, such as sponges and worms that normally inhabit mud bottoms (Dollar 1979; Maragos et al. 1985).

Historical Research

Historical research has recognized sediment as a threat to coral reefs as early as the 1800s (Ehrenberg 1834). Charles Darwin in 1850 described sedimented regions with decreased coral coverage (Darwin 1842). Laboratory and field experimentation in the early 1900s confirmed prior observations correlating sedimentation with mortality of corals (Edmunson 1928). Continued, detailed studies revealed the sublethal effects of sedimentation. For example, the effects of sedimentation on coral growth, morphology and size were determined from early observations by Marshall and Orr (1931). More recent studies further established a link between sediment and coral development at all life stages (Grigg and Birkeland 1997; Te 2001). Sublethal effects of sedimentation include reduced reproductive output and lower recruitment rates (Birkeland 1977; Rogers 1990), lower accretion rates and decreased calcification (Randall and Birkeland 1978), morphological changes (Dustan 1975; Brown et al. 1986; Hubbard et al. 1987), metabolic changes (Rogers 1979; Edmunds and Davies 1989; Te 2001), behavioral alterations (Brown and Howard 1985; Rogers 1990), increases in pathological diseases (Brown and Howard 1985; Hodgson 1989), and increased bleaching attributed to loss of zooxanthellae (Brown and Howard 1985).

Recent research has also identified lethal and sub-lethal effects to corals from substances associated with sediment (Glynn et al. 1989). Associated organic and inorganic sediment substances can produce adverse secondary effects in corals. Even low levels of these toxins can dramatically affect coral physiological processes (Glynn et al. 1986).

Factors Affecting Coral Survivorship

Most coral have adapted to tolerate low levels of sedimentation. High wave energy regimes can flush sediment away from coral colonies. Some corals can move particles away from the colony using their tentacles. Others produce mucous to shed silt from their tissues. Still others are known to efficiently ingest sediment (Anthony 2000). Yet, large amounts of sediment can be debilitating to corals. Coral survival is affected by particle size, sediment type, intensity and duration of the event and sediment resuspension. Habitat location is a dominant influence in coral tolerance to sedimentation. Species of corals found near the coast have greater ability to remove particles than species found in deeper, less turbid waters; and species with smaller polyps are less capable in particle removal (Salvat 1987).

Other Disturbances

Other comprehensive human impact studies include research focusing on introduced species (Eldredge 1994; Laws and Allen 1996; Rodgers and Cox 1999), coastal development (Maragos 1993) and dredging (Brock et al. 1965; UNESCO 1985; Uchino 2004).

1.4 Indicators

To protect coral reefs, predictive indicators of decline must be established. Such an approach can detect impairments to biological integrity and evaluate severity (EPA Guidelines 2001).

Extensive and effective use of biological indicators in monitoring pollution in freshwater habitats has been well established (Green and Vascotto 1978; Lenet et al. 1988; Barbour et al. 1992; Rosenburg and Resh 1993). Many temperate marine environments have also developed biological indicators of stress (Faith 1990; Jones and Kaly 1996; Gibson et al. 1997). In contrast, there has been relatively little development of bioindicators of impact on coral reef ecosystems (Jameson et al. 1998).

Specific organisms have historically been used to assess levels of environmental quality in coral reefs, yet, due to the biological complexity of reef systems, few attributes have emerged as reliable indicators of overall reef condition (Karr and Chu 1999). To establish a quantitative index of coral reef condition for monitoring purposes, it is necessary to classify the various reef habitats, establish reference conditions for them and identify biological criteria for assessing impact.

Monitoring select biological organisms or assemblages of organisms can be used to integrate the effects of change to the environment; and this will allow detection of a range of impact from low to high levels of perturbation under sustained (chronic) or temporary (pulse) conditions. These organisms or biotic groupings respond to anthropogenic impacts, often reacting differently to natural variability and human activity. The responses of the biota to negative impacts can be detected through biological and habitat assessment, thus assisting in the identification of forcing functions on the community. In conjunction with habitat assessment, biocriteria can help identify possible causes of perturbation to the environment that water quality analyses can not detect.

1.4.1 Selection of Biological Factors to be Measured

Some attributes of stenoecious marine species, characterized by high sensitivity and narrow environmental tolerances, have been used to detect specific influences. For example:

- Benthic infauna and macroinvertebrates have been used successfully to assess environmental quality and sediment contamination (Lenat et al. 1980; Faith 1990; Rogers 1990; Rosenberg and Resh 1993; Erdman and Caldwell 1997).
- Tissue analysis and ecotoxicology research has revealed bioaccumulation of metals, pesticides, and other contaminants in both vertebrates and invertebrates (Ashanullah 1976; Hungpreng and Yuangthong 1984; deKock and Kramer 1994; Phillips 1994).
- Fish otolith examination provided a temporal record of exposure to toxic substances (Secor et al. 1995).

Neither single species laboratory tests nor the typical approach of conducting a battery of toxicity tests, can be predictably transferred to the ecosystem level where complex interactions prevent reliable interchange. Laboratory toxicity tests on single species may overstate effects, while opposite results have been demonstrated where toxins determined to be relatively safe in the lab have exhibited adverse effects on populations in the field (Kimball and Levin 1985).

1.4.2 Selection Criteria for Indicator Organisms

Organisms used as indicators of environmental stress must be able to provide a detectable early warning of deteriorating conditions. Indicators that respond to a wide range of impacts can be used in conjunction with diagnostic measures to determine overall levels of habitat stress. In addition, organisms with a particular sensitivity to a given stress can be useful indicators of specific stress mechanisms. In order to be useful, these indicators must respond consistently to stressors in the environment and exhibit quantifiable levels of variability.

Reef corals, reef fishes, and benthic algae are the bioindicators of choice in this work for defining the biological status of coral reef communities. These biota meet all the criteria described by Jameson et al. (1998) for dependable bioindicator organisms:

- Primary habitat forming organisms (corals and algae)
- Narrow environmental tolerances (corals)

- Respond to a variety of anthropogenic stressors (corals, algae, reef fishes)
- Sessile, benthic organisms that remain in place and are continually exposed to stress (corals and algae)
- Long-lived organisms that provide an integrated signal of prevailing stresses while large individuals can indicate excellent environmental condition (corals)
- Abundant throughout the assessment area (corals, algae, fishes)
- Organisms easy to sample objectively (corals, algae, fishes)
- Not subject to human exploitation (corals)
- Stable taxonomy (corals, fishes)
- Easily taught to non-specialists (corals, fishes)

An extensive review of indicators by Jameson and Kelty (2004) acknowledges the need for an integrated approach to diagnostic monitoring and assessment of coral reefs.

Characteristics indicative of a general response to environmental stress include declines in species abundance, species size, community diversity, shifts in dominance levels, and species composition (Loya 1976; Brown and Holley 1982; Dodge et al. 1982; Rogers et al. 1982; Bouchon 1983). A wide variety of other stressor, exposure, and response indicators have been used to identify specific and cumulative impacts (Table 1.1).

New potential assessment tools for use in marine environments have recently been introduced. On a cellular level, biomarkers such as heat shock proteins (Smith et al. 2004), antioxidant enzymes, and changes in gene expression (Brogdon et al. 2004) are currently being explored to identify stress in corals. Pulse amplitude modulation (PAM) has been tested with algae to detect environmental stress (Runcie 2002). Yet, many of these molecular techniques are cost restrictive and involve highly specialized skills.

Table 1.1 Biological and physical parameters used to determine impacts to marine environments

Biological Parameters	Determinant	References
Growth	Anthropogenic impacts	Birkeland et al. 1976; Hudson et al. 1982; Dodge 1983; Brown and Howard 1985
Size and/or age distribution	System stress	Grigg 1975; Bak and Meesters 1998; Birkeland 1998
Recruitment	Pollution	Rogers 1990
Community Shift	Pollution, Eutrophication	Rose and Risk 1985; Sammarco and Risk 1990; Holmes 1997
Introduced Species	Resource competition	Rodgers and Cox 1999
Bleaching	Thermal stress	Jokiel and Coles 1977; Bak 1978; Jaap 1979; Rogers 1979; Dustan 1979; Thompson et al. 1980; Neudecker 1983
Metabolic Changes	System stress	Coles and Jokiel 1977; Rogers 1979; Dallmeyer et al. 1982; Szmant-Froelich et al. 1983
Behavioral Responses	System stress	Lewis 1971; Bak and Elgershuizen 1976; Thompson et al. 1980; Dodge and Szmant-Froelich 1974
Physical Parameters	Determinant	References
Spatial Complexity	Population dynamics	Done 1981; Bak et al. 1982; Porter et al. 1982; Rogers et al. 1982
Wave Exposure	Population structure	Grigg 1983
Depth	Population dynamics	Conover 1968
Temperature	Thermal stress	Coles and Jokiel 1977, 1978

The next logical step is to test a suite of indicators that can be rapidly and easily quantified to see what influence each has on Hawaiian coral reefs.

1.5 Assessment Design

1.5.1 Conceptual Framework

An Index of Biotic Integrity (IBI) and a Hydrogeomorphic Model (HGM) have been widely used in freshwater systems to assess the condition of ecosystems, to assist in management decisions and policymaking (Smith et al. 1995, Karr and Chu 1999).

The IBI was developed for use in warm water streams in the U.S. Midwest in 1981 (Karr and Chu 1999). It uses a multimetric design that integrates attributes that respond to anthropogenic influence. Comparison of fish community characteristics to reference conditions result in a score of 1 to 5, with a score of one having the lowest biotic integrity. All organic attributes are included for each site. Scores for these attributes are then summed, culminating in a single, unitless, index value. Use of IBI as a measurement value grew rapidly, expanding to other regions and stream types. As its application grew, the basic design was retained, although the scoring and attributes varied in response to differing environmental conditions. The central premise of IBI involves environmental classification, attribute selection, methodological development, and statistical design.

The HGM approach, using function, geomorphic position, and hydrology to assess wetlands, recognizes the influence of hydrology and geomorphology on biology. It was developed by scientists at the US Army Corps of Engineers (Smith et al. 1995) to measure the ability of a wetland to perform critical functions. Its functional capacity index which estimates the operational ability of wetland processes, ranges from 0 to 1. It was originally developed to assist in permit review and mitigation, by identifying and assessing environmental impacts. HGM involves classification, function definition, and reference development. The general HGM principles are similar to the IBI approach. Both models initially develop an environmental classification scheme and depend on reference conditions to define system integrity. They differ in that HGM is based on functional rather than environmental classification and attributes are not solely biological.

Attempts are currently underway to extend these models to nearshore marine environments (Coral Reef Functional Assessment Workshop 2004). In an extensive literature review of coral reef assessments, Jameson et al. (1998) concluded that there is insufficient information to develop biocriteria guidelines for coral reefs. The complexity and diversity of Hawaiian coral reefs makes attribute selection and establishment of reference conditions difficult.

The following tasks are required to develop a model that can be applied to Hawaiian coral reefs and to test the above hypotheses:

1. Division of the ecosystem into habitat classes based on physical/biological characteristics.

2. Selection of multiple reference sites for each class.

3. Conduct field surveys at reference sites and at sites that range along a gradient of anthropogenic impact.

4. Use of biological data from surveys to determine if the habitat classes correctly reflect the biological communities of the reference sites.

   a. continued refinement until there is less variability within a class than between a class.

5. Integration of process and attribute measurements to assess status of biological condition.

6. Multimetric evaluation to identify potential parameters possessing ecological relevance and exhibiting a reliable relationship to anthropogenic influence.

   a. Isolation of individual parameters to determine effect on overall assessment and potential value to indicate causes.

   b. Identification of relationships among different species (i.e., those with informative distributions that systematically change along a disturbance gradient) and samples.

   c. Extrinsic Analyses to incorporate environmental and/or historical data for community analyses, and to compare with oceanic (wave energy) and terrestrial (watershed, population) factors.

   d. Environmental interpretation through ordination analyses.

7. Identification of environmental changes from reference conditions.

8. Model development through the evaluation of relevant parameters to distinguish among gradients of degradation.

9. Testing of model to determine predictive quality.

1.6 Relevant Applications

The development and testing of a multivariate statistical model to predict conditions at sites not previously surveyed will be valuable in establishing management priorities, regional policy and evaluation of existing programs in the Hawaiian Islands. Application of a model would allow management to implement a preventative approach to environmental degradation.

Baseline conditions for biological communities will be established. These data will provide a foundation for investigating spatial and temporal change and elucidate the need for protection of future designated marine protected areas and sanctuaries in Hawai‘i.

1.7 Biological Criteria and Integrity

IBI compares biological criteria in undisturbed streams to those in degraded streams to determine the deviation from original conditions (Karr and Chu 1999). To quantify this departure, establishment of reference conditions within each stream classification is necessary.

Biological criteria describe the conditions that should be present in a specific habitat, thereby providing standards to compare against assessment data. It encompasses a sequence of ambient conditions relative to the biological integrity within a particular geographic classification. Biological integrity is synonymous with natural, pristine conditions. This state is homologous with minimally or undisturbed environments which serve as reference sites. Assessment and monitoring data can be converted to biological indices and compared to biocriteria at these reference sites.

Impairment of the habitat can be evaluated based on its departure from the biocriteria. To develop biocriteria that describe the biological condition of a community, its structure and function is characterized by numeric or narrative values based on the assessment of the organisms present.

Selection of biocriteria should be based on the following attributes.

- Accommodate seasonality
- Quantifiable parameters
- Based on established scientific principles
- Defined as a range
- Representative of natural conditions
- Sensitive enough to identify marginally degraded areas
- Legally defensible

The biological integrity of a region reflects the ability of the community to maintain a balance of organisms and interactions under natural, unperturbed conditions. This integrity is compromised when components of the functional organization depart from original, pristine conditions. An accurate description of the community will include aspects of the system that respond to anthropogenic perturbations. Subsequent contrasts can then be made between comparable habitats.

1.8 <u>Classification</u>

Parallel to freshwater IBIs, a marine index would require environmental classification to address habitat differences that influence biological populations.

Biogeographical differences within the coral reef ecosystem occur on spatial, temporal, structural and functional levels. The heterogeneity of the biological condition makes habitat classification a critical first step to the development of bioindicators. Prior coral reef classification systems were based on geomorphological features, ignoring critical biogeographic communities.

Biogeographic classification groups similar ecological (algal ridge, seagrass beds), geomorphological (reef flat, fringing reef, reef slope), chemical (nutrients, salinity), and physical (depth, wave exposure) characteristics that are not dominated by anthropogenic disturbance. Presumably, each of these groups would have followed a similar pattern of ecological responses subsequent to human perturbation. For example, many marine organisms are stratified by depth and exposure. By dividing sites into groups based on these dominant natural forcing functions, much of the natural variability associated with the physical setting can be separated from the variability associated with anthropogenic influences.

Each system class would have its own specific reference conditions and biological criteria. It is also feasible to stratify classes by grouping differences in the biological community together using multivariate procedures. From a practical standpoint, the number of classes must be limited since each class must have several associated reference sites and a range of impaired sites. Attempting to classify systems at a fine resolution would be prohibitive in terms of sampling and/or severely limit the statistical power for detecting differences among sites.

1.9 Reference Conditions

Coral reef research has failed to establish the biological integrity necessary for well-defined frameworks that can compare changes at impaired sites. These reference conditions provide a standard against which impaired conditions can be evaluated. They consist of physical, chemical or biological conditions at unimpacted or minimally impacted sites that are representative of sites with the same classification within that region. This status provides a baseline “with the ability to support and maintain a balanced, integrated and adaptive community of organisms having a species composition, diversity and functional organization comparable to those of natural habitats within a region” (Karr and Dudley 1999). In establishing reference standards, biological parameters or characteristics of the environment that respond to human perturbation are measured.

Establishing standards of reference are basic to the development of biological indicators. These reference conditions provide a baseline and also function as sites for future use in long-term monitoring efforts to detect declining conditions on reefs.

CHAPTER 2 APPROACH AND METHODS

2.1 Background Information

This section summarizes relevant previous methodology and justifies the selection of methods used in this investigation.

2.1.1 Selection of Sampling Method

Benthic Assessment

Numerous methods have been used to evaluate benthic environments. Selection criteria for benthic sampling methods should include the population of interest, statistical power, accuracy, precision, sources of variability, the focus of the study and the spatial scale involved. Time, cost and effort must also be evaluated.

A photographic transecting method was selected for use in this research for several reasons. Method selection criteria required data compatibility with sites incorporated into this study (CRAMP 2000). A quantitative method is critical to most advanced statistical procedures. The photographic method is not restrained by the limitations of many other benthic sampling methods (Table 2.1). Precision using this photographic technique was determined to be high (~95% similarity among observers) compared to insitu observations (Brown et al. 2004). Although initial costs are high, cost effectiveness surpasses visual techniques after only ten surveys (Brown et al. 2004). While post processing time increases, costly underwater dive time is greatly reduced with the use of photographic techniques. Photographic methods allow for archiving and data verification, which is critical in addressing further questions, and in quality control. The disadvantage of limited resolution has been resolved with recent technological advances.

Table 2.1 Benthic sampling methods used in coral reef investigations

Method	Type	Description	Limitations
Presence/ Absence	Qualitative	Lists species	No abundance data Records species only
Relative abundance	Semi-Qualitative	Categories ranging from common to rare	No absolute data
Quadrat	Quantitative	% cover of substrate types are recorded	High observer variability
Planar Point Intercept	Quantitative	Substrate type under each intersection is recorded	No absolute value can be calculated
Line Transect	Quantitative	Lengths of substrate types underlying the transect line are recorded	Small or rare species can be missed
Nearest Neighbor	Quantitative	Distance of organism from random transect point is recorded	Determines only abundance of target species
Point-Quarter	Quantitative	Coral colony measurements are taken from a haphazardly determined point	Greater variance Vertical overlap possible
Photographic Transect	Quantitative	Video or digital still images	Resolution

Fish Survey Techniques

Numerous methods have been developed for sampling fishes. Method selection depends on the focus of the research and the spatial and temporal scales involved. Accuracy can depend on the number and size of transects and whether transect locations are randomly selected, stratified random (e.g. following depth contours), or fixed. Fixed transects may not be representative of the entire community of interest but allow for more accurate repeated measurements.

Spatial and temporal variability of fishes can be extremely high due to mobility and large home ranges. Many fish species are cryptic, rare or transient. There are also diurnal/nocturnal and seasonal sources of variability. To quantify absolute values for fish populations an extremely large sample size is required especially for heterogeneous habitats. Relative values are often used to determine differences between sites. The methods in Table 2.2 were considered for use in this investigation.

Table 2.2 Visual fish censusing methods used in nearshore marine sampling

Method	Type	Description	Limitations
Presence/ Absence	Qualitative	Lists species	No abundance or density data Records species only
Timed Swim	Qualitative	Surveyor swims within defined area for specified length of time recording species observed	No size estimates
Relative Abundance	Semi-Qualitative	Records abundance of species	No density estimates
Reed Method (Reed 1980)	Semi-Qualitative	Surveyors record species only once, in the order they are sighted	No size estimates
Rapid Visual Transect (Sanderson and Solonski 1986)	Semi-Qualitative	Species are recorded only once and assigned to a time interval based on when they were observed	Underestimated patchy
Species Abundance	Quantitative	Records number of individuals and size	Time constraints
Line/Strip/Belt transect (Brock 1954)	Quantitative	Line laid prior to observations Records number of individuals and size	Speed variability: rare and cryptic species overlooked, highly mobile species overestimated
Video Transect	Quantitative	Video recording	Limited resolution
Circular Plot	Quantitative	Visual or video recording of all fishes in a 360^{o} arc in a designated time period	Water visibility estimate necessary High variability

Species abundance estimates were selected to maximize data and statistical comparability, allow for length to biomass conversions, and avoid limitations inherent in some other methods. This method includes two measures of abundance: numerical and biomass. These are both important population parameters that address different aspects of fish community structure. Unlike the belt transect method, species abundance estimates do not require additional survey time to allow for fish equilibrium to occur. The transect line is spooled out as the survey is conducted to avoid fish dispersal. Although additional dive and training time must be allotted to estimate fish length, post processing of data is relatively rapid.

2.1.2 Statistical Methods

Coral reef communities encompass large spatial and temporal scales that are often extremely heterogeneous and vary in their type and severity of disturbances, thus susceptible to highly variable data collection. Complex interactions and numerous causal relationships add to this variability. Causes of variability have been attributed to chance distribution of individuals, local disturbances, animal movement, statistical and methodological limitations, error and environmental heterogeneity. This variability can significantly reduce statistical power (Brown et al. 2003).

When working with such an extensive, diverse database involving numerous parameters, multivariate techniques are commonly used to group similar sets of samples. This type of analysis is highly efficient in summarizing data for intrinsic analysis of ecological communities (Gauch 1982). Multivariate analysis can reveal the distribution of species along environmental gradients, highlight patterns in the data through spatial comparisons and habitat characterization, clarify habitat relationships and reveal trends and patterns with minimal expression of the noise typical in community data. With ordination techniques, similar entities are placed close to each other while dissimilar species or samples are located far apart in ordination space.

In community analysis involving large data sets that have several community gradients and high variability, as in the case of this research, detrended correspondence analysis (DCA) and non-metric multidimensional scaling (MDS) have been shown to be highly effective (Gauch 1982; Clarke and Warwick 2001). These robust methods of multivariate analysis are relatively free from distortion and give equal emphasis to all data. These quantitative techniques are useful in identifying differences in community types and environmental gradients. Principal components analysis (PCA) is more appropriate for environmental variables than for species data with its large percentage of zero counts. Axes can be normalized so all data have comparable, dimensionless scales. Extrinsic analysis linking environmental variables to biological factors can then provide environmental interpretation.

2.2 Biological Parameters

The biological parameters selected for measurement include coral, fish and algal populations that respond in a quantifiable way to environmental stress. Detection of conditions over a wide range can be derived from targeting these assemblages that can reveal a broad range of perturbation.

One consideration in evaluating which specific factors of these populations to measure is the time and cost constraints that must be weighed against greater spatial coverage. Often, the quantification of a few parameters can yield many meaningful attributes. For example, fish surveys were designed to record species, count, and length. From this rapid quantification, various useful parameters can be derived: numerical abundance, biomass, endemism, trophic levels, feeding guilds, species composition, size distribution, diversity and evenness.

2.2.1 Benthic Populations

Rapid Assessment Technique (RAT)

Biological characteristics of the coral reef community sensitive to environmental degradation include coral cover, species richness and diversity. To identify these properties, a quantitative assessment protocol was established. This assessment technique is robust enough to detect relationships among environmental factors and spatial distributions of reef organisms. This protocol was designed to produce quantitative spatial data, consistent and comparable to data recorded at the CRAMP permanent monitoring sites.

To optimize the power of the biological assessments, macroinvertebrates, fishes and algal functional groups (macroalgae, coralline and turf) are surveyed. All methods used are environmentally benign, not significantly altering the habitat or biota surveyed. SCUBA is used to conduct all surveys. Depth is recorded at each transect. RATs also measure topographical relief and replicate bulk sediment samples are collected from each site.

Site Selection

Fifty-two sites, including all eight main Hawaiian Islands: Hawai’i, Maui, Kaho’olawe, Lāna‘i, Moloka’i, O’ahu, Kaua‘i and Ni‘ihau (Figure 2.1) were sampled.

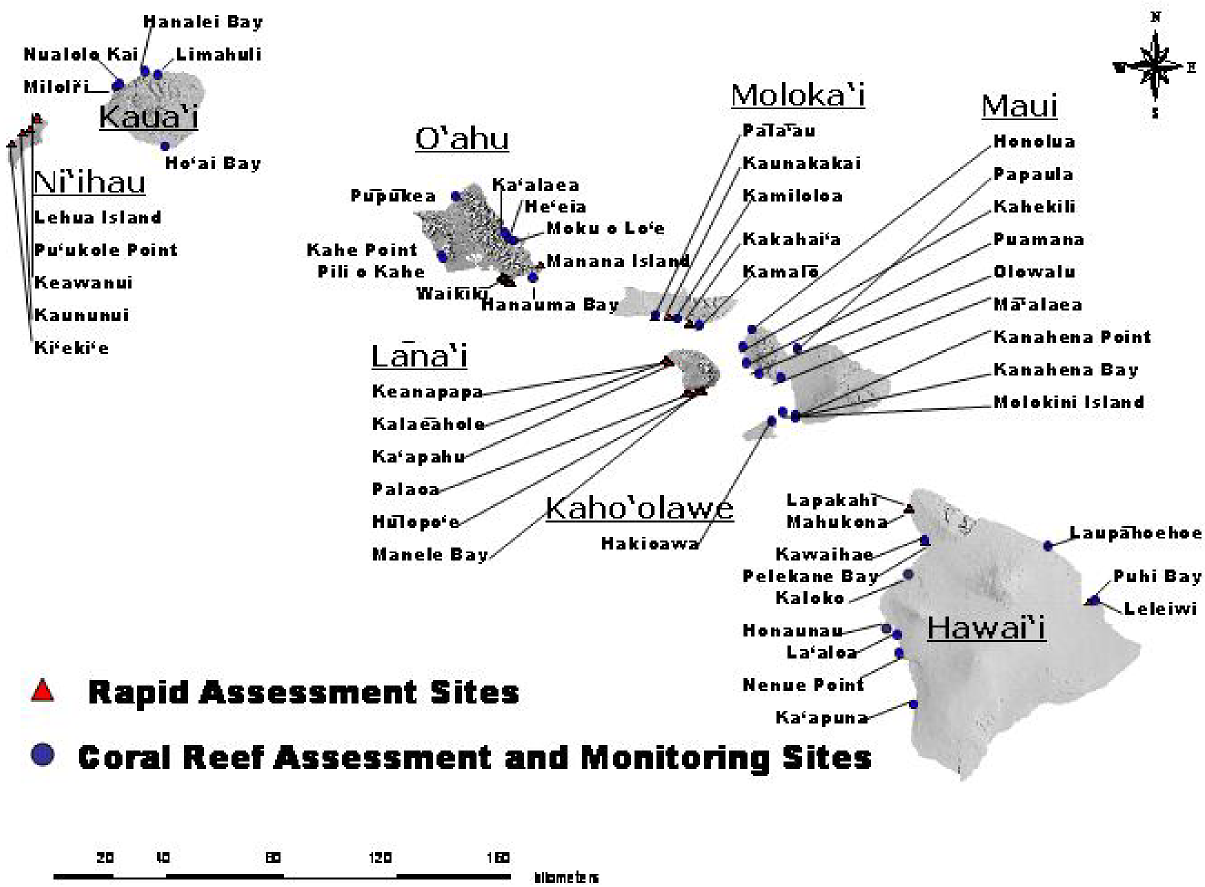


Figure 2.1 Main Hawaiian Islands assessment sites n=52.

Location of each assessment site was determined using habitat maps. A diverse spectrum of environmental conditions was selected to provide accurate representation of the main islands in the State of Hawai'i. The following criteria were used in the site selection process:

- A range along a gradient of anthropogenic impact from heavily impacted sites to sites with limited human activity;
- Sites with specific impacts including fishing, sedimentation, eutrophication and introduced species ;

- Naturally occurring conditions as close to original as possible;
- Sites that encompass the entire scope of wave exposure and direction;
- Sites that provide a wide range in human population;
- A range of legal protection including sites with various levels of marine protection and open access;
- Wide spatial gradients to encompass longitudinal differences;
- Accessibility.

Transect Selection

To encompass as wide a spatial range as possible and to assess spatial variability, a “many but small” sampling strategy was adopted (McCune and Lesica 1992). The RAT is a trade-off between size and number of sampling units. This technique provides an efficient sampling design to assess extremely large areas as in this study. There are many advantages to selecting many, short transects over fewer transects of longer length (McCune and Grace 2001).

- Cover of common species is more accurately and precisely estimated
- Larger coverage of sites increases environmental representation
- Smaller sampling units reduce bias against cryptic species by forcing visual contact to specific spots, avoiding selective species detection.
- Reduces overestimation of rare species
- Sampling effort and efficiency are not compromised

Transects within each site are randomly selected by generating 100 random points onto habitat maps using GPS Pathfinder Office 2.8. To assure adequate coverage of the different habitats and full representation of each site, a stratified design is employed. Points are stratified within depth ranges (<5 m, 5 to 10 m, and >10 m) and habitat types (coral, sand and macroalgae). Not all habitat types are present at every site. Navigational GPS is used in the field to determine the exact position of each point, marking the beginning of a transect. Where habitat maps are not available, a visual assessment of habitat type is conducted and depth is determined using either a depth gauge or fathometer.   A random number of fin kicks is used to designate the beginning of each transect.

Benthic Surveys

To assess the characteristics of benthic populations, high resolution digital images are taken along a 10 m transect using an Olympus 5050 zoom digital camera with an Olympus PT050 underwater housing. The camera is mounted to an aluminum monopod frame, 1.7 m from the substrate to provide a 50x69 cm image. A 6 cm bar provides a measurement scale. The software program PhotoGrid (Bird 2001) is used to quantify percent cover, richness and diversity of corals, algal functional groups and substrate cover.

Images are downloaded and the 20 non-overlapping images from each 10 m transect are imported into PhotoGrid where 50 randomly selected points are projected onto each image. These data are saved in a comma separated values (CSV) file, proofread in Excel and imported into Microsoft Access XP, a relational database. Access data is queried and exported to statistical programs for analyses.

Statistical Analyses

Transformations

In order to determine whether transformations were appropriate, prior to analyses, residual distribution, partial regression plots and coefficient of variation were examined. Data transformations were conducted to satisfy the assumptions of normality, linearity, and homogeneity of variance required for some of the formal statistical tests performed.

To determine the best transformation, histograms and normality plots were generated. Normality was assessed using the Ryan-Joiner test, which is similar to Shapiro-Wilk. Direction and strength of skewness were determined since strong skew can cause leverage problems. Partial regression plots were generated to determine leverage. Since large data sets such as the one this research generated are quite robust against normality violations due to the central limit theorem, data were left in its original form whenever possible. Independent variables that were calculated as percentages and species data containing numerous zero values were transformed.

The transformations used to meet the assumptions of normality and homogeneity of variances included:

- Arcsine square-root, in which variables in percentages were changed to proportions in order to normalize data and obtain a continuous variable. Distributions of proportion data are skewed because they are between 0 and 1 and thus have no tails. Arcsine transformation was used to stretch out the tails on both ends for a more bell-shaped, normal distribution. These are useful in extreme proportions <0.2 or >0.8. Data in degrees was changed to radians.

- Log transformation, in which variables with high positive skewness were log transformed.
- Log (X+1) transformation, in which variables that are counts were log(x+1) transformed to reduce skewness. Variables that contained zero values were also log(x+1) transformed because the log of zero is undefined.
- Square root (X+1/2), in which coral species abundances were square root (X+1/2) transformed since the community ecology matrix is sparse, containing few non-zero values.
- No transformation applied, in which data with a coefficient of variation below 100% were retained in their original form.

Univariate and Multivariate Statistics

Statistics were computed with Minitab 13.0. Explanatory variables were selected from among 23 environmental predictors. To avoid multicolinearity, variables that were highly correlated (>90%) were dropped from the analysis without loss of information (Clarke and Gorley 2001).

Coral species richness data may not be suitable for use as a response variable since it is strongly dependent on sampling effort and observer variability, making it difficult to compare across sites. Richness values were determined from coral cover data. Some species of corals may be missed in data collection.

Diversity was not used as a response variable since coral diversity is low in Hawai'i and may not be an appropriate indicator of environmental conditions in this region. Hawaiian communities are often dominated by a few primary species where diversity does not decline with decreasing latitude as in other regions (Grigg 1983). Due to geographic isolation, corals in Hawai'i are depauparate relative to the Indo-West Pacific. Only 16 genera containing 42 species have been documented from the Hawaiian Islands. Difficult field identification and detection of cryptic or deep species and low digital resolution may also reduce the predictive ability of diversity.

To determine which environmental variables best explain coral cover and species richness, a general linear multiple regression model was used. Stations without coral were removed prior to analysis. Of the 152 stations at the 52 sites, 12 had no coral cover. Coral cover and species richness were regressed against the following environmental variables: rugosity, depth, sediment composition and grain-sizes, wave parameters, human population parameters, precipitation, distance from a perennial stream, watershed area, and geologic age of site. Legal protection rank and Windward/Leeward divisions were included in the model as categorical variables. A Best Subsets routine was utilized in Minitab 13.0, applying Mallows C_p and R^2 as the criteria in model selection. A lack of fit test was conducted to verify the model selection. Coral diversity was not used as a response variable since coral diversity is relatively low in Hawai'i and digital quality may restrict detection of small or cryptic species.

A simple linear regression was used as an indicator to predict coral cover by *Chaetodon* abundance.

To determine species tolerances, relative percent coral cover of each taxon was plotted against percent of organics and percent of silt/clay.

One-way analysis of variance (ANOVA) was conducted to determine differences in abundance of coral species between Windward and Leeward sides of the islands.

Ordination methods were used to highlight patterns in the data through spatial comparisons and habitat characterization. Ordination techniques can clarify habitat relationships and reveal trends and patterns with minimal expression of the noise typical of community data (Gauch 1982). Sample and species relationships are represented in a low-dimensional space with ordination techniques. Similar entities are placed close to each other while dissimilar species or samples are located far apart in ordination space allowing a visual representation of sample similarity.

Multivariate statistical analyses were conducted using Primer 5.0 and Multivariate Statistical Program version 3.0 (MVSP). These include the following statistical tools and techniques:

- Correspondence analysis (CA) was performed on data from the six most abundant coral species in Hawai'i: *Porites lobata, P. compressa, Montipora capitata, M. patula, M. flabellata and Pocillopora meandrina.*
- A site similarity matrix was generated to evaluate coral species distributions.

- A BIOENV procedure was used to link biological data to environmental data so that patterns in coral communities could be identified.
- SIMPER was used to determine the contribution of each species to the dissimilarity between sites.

2.2.2 Fish Populations

Fish populations were quantified using standard visual belt transects (Brock 1954). Transect location was determined using pre-selected random points. SCUBA divers swam along one 25 m x 5 m transect (125 m^2) at each station recording species, quantity and total fish length. All fishes were identified to the lowest taxon possible.

Total length was estimated to the nearest cm in the field and converted to biomass estimates (tons/hectare) using length-weight fitting parameters. In order to estimate fish biomass from underwater length observations, most fitting parameters were obtained from the Hawai‘i Cooperative Fishery Research Unit (HCFRU). Additionally, locally unavailable fitting parameters were obtained from Fishbase (www.fishbase.org) whose length-weight relationship is derived from over 1,000 references. Congeners of similar shape within certain genera were used in those rare cases lacking information.

Convertions between recorded total length (TL) and other length types (e.g. fork length FL) contained in databases involved the use of linear regressions and ratios from Fishbase linking length types. A predictive linear regression of logM vs. logL was used in most cases to estimate the fitting parameters of the length-weight relationship. Visual length estimates were converted to weight using the formula $M = a \cdot L^b$ where M=mass in grams, L=standard length in mm and a and b are fitting parameters.

Any anomalous values were detected by calculating a rough estimate for a given body type. The general trend for a 10 cm fish of the common fusiform shape should be approximately 10 g. Gross deviations were replaced with values from the alternate source.

Trophic levels for fish species were determined using published Fishbase data. The trophic categories included: piscivores, herbivores, detritivores, mobile and sessile invertebrate feeders, and zooplanktivores.

To minimize observer variability, only two divers were used in fish assessments. Calibration of the divers was conducted at Kahe Point, Oʻahu (four transects) and Puhi Bay, Hawaiʻi (eight transects). No significant differences were found between the two divers for estimates of number or length of fishes.

Statistical Analyses

An index of relative dominance (IRD) was generated by multiplying the frequency of occurrence of each fish species (%) on each transect by their relative biomass (%) and multiplying by 100 (Greenfield and Johnson 1990).

CRAMP transects were standardized to meet statistical compatibility requirements with RAT transects by randomly selecting one of the four 25 m transects at each station.

Minitab 13.0 was used to perform all univariate, formal statistical tests. Spreadsheet and relational database software were used to determine population characteristics including; dominant and rare species, biomass and abundance rankings, feeding guilds and endemism status.

A non-parametric Kruskal-Wallis test was applied to compare fishing pressure and target fish species. This test compares several populations of independent random samples, ranking responses and applying a one-way ANOVA to the ranks rather than to the original observations. A traditional ANOVA was rejected on the basis of non-normal data including strong outliers.

Target fish species were selected to include popular food fishes. The genera selected were *Acanthus, Aphareus, Cephalopholis, Carax, Scarus, Chlorurus, Seriola, Sargocentron, Priacanthus, Kyphosus, Mullodicthys, Parupeneus* and *Decapterus*. Degree of fishing pressure at each site was based on management protection status and subjective expert knowledge by coral reef biologists. Sites were placed into one of three levels of fishing pressure: high, medium and low.

A simple linear regression was used to predict herbivore abundance by macroalgal abundances.

Multivariate statistical analyses included the same procedures used in the analysis of benthic data with the exception of a non-metric, multi-dimensional scaling technique, used to identify groups of similar sites. Environmental variables were overlaid on the ordination to identify the factors and their directions that are most important in structuring of fish communities.

2.3 Physical Parameters

2.3.1 Bulk sediments

Site Selection

Bulk sediments were collected from each site surveyed. Transects within each site were selected for sediment collection based on habitat type. Bulk sediments were collected from at least one transect of every habitat type represented at each RAT site.

Habitat types include:

- colonized hardbottom (>10% coral cover)
- uncolonized hardbottom (<10% coral cover)
- submerged algal vegetation (>10% algal cover)
- unconsolidated sediments (sand or silt)

Replicate samples were collected from each of the 94 stations representing each of the 52 sites. No sediment was found along the transect at the 10 m site at Kamalō, Moloka'i. Depths ranged from 1 m to 23 m.

Sediment Grain-size

Subsamples were taken from each of two replicate samples collected from every transect. Standard brass sieves were used to determine size fractions: 2.8 mm, 500 µm, 250 µm, and 63 µm (USA Standard Testing Sieve: A.S.T.M.E.-11 specifications). A brass catch pan was used to collect the silt/clay fraction. Five size fractions were determined: granule (>2.8 mm), coarse and very coarse sand (500 µm-2.8 mm), medium sand (250-500 µm), fine and very fine sand (63-250 µm), and silt/clay (<63 µm) in accordance with the Wentworth scale (Folk 1974).

Each size fraction was collected in pre-weighed Whatman 114 wet strength filters, air dried and weighed to determine the proportion of each size fraction. Extremely large pieces were removed prior to sorting to reduce variability and eliminate overweighting of some samples by a single piece of material. Only the four smallest size fractions were used in the analyses.

Sediment Composition by Loss on Ignition

Approximately 500 cm^3 of sediment were collected by hand along the transect at each site and secured in Fisher brand 9x18 cm sample bags. Sediment grain-size and composition were determined using standard sieving procedures after air drying for two weeks (Parker 1983; McManus 1988; Craft et al. 1991). To determine the inorganic-organic carbon fraction, 20 g of bulk sediment was finely ground using a mortar and pestle. Subsamples were taken from each replicate to determine variability. Samples were then oven dried for 10 h at 100 ^oC to remove moisture, placed in a desiccator and massed. To remove the organic fraction, 10 g were burned in a muffle furnace for 12 h at 500 ^oC (LOI_{500}), placed in a desiccator and massed (Parker 1983; Craft et al. 1991). For removal of carbonate material, samples were placed in a muffle furnace for 2 h at 1000 ^oC (LOI_{1000}), cooled in a desiccator and massed (Craft et al. 1991). The percent organic material and the carbonate fraction was calculated from these data.

Sediment Analysis

The gravel fraction was removed prior to analyses to reduce overweighting proportions of other size fractions by large material. To avoid multicollinearity, one size fraction (very fine sand) was removed from the analysis. Additionally, partial F-tests determined that this grain-size to contribute the least in explaining sediment variability among sites.

Bulk sediments were collected from 94 of the 152 stations at 52 sites. At stations where sediments were not collected, sediment data from stations at the same site with similar biota and environmental conditions were substituted (>90%) using a similarity matrix. Stations not meeting substitution criteria were omitted from the analyses (15).

Five sediment parameters were used in analyses:

- Loss on ignition (LOI_{500}) was used as an index of organic material content
- The mass loss between LOI_{500} and LOI_{1000} was used as a proxy for the carbonate fraction ($CaCO_3$)
- Medium sand fraction
- Fine sand fraction
- Silt/clay fraction

Principal components analysis (PCA) was used to define the position of stations in relation to the sediment variables.

2.3.2 Waves

Quantification of all wave variables was generated using significant wave height and mean wave direction from Naval Oceanographic WAM models downloaded during 2001 (www.navo.navy.mil). Hawai‘i forecasts are generated from data collected by instruments on buoys surrounding the Hawaiian Islands.

Wave factors used in data analysis include mean, minimum and maximum annual and seasonal wave heights and mean annual wave direction.

2.3.3 Terrestrial Factors of Human Population, Watershed, Streams and Precipitation

Terrestrial variables used in statistical analyses included human population within 5 km and 10 km of each site, human population within the adjacent watershed, total watershed area, mean annual precipitation, and perennial stream lengths. All geographic Information system layers were obtained from the State of Hawai‘i GIS database (www.state.hi.us/dbedt/gis).

Political boundaries and administrative layers included census tracts and blocks and fisheries management areas. Population data were originally five county layers downloaded from www.geographynetwork.com and merged into a single layer. The geographic extent of these 2000 census tracts and blocks covers the entire MHI.

Natural resources and environmental layers included rainfall and watersheds. The geographic extent of the watershed layer encompasses the eight MHI while rainfall contours cover the six largest Hawaiian Islands. Watershed unit boundaries were originally generated in Arc/Info and GRID using USGS Digital Elevation Model data (1995). The State Department of Land and Natural Resources served as the original source of median annual precipitation data.

Physical features and basemap layers included; coastline, hillshade, islets and perennial streams. The Commission on Water Resource Management, Hawai‘i Stream Assessment Project provided the original perennial stream data (1993).

The data projection for all layers was Universal Transverse Mercator (UTM), Zone 4 (meters), Old Hawaiian Datum. Projection conversions were applied to geographic coordinates for georeference compatibility using the ArcView extension, Hawai‘i Datums and Projections and the software program, Corpscon. Distances were calculated utilizing the Spatial Analyst version 1.1 extension for ArcView GIS version 3.1.

2.3.4 Rugosity

Rugosity measurements to determine topographical relief and spatial complexity were conducted along each transect. A 15 m chain marked at 1 m intervals with 1.3 cm links was draped along the length of the transect (10 m) following the contours of the benthos. An index of rugosity was calculated using the ratio of the reef contour distance as measured by chain length, to the linear, horizontal distance (McCormick 1994).

2.3.5 Depth

Depth was determined at each transect with an electronic depth sounder at the surface. To provide a range of depths along the entire transect a digital dive computer (Suunto) was used on the benthos.

2.3.6 Age of Islands

The geologic age of each site was estimated using the age of the source volcano in millions of years (Clague and Dalrymple, 1994). These data were determined using radiometric dating and paleontologic ages. Dated fossils and island age progression are consistent with this data.

2.3.7 Legal Protection Status

Protection ranks were assigned to each station based on geographically defined management status. Five types of marine protected areas (MPA) were used in the rankings. Areas without legal protection were classified as open access stations. The four ranks of MPA are described below.

- Rank 1: Full protection accorded to Natural Area Reserves (NARs), Fisheries Management Areas (FMAs), Marine Life Conservation Districts and Kaho‘olawe Island Reserve where fishing is strictly prohibited except for extremely limited indigenous use.
- Rank 2: Partial protection for Marine Life Conservation Districts (MLCDs) which allows very limited fishing and other consumptive uses. Specific gear restrictions or specific species closure may apply.
- Rank 3: Limited protection for Fisheries Replenishment Areas (FRAs) restricted aquarium fish collecting.
- Rank 4: No legal protection, i.e., open access areas, includes stations without geographically designated restrictions.

2.3.8 Geographic Coordinates

Latitude and longitude and UTMs were established at each site using differential GPS (Trimble GeoExplorer 3). Data projection was based on UTM, NAD 83 datum. Field characteristics were input into a pre-composed data dictionary. GPS data were processed in Pathfinder Office 2.8 and displayed using ArcView GIS version 3.1 software.

CHAPTER 3 CORAL REEF COMMUNITY STRUCTURE

3.1 Results

3.1.1 Coral Community Structure

The average coral cover in the Main Hawaiian Islands is 21.7 ± 1.6% (±SE n=152). The most dominant species are shown in descending order in Table 3.1. A total of 21 species of corals were recorded from transects statewide.

Table 3.1 Average reef coverage of the six dominant coral species in Hawai'i

	RATS n=92	CRAMP n=60	Mean (%)
Porites lobata	7.0	6.4	6.7
Porites compressa	4.2	4.7	4.5
Montipora capitata	4.5	4.2	4.4
Montipora patula	1.4	3.7	2.6
Pocillopora meandrina	2.8	1.3	2.1
Montipora flabellata	0.4	1.5	1.0
Other species (15 sp.)	0.4	0.9	0.7
Total	**20.6**	**22.7**	**21.7**

The six most abundant species were used in a Correspondence Analysis (CA) to determine coral community structure (Figure 3.1). Three main gradients are apparent. Sites dominated by *Porites compressa* group in the lower right quadrant of Fig. 3.1, while those dominated by *Pocillopora meandrina* cluster towards the lower left of the ordination. Those communities with a high percentage of *Montipora flabellata* cluster away from other sites, while the sites dominated by the species, *Porites lobata*, congregate in the center of the linear cluster.

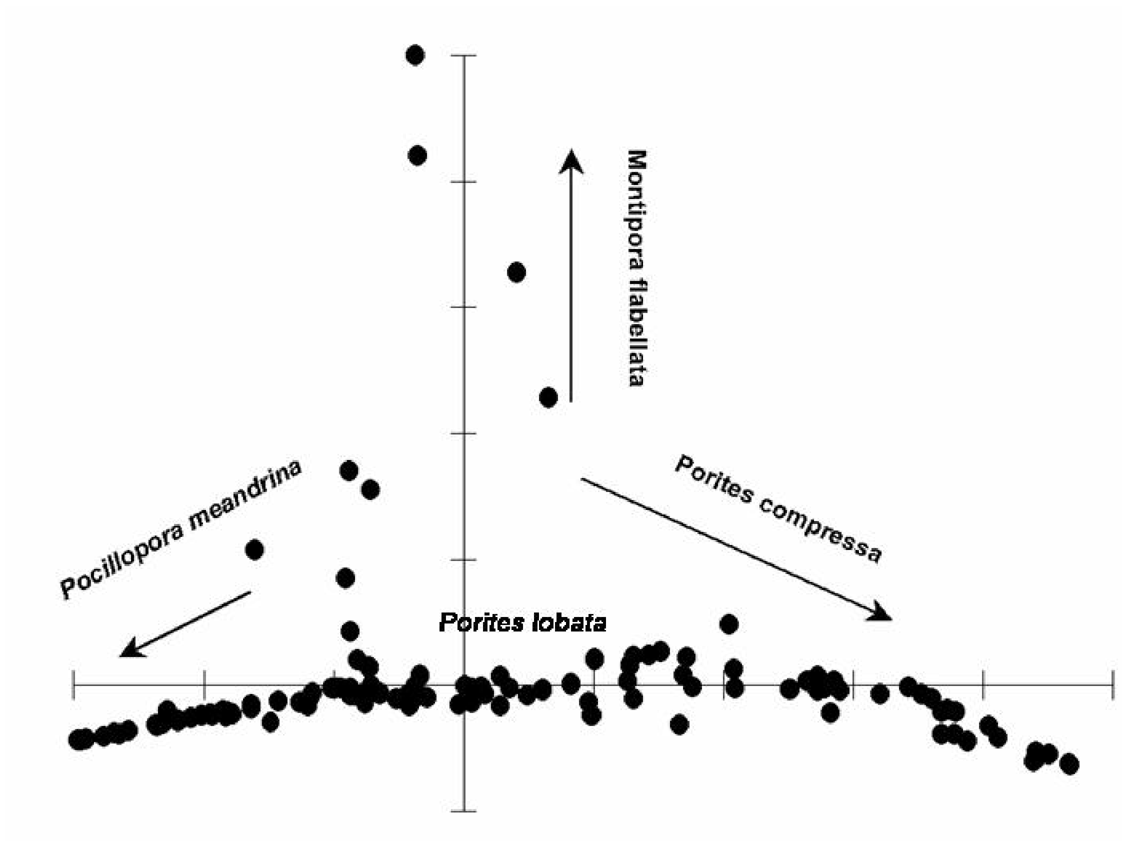


Figure 3.1 Multivariate Correspondence Analysis of coral community structure

To link dominant coral species to multivariate environmental patterns, a biota and environmental matching procedure (BIOENV) in PRIMER was applied. This procedure uses rank correlations to produce the optimal combination of environmental factors that best explains the variation in the biological data. The environmental variables included: latitude, age of islands, precipitation, distance from stream, watershed size, wave height maximum, wave direction, depth, rugosity, population within 5km, sand, organic matter, $CaCO_3$ and select grain-sizes. The coral community among sites was best explained by the environmental variables silt/clay, latitude, rugosity, maximum wave height and wave direction. These five variables combined to produce the highest matching coefficient (0.34) in a range of 0-1.

3.1.2 Coral Cover

A multiple regression was used to determine the best model for predicting coral cover regardless of depth class. The regression model using coral cover as the response variable was significant among the stations (R^2 (adj.) =49.1%, p<0.001). The variation in coral cover is best explained by rugosity (t= 8.4, p<0.001), population within 5 km (t=-3.4, p=0.001), depth (t=3.0, p=0.003), distance from a perennial stream (t=-2.8, p=0.006), wave direction (t=-2.7, p=0.009) and maximum wave height (t=-2.3, p=0.023).

A general linear multiple regression model was developed for sites with a depth <5 m. The variables used in this model include: rugosity, biomass, richness, wave max, organics and total fish. Variables used in explaining differences in coral cover at deep sites >5 m included: sand, human population, rugosity, fish biomass, latitude and coral diversity. Wave energy is only important in shallow water (p<0.001). This is correlated with a statistically significant increase in coral cover with depth (p=0.004). Sites<10 m in depth have an average total coral cover of 17.4% ±15.3 (SD), while deeper sites (>10 m) average 27.8% ±24.1 (SD). Species with the strongest skeletal strengths, *Montipora flabellata, Pocillopora meandrina*, and *Porites lobata* (Rodgers et al. 2003) have higher mean cover in shallower waters (Figure 3.2).

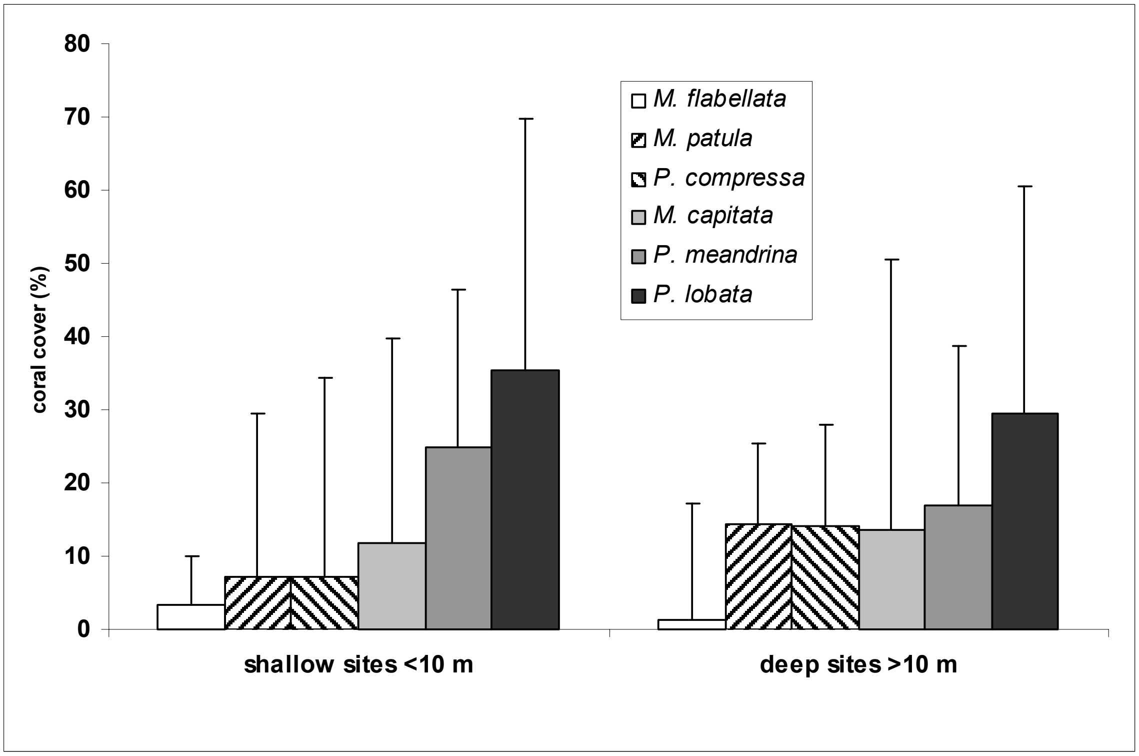


Figure 3.2 Percent cover of dominant Hawaiian coral species at shallow (<10 m) and deep (>10 m) depths ±sd.

The regression model using coral richness as the response variable included the environmental variables: rugosity, depth, organics, distance from a stream, legal protection status, maximum wave height and direction and population within 5 km. This model is statistically significant (R^2 (adj.)=23.5%, p<0.001). The variation in coral richness is best explained by organics (t=-4.6, p<0.001), wave direction (t=-3.9, p=0.01), population within 5 km (t=-3.8, p<0.001), distance from a stream (t=-2.8, p=0.006) and maximum wave height (t=-2.3, p=0.025).

3.1.3 Indirect Measures of Coral Cover

Bivariate linear regression was used to predict coral cover based on *Chaetodon* abundance. The test was statistically significant (p<0.001) with an r^2 of 16.3%. A simple linear regression of only corallivorous *Chaetodons* had a slightly stronger correlation than when using all species of butterflyfishes in the model (r^2=19.9%, p<0.001). Of the 152 stations sampled, 60% (91 stations) had no corallivorous *Chaetodons* present. The other stations ranged from 1 to 5 fishes.

Other statistically significant (α=0.05) simple indicators of coral cover include rugosity (r^2=35.5%), fish biomass (r^2=12.3%), total number of fishes (r^2=10.1%) and depth (r^2=8.7%).

3.1.4 Species Tolerances

To determine species tolerances to sedimentation and wave regimes, relative percent coral cover of each taxon was related with the mean percent of silt/clay and the maximum wave height at each station (Table 3.2). This allowed examination of the width of the environmental gradient in relation to the niche of the coral species. The relationship may also be due to other confounding variables not examined.

Thresholds were extremely low for *Montipora flabellata* (2%) and *Pocillopora meandrina* (9%) (Figure 3.3).

Table 3.2 Tolerance threshold of the six most abundant coral species to silt and waves.

Species	silt/clay (%)	Wave height maximum (m)
Montipora capitata	62	4 (13 ft)
Porites compressa	55	4 (13 ft)
Montipora patula	50	12 (40 ft)
Porites lobata	50	12 (40 ft)
Pocillopora meandrina	9	12 (40 ft)
Montipora flabellata	2	12 (40 ft)

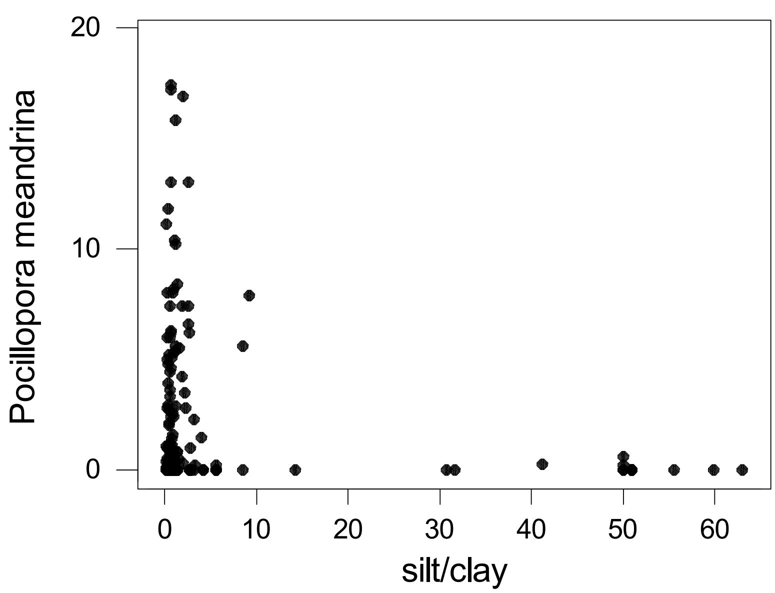


Figure 3.3 *Pocillopora meandrina* (relative cover %) vs. silt/clay (%).

Porites compressa (55%) (Figure 3.4) and *Montipora capitata* (62%) inhabit areas with high levels of fine material (<63 μm; silt/clay).

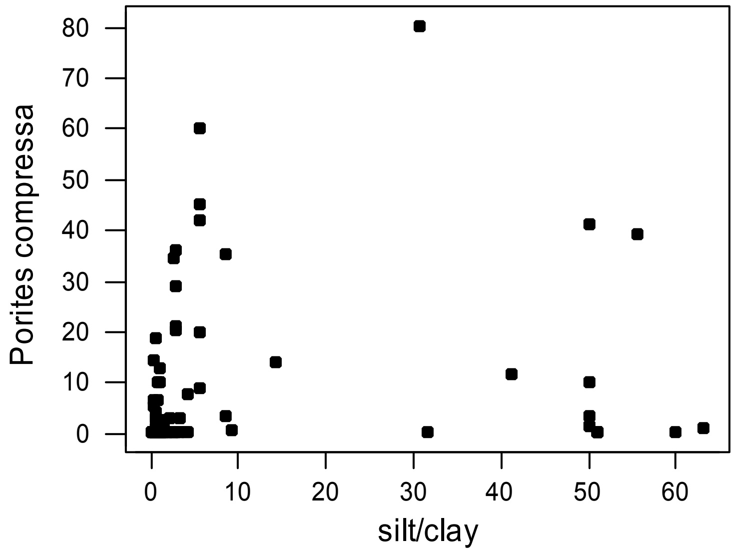


Figure 3.4 *Porites compressa* (relative cover %) vs. percent silt/clay (%).

Porites compressa (Figure 3.5) and *Montipora capitata* are not found at the maximum wave height of 12 m (40 ft) while all other coral species can tolerate this wave regime (Figure 3.6, Table 3.2).

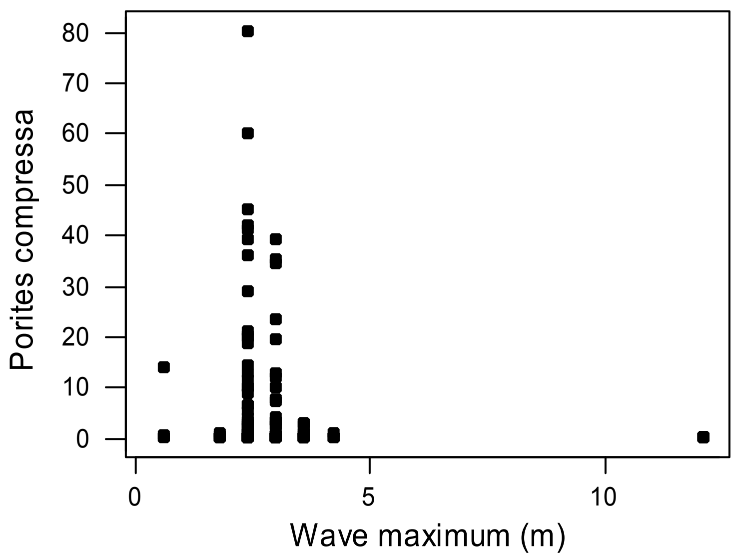


Figure 3.5 *Porites compressa* (relative cover %) vs. wave height maximum (m).

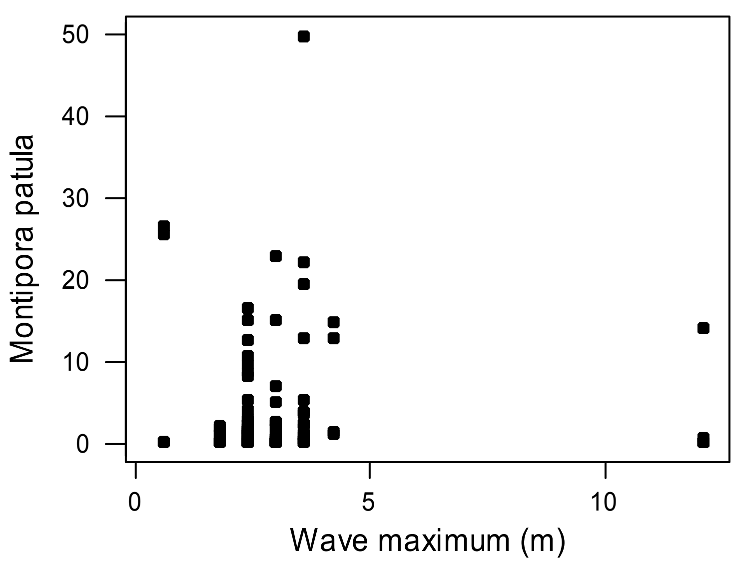


Figure 3.6 *Montipora patula* (relative cover %) vs. maximum wave height (m).

3.1.5 Windward/Leeward Differences

Kruskal-Wallis tests were used to determine whether statistically significant differences occurred between the Windward and the Leeward sides of the islands. Fig. 3.7 shows which sites are affected by these Windward/Leeward differences.

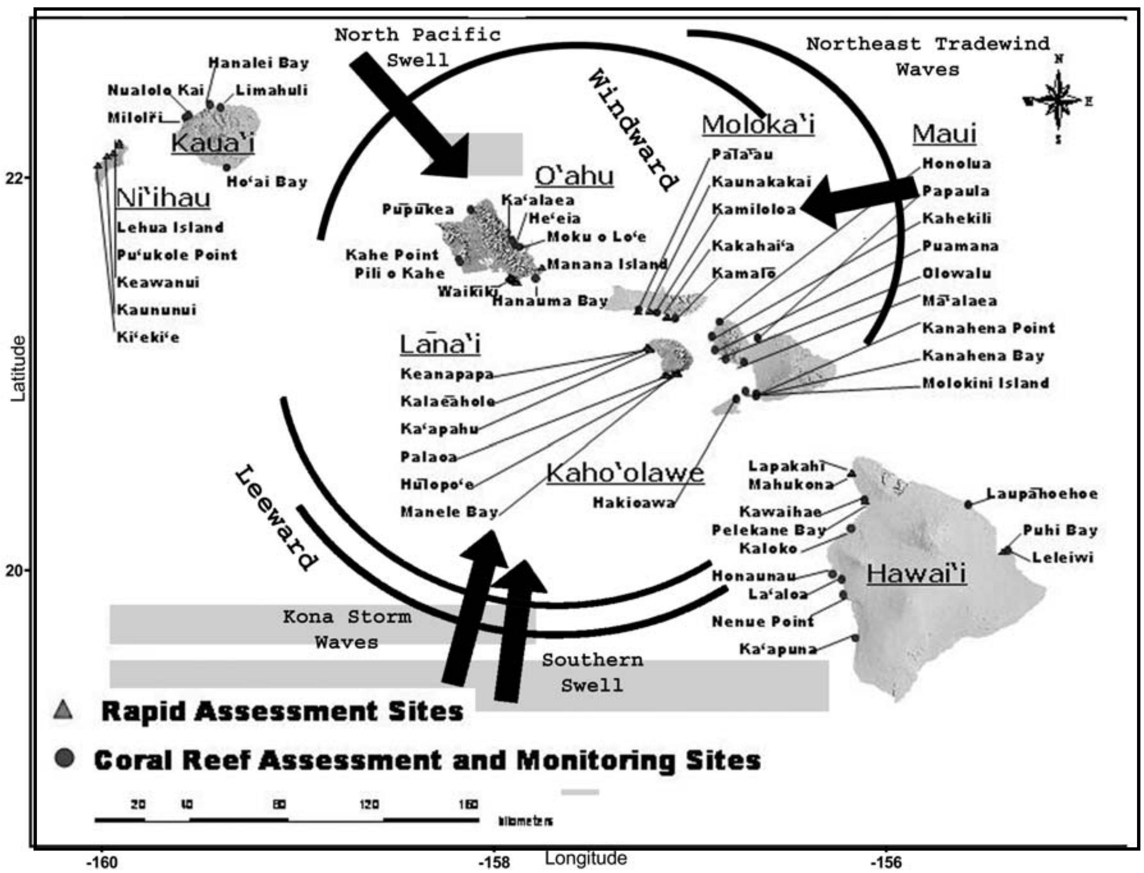


Figure 3.7 Map of Main Hawaiian Islands with 55 sites showing general wave direction and Windward/Leeward influences.

Statistically higher values on Leeward sides include carbonates, fine grain-sizes, *Porites lobata*, and watershed area. Variables that were significantly higher on Windward sides include organics, large grain-size, *Montipora flabellata*, and small fishes (Table 3.3). Higher rain and wave regimes are well documented on Windward sides of islands.

Table 3.3 Statistically significant differences between Windward and Leeward sides of the Hawaiian Islands.

Parameter	Windward (*p*-value)	Parameter	Leeward (*p*-value)
Organics	0.027	Carbonate	0.15
Large grain-size (500µm-2.8mm)	0.037	Fine and very fine grains (63-250µm)	0.005
Montipora flabellata	<0.00	Silt/clay (<63µm)	0.060
Wave height mean	<0.00	*Porites lobata*	0.043
Precipitation	<0.00	Watershed acres	<0.00
Small fishes (<5 cm)	0.01		

Multiple regression analysis using coral cover as the response is not significant for wave direction and maximum wave height when only sheltered sites are included in the model. When examining Windward sites alone using coral cover as the response, maximum wave height ($p=0.03$) and direction ($p=0.01$) are significant (R^2 (adj.) =25.1%), although Leeward sites are not significant (R^2 (adj.) =10.8%) for wave parameters. The model used the same variables determined to be most suitable in regression analysis for coral cover.

The species richness model explained over 98% of the variability at Leeward sites where wave parameters were significant (R^2 (adj.) =97.9%). The regression model included the environmental variables: rugosity, depth, organics, distance from a stream, legal protection status, maximum wave height and direction and human population within 5 km.

3.2 Discussion

3.2.1 Coral Community Structure

Historically, surveys have been conducted at specific sites on small spatial scales to answer specific questions. These surveys are usually conducted in areas with relatively large coral populations, leading to high estimates of coral cover.

This statewide survey provides a more accurate representation of the mean total coral cover (22%) and species abundances on a large scale (Table 3.1). Hawaiian reefs are predominately *Porites* reefs, with *P. compressa* and *P. lobata* comprising nearly half of the total coral cover in the MHI. Of the 42 species documented from the State of Hawai'i, half were recorded on the transects (21). Species not documented were most likely due to small colony size, difficult field identification, NWHI endemism, species occurring at greater depths, photographic resolution or cryptic species.

Coral communities correspond to wave disturbance and population. A spatial gradient of coral communities is evident from the multivariate analysis. Reefs in Hawai'i have been characterized by a single species of coral that can dominate certain sites (Gulko 1998). Three species of coral were shown to be influential. The species abundance gradients accompany wave energy patterns. *Montipora flabellata* are found in highest abundance on north facing, windward shores of islands. *Pocillopora meandrina* can be indicative of high wave energy environments, while *Porites compressa* most often inhabits calmer waters.

The multivariate environmental patterns most closely linked to coral species are sedimentation, latitude, rugosity, maximum wave height, and wave direction.

3.2.2 Coral Cover and Species Richness

Rugosity and depth have a positive correlation with both coral cover and species richness while maximum wave height, wave direction, population within 5 km and distance from a stream have an inverse relationship. Organics are also correlated with species richness. In all statistical analyses, wave regimes were found to strongly influence coral communities.

From regression analysis, wave energy is statistically significant in shallow waters but less important in explaining coral cover at deeper sites where lower wave energy exists. Coral cover (<10 m, 17.4%±15.3%, >10 m, 27.8%±24.1%) is also stratified by depth.

Prior research has demonstrated depth stratification of coral assemblage characteristics (Dollar 1982). The validity of this model in verifying these established processes provides support of the power to detect true trends and patterns. By substantiating this stratification, it lends credence to other significant correlations, while establishing these relationships on a statewide scale.

Wave energy has been reported to be the primary forcing function in determining coral reef communities (Dollar 1982; Grigg 1983). Coral cover is higher in deeper waters, reflecting lower wave disturbance. The significance of depth in explaining coral cover is analogous to stratification of vegetation by elevation, the most pronounced environmental gradient in terrestrial ecology. The rise in coral cover with increasing depth is partially a function of decreasing wave energy. Research conducted in the eastern Pacific (Glynn 1976) suggests that physical factors control shallow environments, while biological factors are the forcing function in deeper waters.

Coral zonation patterns also reflect their morphology and skeletal strength. This distribution may have evolved as an adaptive response of coral species to disturbance by waves (Rodgers 2001). Species with highly branched morphology, low skeletal strength and high fracture rates, reside in regions with little wave exposure, such as in bays and near sheltered shorelines. Species with lobate or encrusting forms tend to inhabit regions with high wave energy.

Sediment associated organics and fine particles of silt and clay are also correlated with coral species abundance. This is also partially structured by wave energy. Winnowing of fine grain particles in high energy regimes selects for larger, coarser grain sizes while smaller organic particles can remain in areas with little wave disturbance (Te 2001). High organics in sediments may result from human impacts in terrestrial environments. Where fine sediment overwhelms the system, sedimentation rather than wave energy, becomes the dominant forcing function on community structure.

Mean wave direction is also important in explaining coral abundance and species richness. This is directly related to the maximum wave height in Hawai'i. Distinct and consistent directional wave patterns prevail throughout the year (Fig. 3.7). A storm surf gradient exists along Hawaiian shorelines, increasing in a clockwise direction. Larger winter swells arrive on the north shores of the islands, originating from the North Pacific Swell, while less exposed south shores receive lower energy from South and Trade Wind Swells (Juvik and Juvik 1998). These long period swells are influential in biostratification of species, spatial heterogeneity and structuring of coral reef communities. Anomalous changes in wave direction can significantly impact coral communities (Jokiel and Brown 2004).

Although wave energy plays a dominant role in the structuring of coral reefs, other factors also explain the variation in coral communities, particularly in sheltered bays, harbors and shorelines and in deeper waters. Coral reefs are complex, interrelated systems influenced by numerous physical, biological and chemical factors that continually interact.

Rugosity explained a large percentage of the variation in coral cover (r^2=38.2%), as well as in fish abundance (r^2=24.7%) (see Chapter 4: Near-shore fish community structure). Areas indicative of high rugosity (>1.5) provide stable attachment sites for coral recruits, thus increasing vertical relief. In comparison, unstable habitats consisting of sand, rubble or silt have relatively low spatial complexity (Birkeland et al. 1981).

Human factors can also be important in the structuring of coral reef communities. Impacts affecting reefs such as sedimentation, eutrophication, introduced species, overfishing and coastal development are usually a direct result of increased human population. Regression analysis indicated that sites in close proximity to high human population and perennial streams had lower coral cover and species richness. Although technological advances in transportation and close geographic proximity of the MHI allows access to most areas, higher activity is found closer to population centers. A large percent of Hawai‘i’s reefs are easily accessible to the human population, located within close proximity of major urban centers of resident and tourist concentration (Gulko 2000).

Streams in Hawai’i have a history of alteration and diversion. Water quality reflects the resident population and adjacent watershed uses. Physically tied to the ocean, streams affect the marine ecosystem. Of the 366 perennial streams in the state of Hawai‘i, 55 had been significantly altered by 1978 through channel realignment, lining or filling of channels, clearing of riparian vegetation or elevation or extension of the culvert or revetment (Timbol et al. 1978). Modifications have been made to over 150 km of stream channels. Lined channels are the most common type of modification, comprising over 40% of stream channel alterations, with over 90% of these located on the island of O‘ahu (Timbol et al. 1978). Water has been diverted from over half of all perennial streams for irrigation and other uses in drier Leeward areas.

By 1978, only 51 of these 366 streams were considered “physically pristine,” none of which occurred on O‘ahu. Only 95 streams were considered of “high ecological quality” and therefore designated for pristine-preservation use, including streams from all islands, with the exception of O‘ahu (Timbol et al. 1978). No “biologically pristine” streams were reported (Timbol et al. 1978). Every perennial stream sampled on every island had at least one introduced species.

Few intact streams remain today and the resultant impact to the nearshore biota has undoubtedly been significant.

3.2.3 Indirect Measures of Coral Cover

Factors that were found to be significantly correlated with coral abundance in multiple regression analyses were investigated to determine whether any single indirect measure could be substituted as a proxy for coral cover.

Reese (1981) supports the monitoring of abundance and territory size of obligate, corallivorous butterflyfishes to monitor the "health" of coral reefs. In support of this hypothesis, a statistically significant correlation was found in this study (r^2=19.9%). A stronger correlation is probable with increased transect length. Few butterflyfishes were recorded on each transect (1-5) and were present on only 40% of the transects. This absence is most likely explained by the survey method selected. Designed as a rapid assessment to allow greater spatial coverage, it limits the sample size and accurate representation of observations. One 25 m belt transect cannot encompass the variability in fish populations at a station. Many butterflyfishes have large home ranges and may not be encountered using this abbreviated method. Although butterflyfishes were absent from the majority of stations, the regression analysis showed a statistically significant, positive correlation between corallivorous *Chaetodons* and total coral cover, explaining approximately 20% of the variation.

A weaker correlation between all fish species and coral cover was also found to be statistically significant (abundance r^2=10.1%, biomass r^2=12.3%). Corals provide food, shelter and protection for fishes by increasing vertical relief.

Friedlander et al. (2003) found a strong correlation between habitat complexity and fish communities.

Although rugosity, depth, fish abundance and biomass have a statistically significant relationship with coral cover, no one factor can substitute as a proxy. Substitutions are recommended only with coefficients of determination >95% (Clarke and Warwick 2001). The structuring of coral reefs involves complex interactions; therefore each factor alone is a weak predictor of coral cover, explaining only a portion of its variability.

3.2.4 Species Tolerances

Silt thresholds for *Montipora flabellata* and *Pocillopora meandrina* were found to be very low. The occurrence of these species at low silt levels may be a function of its distribution rather than its tolerance level, although it strongly suggests that these species do not typically occur in environments where silt dominates. These two species do occur in high to moderate wave energy environments (Gulko, 1999) where finer particles are winnowed out. For example, *Pocillopora meandrina* is found in shallow waters with strong currents where fine sediment can also be swept away. Both *M. flabellata* and *P.meandrina* were found to tolerate maximum wave heights of 12 m.

Montipora capitata and *Porites compressa* are found in areas with high levels of silt suggesting a high tolerance to sedimentation. Field studies on the Great Barrier Reef found corals surviving in extremely turbid zones with sediment input levels at approximately 140 mg/l (Woolfe and Larcombe 1998). Morphological plasticity may partially explain the high tolerance to silt. Foliose or lobate forms foster sediment accumulation while branching, vertical morphologies are less prone to sediment retention. The plate form of *M. capitata* is an example of morphological change in response to wave action that occurs in high energy environments, while the branching form of this species occurs more commonly in low wave energy environments. Encrusting or lobate forms of corals dominate high wave energy environments while branching, more delicate forms are correlated with low wave energy environment. These species were absent from areas with maximum wave heights of 12 m.

3.2.5 Windward/Leeward Differences

Porites lobata, detritivores and very fine sands occurred more frequently on the Leeward sides of the islands, while *Montipora flabellata,* maximum wave height, precipitation, small fishes and large grain sediments were more prevalent on the Windward sides of islands.

Higher precipitation on Windward sides of high islands has been well documented. Having verified this established relationship with this dataset provides stronger evidence for other documented correlations.

The Leeward sides of the islands have statistically higher cover of *Porites lobata* (37.6% vs. 25.3% p=0.03) while the Windward sides have higher total cover of *Montipora flabellata* (7.6% vs. 0.1% p=<0.001). No other coral species distribution differed significantly between sides of islands. Since the Windward sides of the islands have higher mean wave heights than the Leeward sides, encrusting corals such as *M. flabellata* occur more frequently. Windward and Leeward sites have significantly different wave regimes that can affect many factors of biotic and abiotic communities. Sorting of sediment grain sizes occur as a result of wave energy that increases erosion. Higher wave energy on north-facing shores reduces fine particles. Consequently, coarser sediments remain on Windward sides, while Leeward shores have significantly higher percentages of finer particles.

Fishes in the smallest size class (<5 cm) are found in statistically higher abundances on the Windward sides (Figure 3.8).

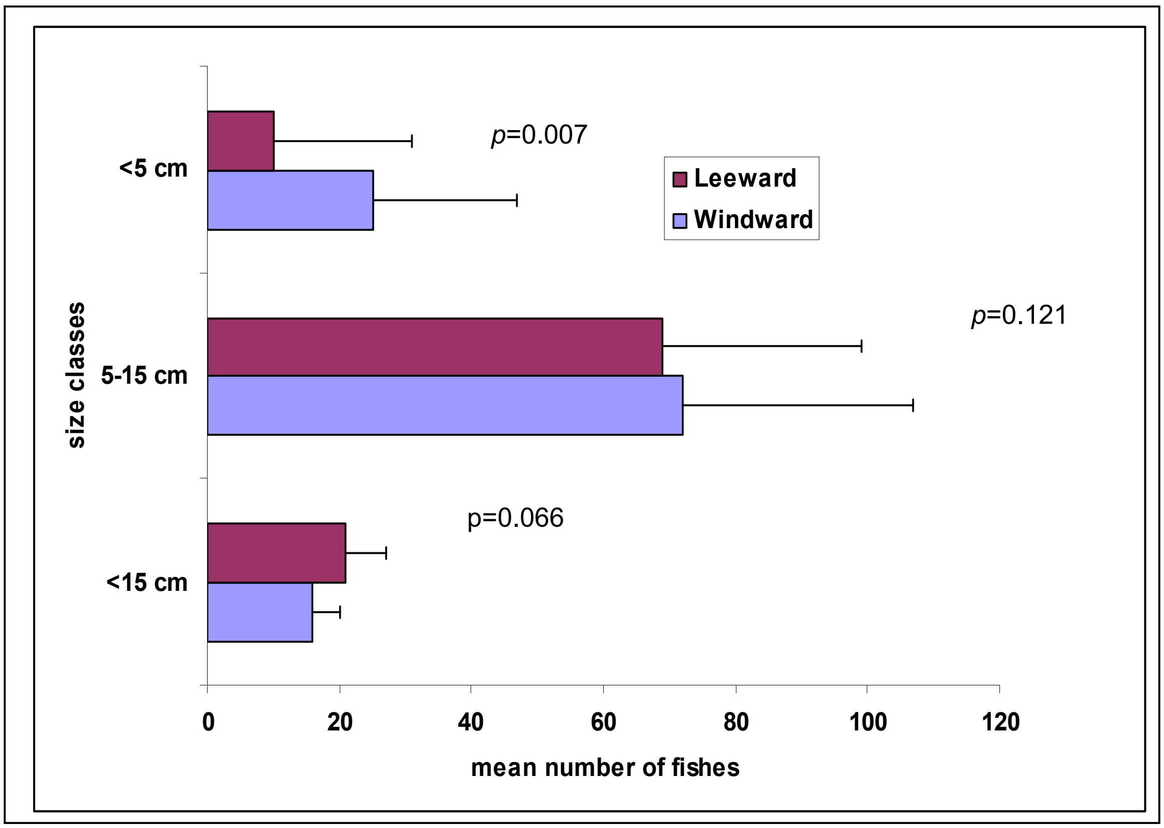


Figure 3.8 Differences in fish size classes between Windward and Leeward sides of islands (±sd).

Even with the Kāne'ohe Bay sites removed, due to large numbers of small *scarids*, the positive correlation is still statistically significant. This demonstrates how a large sample size can overshadow the effects of anomalies to elucidate relationships and trends.

3.3 Conclusion

- Mean total coral cover in the Main Hawaiian Islands is approximately 22%. Hawaiian reefs are predominately *Porites* reefs, with *P. compressa* and *P. lobata* comprising nearly half of the total coral cover in the state.
- The dominant coral species in descending order are *Porites lobata, Porites compressa, Montipora capitata, Montipora patula, Pocillopora meandrina* and *Montipora flabellata.*
- Sites with high coral cover are characterized by high rugosity and low levels of fines, low wave regimes, low population and remoteness from perennial streams.
- Wave energy is important in structuring Hawaiian coral reef communities.
- Both natural (rugosity, depth and wave energy) and anthropogenic factors (population and stream distance) influence coral cover and species richness. These factors are the most influential in explaining the variability in coral community structure.
- No single factor had a correlation strong enough to act as a proxy for coral cover.
- *Montipora capitata* and *Porites compressa* can be found in areas with high levels of fine material and do not occur in high wave energy environments, suggesting a high tolerance to sedimentation and low tolerance to high

wave regimes. In contrast, *Montipora flabellata* and *Pocillopora meandrina* can be found in high wave energy regimes but do not typically occur in environments where fine materials dominate.

- Windward and Leeward sides of the Main Hawaiian Islands are significantly different in coral distribution, sediment grain size and fish composition.
- A small number of factors (rugosity, depth, organics, stream distance, protection status, wave parameters and human population) can explain the variability in coral richness at Leeward sites.

CHAPTER 4 NEAR-SHORE REEF FISH COMMUNITY STRUCTURE

4.1 Results

A total of 184 fish transects were sampled at 56 sites over a four year period from May, 9, 2000 to April 29, 2004 on the MHI. Criteria used to determine site locations are detailed in section 2.2. The vast majority (95%) of transect locations were chosen using randomly selected, predetermined points generated from habitat maps; or in areas where habitat maps were not available, stations were selected haphazardly in the field. A small number of transects (1.6%) were located in habitats of geological or biological interest or at stations of scientific interest with previously established instrumentation (3.3%).

Overall, 153 species of fishes from 31 families were quantified. The mean number of species recorded per transect is approximately 17, ranging from 1 to 33. The average number of individuals pr hectare is 9820, ranging from 0 to 588. The mean biomass of 0.54 ±1.16 Mg/ha (0.6 tons/ha) ranged from 0 to 14.5 Mg/ha (16.1 t/ha). Range for all parameters measured is wide, exhibiting considerable variability.

4.1.1 Summary of Top Species

Abundance

The most abundant fish species in the state is *Chromis vanderbilti*, the black-finned chromis, even though its frequency of occurrence is 52%, recorded in 92 of 184 transects (Fig. 4.1).

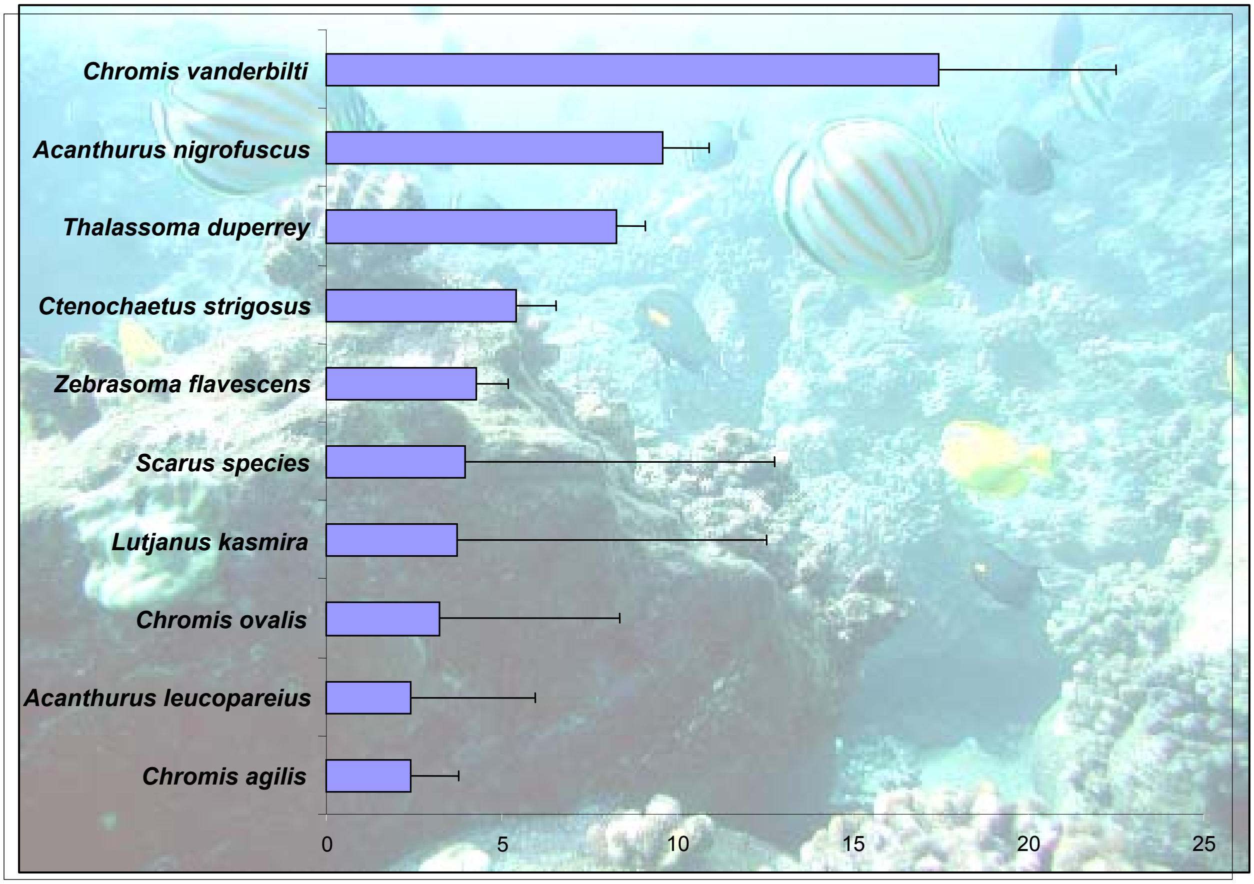


Figure 4.1 10 fish species with the highest abundance (mean number of individuals (% of total ± SD (n=184)).

The high ranking is due to the large number of individuals occurring in a school. Two other *Chromis* species rank within the top ten species in abundance, yet are found on only 13% of transects statewide. These planktivores can be found in large schools throughout the state and are especially abundant along the Kona coast of the island of Hawai'i. Although *Chromis* spp. ranks high in total numbers of individuals, their biomass is relatively low, due to their small size (Table 4.1).

Table 4.1Ten fish species with the highest abundance (mean number of individuals) are shown in descending order with their associated mean biomass and frequency of occurrence.

Taxonomic Name	Common Name	Hawaiian Name	Mean # of individuals (ha)	Mean Biomass (kg/ha)	Frequency of occurrence (%)
Chromis vanderbilti	Black-finned chromis		**1710**	<0.1	52.2
Acanthurus nigrofuscus	Lavender Tang	māi'i'i	**940**	27.2	71.7
Thalassoma duperrey	Saddle Wrasse	hīnālea lauwili	**810**	9.1	87.0
Ctenochaetus strigosus	Goldring Surgeonfish	kole	**530**	27.2	52.2
Zebrasoma flavescens	Yellow Tang	lauīpala	**420**	27.2	41.3
Scarus species	Parrotfish	uhu	**390**	9.1	7.6
Lutjanus kasmira	Bluestripe Snapper	ta'ape	**370**	54.4	12.0
Chromis ovalis	Oval Chromis		**320**	9.1	13.0
Acanthurus leucopareius	Whitebar Surgeonfish	māikoiko	**240**	36.3	27.7
Chromis agilis	Agile or Reef Chromis		**240**	<0.1	12.5

The second most abundant species is the Lavender Tang, occurring on 72% of the transects (Fig. 4.1). This frequency of occurrence is surpassed only by the Saddle Wrasse, which ranked third in abundance and was recorded from more transects than any other species (87%). Other common species found on approximately half of all transects include the Gold-ring Surgeonfish, (52%) and the Yellow Tang, (41%) (Table 4.1).

Two endemic species are included in the top ten species overall, the Saddle Wrasse, and the Oval Chromis. The Bluestripe Snapper is the only alien species with numbers of individuals large enough to be included in the top ten. Several extremely large schools, found on few transects (12%), account for the high abundance. This is similar to juvenile Parrotfishes, with a frequency of occurrence of only 8%, but ranking sixth in abundance overall, due to large numbers found at a few locations (Table 4.1).

Adult Parrotfishes are identified at the species level while juvenile Parrotfishes are recorded at the genus level due to difficulty in identification.

Biomass

The species with the highest biomass is the non-native snapper, *Lutjanus kasmira* (ta'ape) (Fig. 4.2). Originally from the Marquesas, this species was introduced

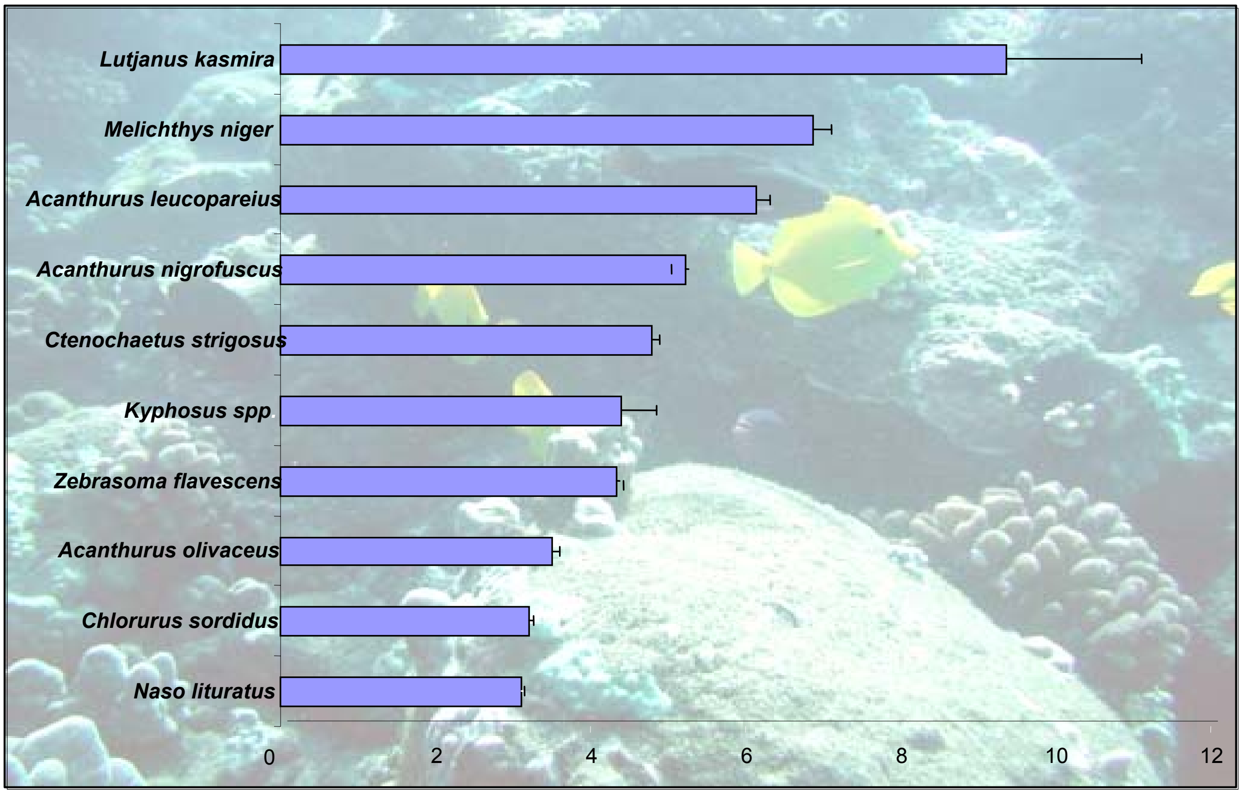


Figure 4.2 Top 10 fish species with the greatest mean biomass (% ± SD) (n=184).

by the Hawai'i Fish and Game for commercial purposes. Contrary to the motive of government introduction, this prolific snapper has not been widely accepted as a food fish among the local population. This consumer resistance has contributed to its widespread ecological success. Its range extends from the shoreline to several hundred meters in depth. They are often abundant in bays, as recorded by Friedlander et al. (2002) who found this species to have the second highest numerical and biomass densities in Hanalei Bay, Kaua‘i. The high ranking of the Bluestripe Snapper in our surveys can be attributed to very large schools on few transects (Table 4.2).

Table 4.2 Ten fish species with the greatest mean biomass are shown in descending order with their associated abundance (mean number of individuals) and frequency of occurrence.

Taxonomic Name	Common Name	Hawaiian Name	Mean Biomass (kg/ha)	Mean # of individuals (ha)	Frequency of occurrence (%)
Lutjanus kasmira	Bluestripe Snapper	ta‘ape	**54.4**	370	12.0
Melichthys niger	Black Durgon	humuhumu‘ele‘ele	**36.3**	140	28.8
Acanthurus leucopareius	Whitebar Surgeonfish	māikoiko	**36.3**	240	27.7
Acanthurus nigrofuscus	Lavender Tang	māi’i’i	**27.2**	940	71.7
Ctenochaetus strigosus	Gold-ring Surgeonfish	kole	**27.2**	530	52.2
Kyphosus spp.	Chub	nenue	**27.2**	90	13.6
Zebrasoma flavescens	Yellow Tang	lauīpala	**27.2**	420	41.3
Acanthurus olivaceus	Orangeband Surgeonfish	na’ena’e	**18.1**	130	32.6
Chlorurus sordidus	Bullethead Parrotfish	uhu	**18.1**	200	31.5
Naso lituratus	Orangespine Unicornfish	umaumalei	**18.1**	90	45.7

The Black Durgon has the second highest biomass in the state with a frequency of occurrence of 29%. The three species of *Acanthurids* within the top ten species cumulatively place *Acanthuridae* as the family with the largest biomass (Table 4.2).

The lucrative aquarium fish trade in Hawai‘i included 103 species that were collected statewide in 1995 (Tissot and Hallacher 2003). Eleven of these species accounted for over 90% of the fishes collected in that year. Three of these are included in the rankings of this research for the top ten species with the highest biomass. The Yellow Tang, which accounts for over half of all aquarium fish collected, ranked fifth in abundance and seventh in biomass. Other highly prized aquarium species, the Orangespine Unicornfish and the Goldring Surgeonfish also rank within the top ten species with the highest biomass statewide.

Numerical and biomass densities by depth

Although both biomass and numbers of fishes have greater densities at deeper sites, diversity and evenness are slightly lower with depth. Evenness is a component of diversity, where diversity is divided by the total number of species present, for an expression of the abundance of different species. Biomass is higher at depths greater than 10 m (653 kg/ha, 0.72 t/ha) relative to shallower stations (517 kg/ha, 0.57 t/ha). The pattern continues with abundance values at deeper sites (>10 m) having higher numerical densities (11,100/ha) than at shallower sites (<10 m) (9,700/ha).

4.1.2 Summary of Top Families

Abundance

The family with the greatest recorded abundance is *Pomacentridae* (Fig. 4.3, Table 4.3).

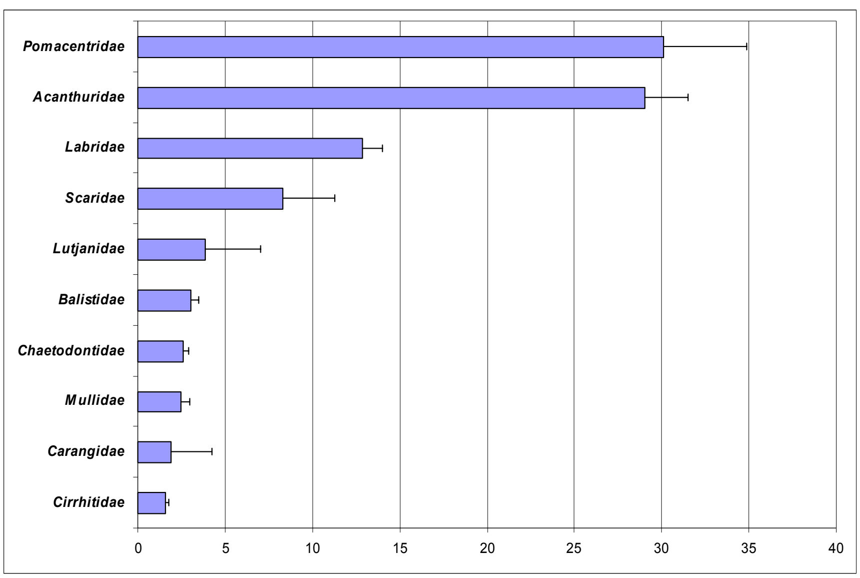


Figure 4.3 Top 10 fish families with the highest abundance (mean number of individuals (% of total ±SD)).

Table 4.3 Top ten fish families with the greatest mean biomass and density (mean number of individuals) and standard deviations are shown in descending order.

mean biomass (kg/ha)				mean number (ha)			
	mean	median	IQR*	family	mean	median	IQR
Acanthuridae	200±254	0.13	0.00	*Pomacentridae*	2,960±4,700	1.16	3.10
Lutjanidae	54.4±635	0.00	0.04	*Acanthuridae*	2,850±2,500	2.52	3.20
Balistidae	54.4±127	0.00	0.06	*Labridae*	1,260±1,200	0.88	1.18
Scaridae	54.4±163	0.02	0.00	*Scaridae*	820±300	0.08	0.48
Carangidae	36.3±408	0.00	0.23	*Lutjanidae*	380±320	0.00	0.00
Pomacentridae	27.2±82	0.00	0.03	*Balistidae*	300±40	0.16	0.40
Kyphosidae	27.2±163	0.00	0.00	*Chaetodontidae*	260±30	0.16	0.40
Labridae	27.2±27	0.00	0.03	*Mullidae*	240±60	0.08	0.24
Mullidae	18.1±73	0.00	0.01	*Carangidae*	190±240	0.00	0.00
Chaetodontidae	9.1±18	0.01	0.02	*Cirrhitidae*	150±20	0.08	0.24

*IQR=interquartile range

The overwhelming majority of the individuals in this family are from the five species in the genus *Chromis* (80%). Six other species from other genus in this family account for the remaining 20%.

Acanthurids rank nearly as high as *Pomacentrids* in number of individuals recorded. Although twenty species were recorded within this family, just two species, the Lavender Tang and the Goldring Surgeonfish, comprise over half of all *Acanthurids*.

The families *Labridae* and *Scaridae* are also important in their abundances (Fig. 4.3). Of the 24 recorded species from the family Labridae, the Saddle Wrasse accounts for nearly 65%, while juvenile parrotfishes, comprise almost half of the fishes in the family *Scaridae*.

Other dominant families of interest include the *Chaetodons* and *Lutjanids*. The fishes in the family *Chaetodontidae*, commonly found throughout the state, include of 16 recorded species of butterflyfishes. The introduced snapper, *Lutjanus kasmira* accounts for over 97% of the individuals in the family *Lutjanidae*.

Biomass

Nine of the families that rank in the top 10 in abundance are also within the top 10 families in biomass (Table 4.3). By far the family with the greatest recorded biomass is *Acanthuridae* with 20 recorded species.

Other families with large biomass include *Lutjanidae*, *Balistidae* and *Scaridae* (Fig 4.4).

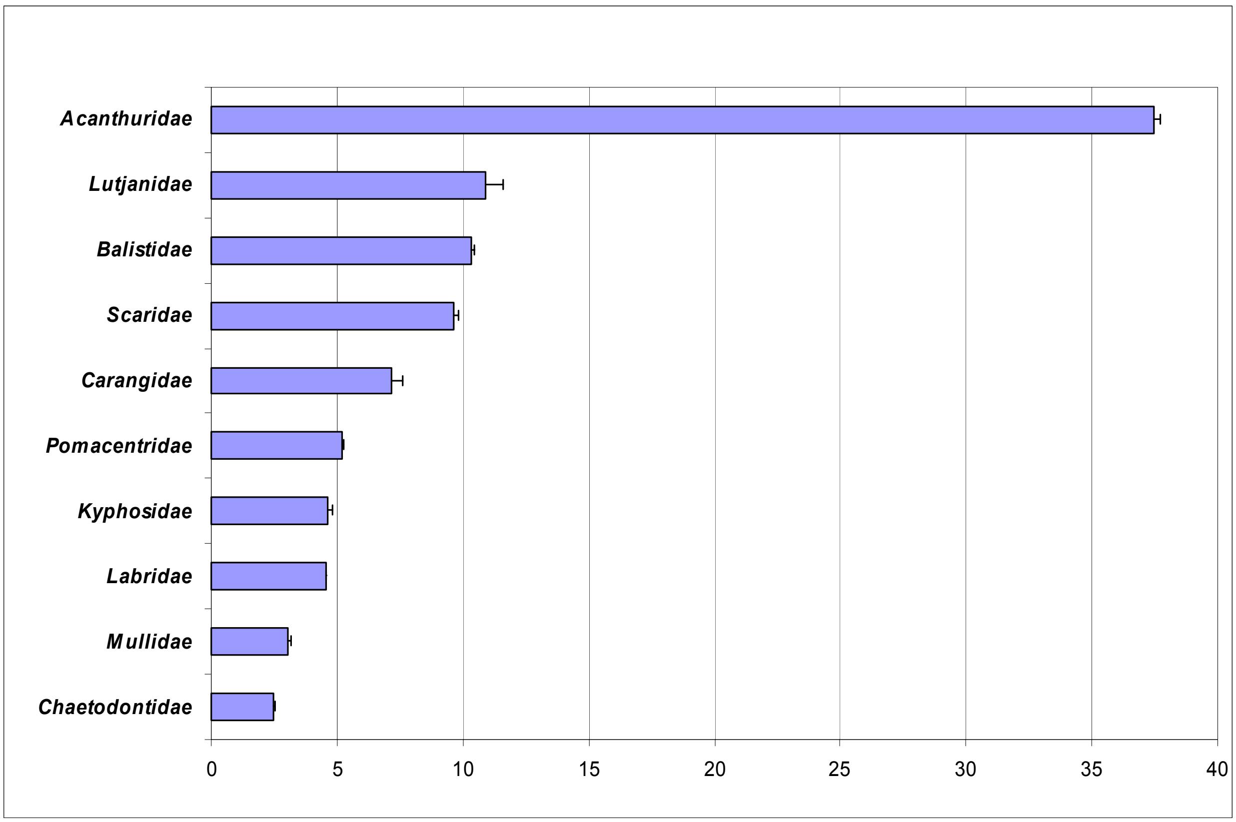


Figure 4.4 Ten fish families with the greatest biomass (% of total ± SD).

The majority (86%) of the biomass in the family *Lutjanidae* is from a single species, the Bluestripe Snapper. The Black Durgon accounts for 67% of the family *Balistidae* and the dominant species influencing the biomass of the *Scarids* is the Bullethead Parrotfish (33%). The inclusion of the family *Pomacentridae* in the top ten of total biomass is mainly influenced by the 5 species of *Chromis* (38%) and the Sergeant Major (37%).

4.1.3 Summary of Trophic Levels

The organization of fish assemblages such as trophic structure is more dependant on local than regional conditions. This makes such assemblages more susceptible to local disturbances of overfishing, pollution, and eutrophication, which can cause shifts in trophic levels. Declines in apex predators are highly evident when comparing feeding guilds in the MHI with the Northwestern Hawaiian Islands (NWHI). Large apex predators, primarily jacks and sharks, comprise over half of the total biomass in the NWHI (54%), while only a small percentage (3%) is represented in the MHI (Friedlander and DeMartini 2002). Other fish assemblage characteristics (density, diversity, endemism, and richness) are also dramatically different, pointing to the heavy exploitation in the MHI.

This study is in concordance with previously published data in the MHI. It recorded habitats that are heavily dominated by herbivorous fishes and significantly fewer piscivorous fishes, in both numbers of individuals and biomass (Figs. 4.5, 4.6).

This is in sharp contrast to the NWHI where piscivores dominate, comprising nearly 75% of the fish biomass. Typical of the MHI, the percentage of piscivores in this study is only 1.4% of the total number of individuals and 11.7% of the total biomass. Planktivores make up nearly a third (30.1%) of the abundance due to the large number of *Chromis* but only 6.7% of the total biomass, due to their small size. Approximately a quarter of the total numbers (25.7%) and biomass (23.3%) are invertebrate feeders. As a result of human fishing pressure and environmental degradation in recent decades, herbivores clearly dominate in the MHI, with well over half of the total biomass (58.3%) and an overwhelming percentage of individuals (42.8%) (Table 4.4).

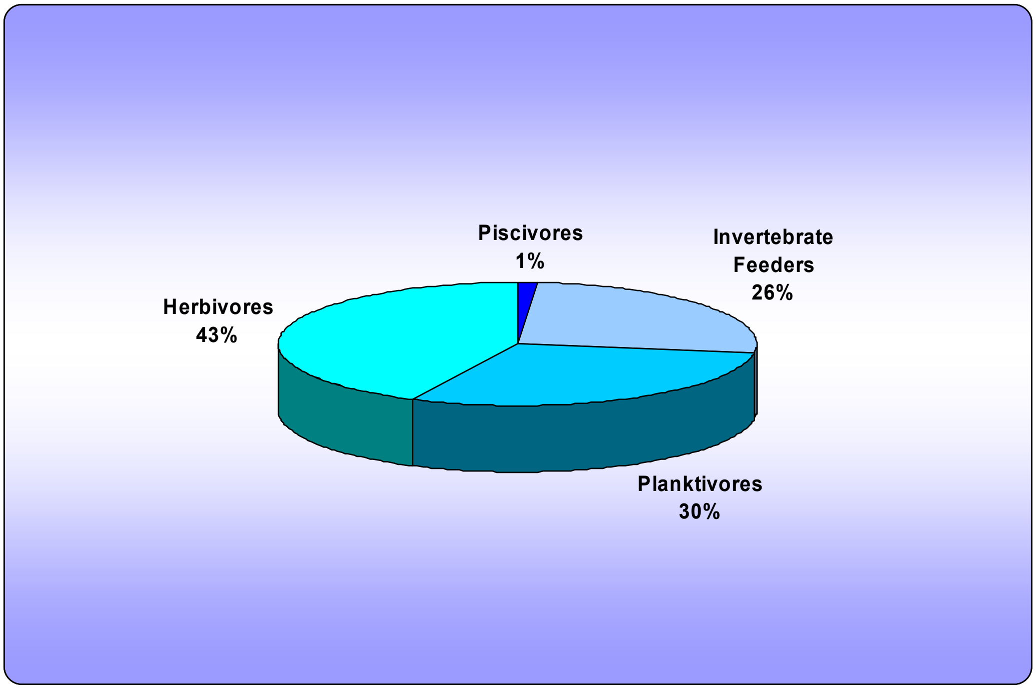


Figure 4.5 Mean abundance (mean number of individuals (%)) by trophic levels in MHI

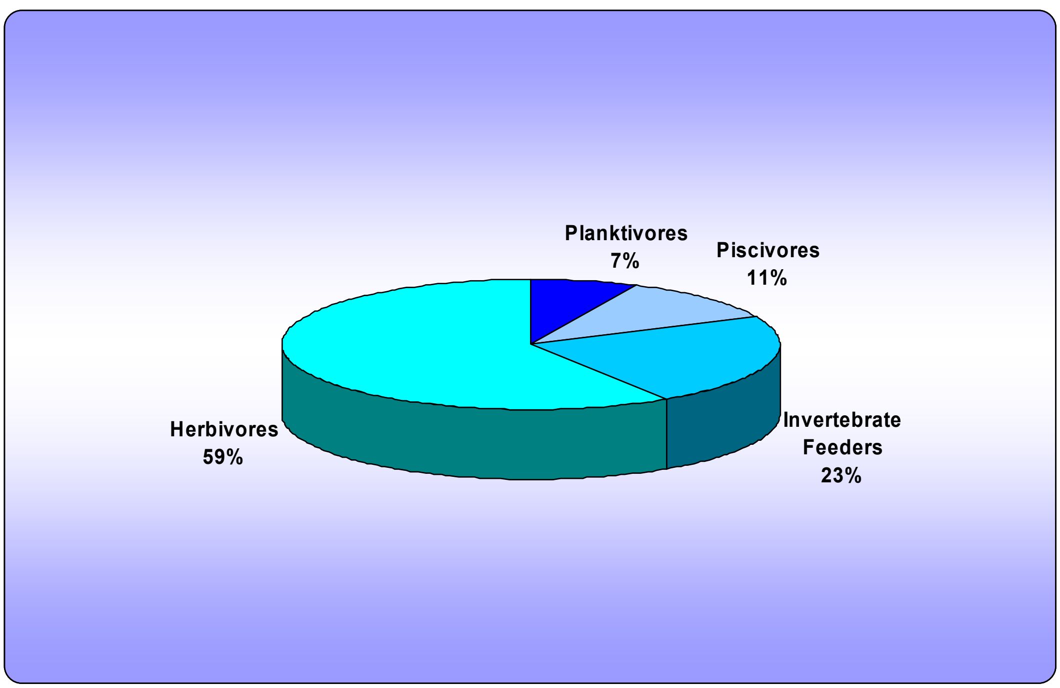


Figure 4.6 Mean biomass (%) by trophic levels in MHI

Table 4.4 Mean biomass and numerical density by trophic levels and their standard deviations are shown in descending order.

Mean numbers of individuals (ha)					Mean biomass (kg/ha)				
	mean	SD	median	IQR		mean	SD	median	IQR
Herbivores	4,200	4,400	3.52	3.96	Herbivores	317	425	0.21	0.33
Planktivores	2,960	5,400	1.88	1.74	Invertebrate Feeders	127	571	0.06	0.07
Invertebrate Feeders	2,520	3,400	0.08	0.24	Piscivores	63	495	0.00	0.01
Piscivores	140	200	0.80	3.50	Planktivores	36	126	0.00	0.03

4.1.4 Summary of Endemic Status

Both terrestrial and marine endemism in the Hawaiian Islands is high compared to the rest of the world, due to geographic isolation which restricts gene flow and favors speciation.

Endemism is a biologically relevant attribute in examining fish assemblages. It relates to conservation of biodiversity, genetic connectivity and spatial patterns of recruitment. Historically, endemic comparisons have been based solely on presence/absence data due to lack of quantitative data. Yet, endemism evaluations are more statistically meaningful when incorporating numerical and biomass densities which allow for elucidation of spatial patterns (Friedlander and DeMartini 2004).

Endemism recorded in this study (23.0%) is highly consistent with published values for fish endemism (23.1%) in Hawaiʻi based on the most comprehensive estimate of reef and shore fishes (Randall 1998). This provides supporting evidence that the sample size of this study was large enough to accurately determine endemic status.

A total of 32 endemic species were recorded in the transect sampling. The species contributing the majority of individuals (36%) and biomass (20%) is the Saddle

Wrasse, commonly observed at more stations than any other species (frequency of occurrence=87%).

Indigenous fish species, which are taxa native but not unique to the Hawaiian Islands marine environment, comprise the vast majority of the abundance (7.2 per ha x 1000 and 73% of the total) and biomass 417 kg/ha (0.46 t/ha) and 77% of the total of fishes recorded (Table 4.5 and Fig. 4.7).

Table 4.5 Mean biomass and mean number of individuals by endemic status.

Status	mean biomass (kg/ha)	SD	median	IQR	mean numbers of individuals (ha)	SD	median	IQR
Endemic	63	363	0.002	0.16	2,250	900	0.16	0.005
Indigenous	417	91	0.008	0.02	7,160	1,300	0.16	0.160
Non-native	64	726	0.180	0.03	410	4,000	0.13	0.080

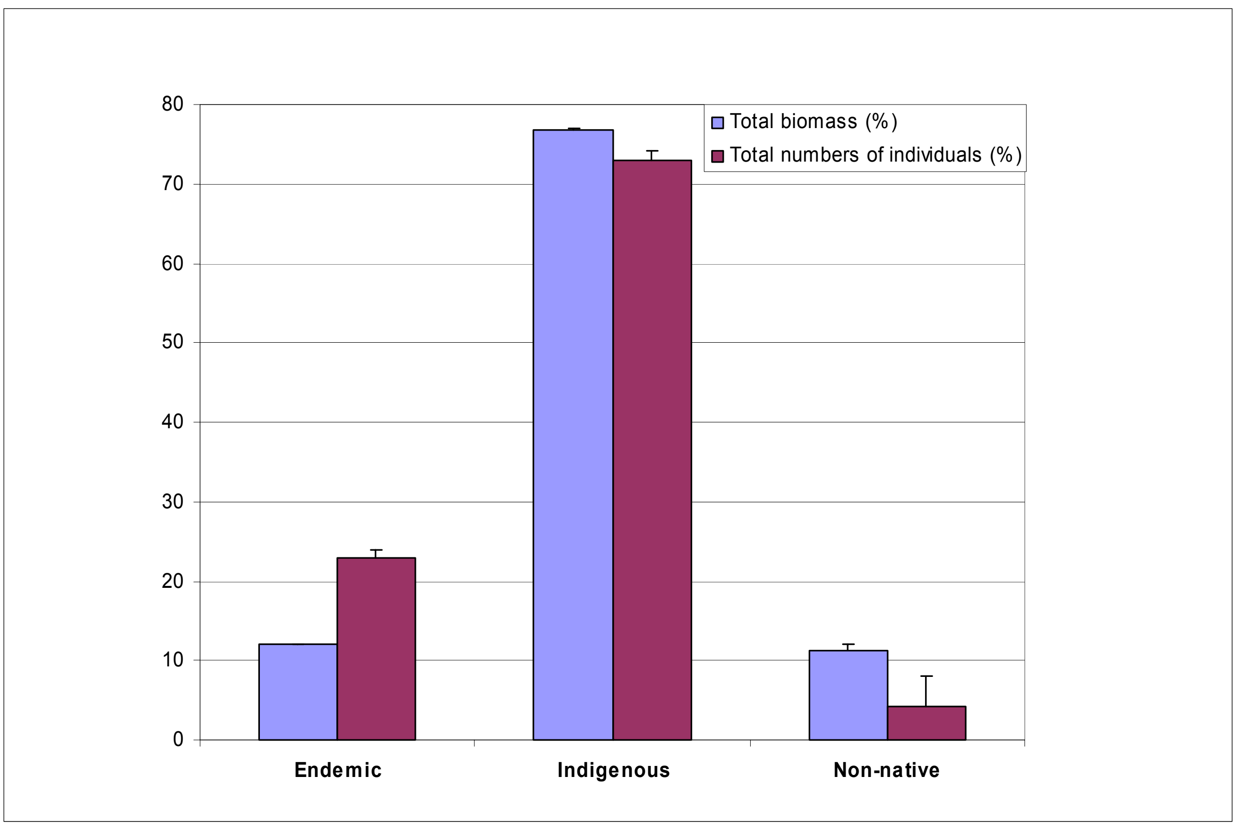


Figure 4.7 Biomass (%) and number of individuals (%) by endemic status.

Only 4% of the total abundance and 11% of the total biomass can be attributed to non-native species (Fig. 4.7). The alien species recorded include two introduced snappers, the Bluestripe Snapper, *Lutjanus kasmira*, (ta'ape) and the Blacktail Snapper, *L. fulvus* (to'au) and a grouper, the Peacock Grouper, *Cephalopholis argus* (roi). Since most snappers occurring in Hawai'i have historically been highly prized food fish ('opakapaka, ehu, onaga), but inhabit depths of over 60 m, the Hawai'i Fish and Game introduced three shallow water snappers from the South Pacific and Mexico in the mid 1950s and early 1960s in hopes of stimulating the commercial fisheries. These are among the 11 demersal species introduced within a 5 year period. *L. kasmira* and *L. fulvus* (to'au) have become widely established, while the third species, *L. gibbus* is extremely rare. None of these species has been widely accepted as a food fish among the local population or become successful in the commercial fisheries and the ecological effects of these aliens have only recently been realized. Histological reports from Work et al. (2003) found that nearly half of the ta'ape examined from O'ahu were infected with an apicomplexan protozoan. Furthermore, 26% were infected with an epitheliocystic-like organism with potential transmission to endemic reef fishes. In Addition, ta'ape from Hilo were found to host the nematode *Spirocamallanus istiblenni* (Font and Rigby 2000). Species of goatfish (weke and kūmū), a popular food fish for humans, may be displaced by ta'ape, which has also expanded its range into deeper water where 'opakapaka reside. Friedlander and Parrish (1998a) looked at patterns of habitat use to determine predation and resource competition between ta'ape and several native species within Hanalei Bay, Kaua'i, but found no strong ecological relationships.

The more common of the non-native snappers, ta'ape, was introduced from the Marquesas in 1958, while to'au was imported two years earlier in 1956. Although only 3,200 ta'ape were released on the island of O'ahu, they have increased their range to include the entire Hawaiian archipelago. The peacock grouper, *Cephalopholis argus* introduced by the state for commercial purposes in 1956 from Moorea, French Polynesia, has had more popularity as a food fish than the introduced snappers. The large size of this species is responsible for a biomass percentage that is 3 times the percent abundance (Table 4.5).

There are higher numerical and biomass densities of endemic and indigenous fishes at shallower depths. In contrast, introduced species are more prevalent in deeper waters. Endemism is twice as high at depths <10 m (14.3%) than at depths >10 m (7.9%) while introduced species have more than 10 times the densities at sites > 10 m (K-W test, $p<0.01$).

4.1.5 Summary of Size Classes

Size structure of fish populations can be an informative means of characterizing fish communities both spatially and temporally. Variations in recruitment processes such as production, transport, settlement, and mortality, can be revealed in missing or reduced size classes. Lack of recruitment can limit population size. Variations in size categories can explain variation in site attached fishes. The condition of different size assemblages can provide clues to causal mechanisms and links to environmental factors. Certain anthropogenic impacts can be detected, including the most influential impact of overfishing, by quantifying absence or highly reduced abundance of food fishes in the larger size classes.

Absence or overabundance in certain size groups can predict future trophic structure and species composition. Size classes can directly influence competition, predation, and shifts in community structure.

The high abundance of fishes in the smaller size class (15.6%) is due to a large numbers of *Chromis*. Although there are large numbers in the smallest size class, they comprise a very small percentage of the total biomass (0.3%). The opposite effect is represented in the largest size class where few fishes (19%) account for nearly 70% of the total biomass. The majority of fish abundance is in the 5-15 cm range (Fig. 4.8).

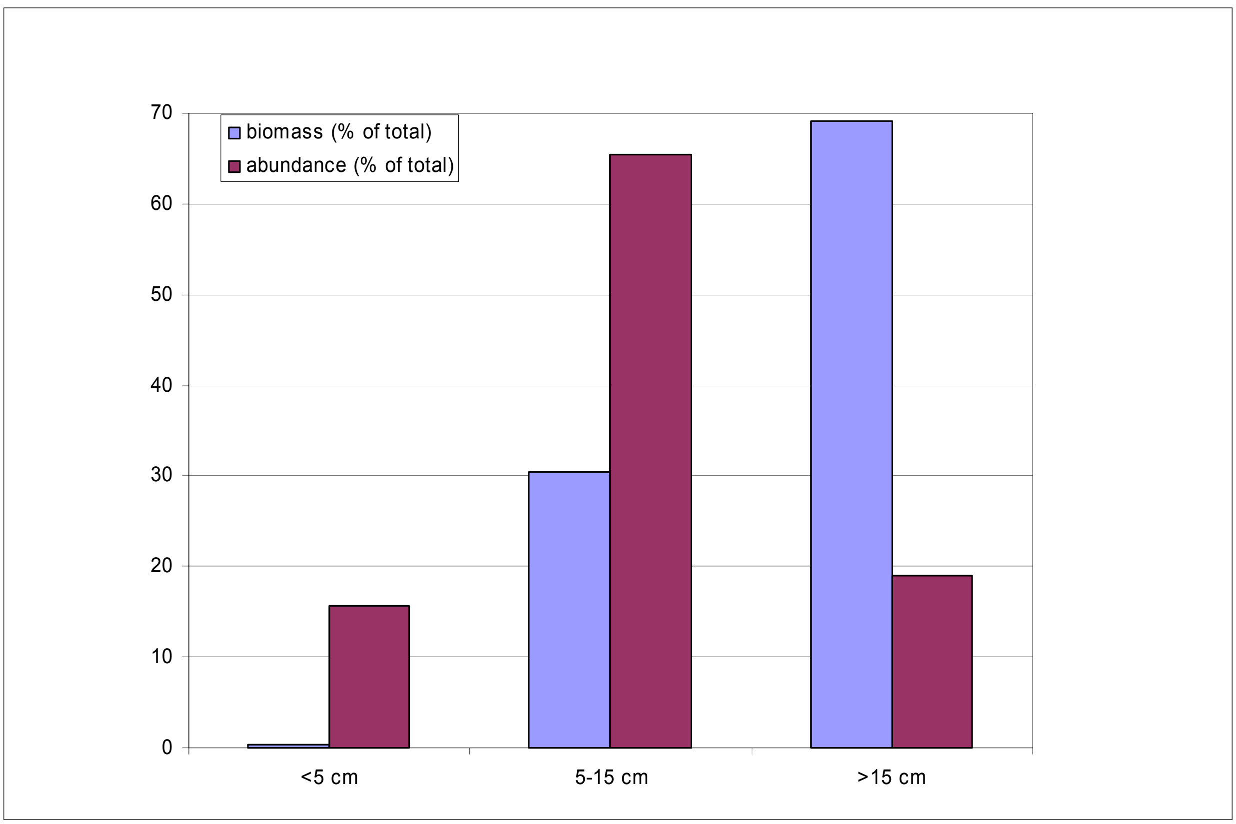


Figure 4.8 Size classes of fishes by biomass (% of total) and abundance (% of total).

4.1.6 Summary Statistics by Transect and Location

Transects within sites vary (Appendix 1) due to depth and substrate. All site information is reported by averages of pooled transects. Several sites rank consistently high in many of the fish parameters. Molokini Island, Maui ranks within the top five for diversity, evenness and biomass and Kanahena Bay (Āhihi Kīnaʻu), Maui scored consistently high for diversity, evenness, and number of species. Hanauma Bay, Oʻahu also ranks within the highest in the state for diversity and number of species. These three locations are all fully protected marine reserves. Molokini and Hanauma Bay are both state Marine Life Conservation Districts, where fishing is strictly prohibited, and Kanahena Bay is located within a federal Natural Area Reserve, where only extremely limited subsistence fishing is allowed.

In contrast, sites with a history of high anthropogenic impacts scored consistently low among the 56 locations surveyed. Waikīkī, Oʻahu and Pelekane Bay, Hawaiʻi are among the bottom five sites for all five parameters summarized (Appendix II). Kamiloloa, Molokaʻi ranks in the bottom five for abundance, biomass and mean number of species. Pelekane Bay and Kamiloloa have a long history of human induced sedimentation (Chapter 5: sediments) while Waikīkī has had chronic, sustained anthropogenic impacts, both of which clearly affect fish populations.

Mean number of species

Of 56 sites, the sites with the highest mean number of species are Molokini (28), Kanahena Bay (Āhihi Kīnaʻu) (28) and Honolua (27), Maui, Hanauma Bay, Oʻahu (27), and Nenue, Hawaiʻi (25). These top five sites are all marine protected areas. In contrast, the bottom five sites with the fewest mean number of species recorded all have open access to fishing. High sedimentation due to runoff and nearby dredging of Kawaihae Harbor placed Pelekane Bay, Hawaiʻi at the bottom of the hierarchy with an average of 1.7 species per transect. The majority of transects at Pelekane Bay had no recorded fish. Due to the heavy anthropogenic use of Ala Wai (12) and Waikīkī (8.8), areas of Oʻahu ranked in the bottom five. Unlike the other locations with the fewest species, Kaʻalaea (9.5) (Waiāhole) and Manana Island (10.5) (Rabbit Island), Oʻahu have few species but high numbers of fishes (Appendix II).

Diversity

Diversity is an important factor in many ecological and conservation issues. It can be an important factor in assessing the effectiveness of management regimes. Reductions in diversity can be indicative of overfishing, which selectively removes specific species. Other anthropogenic impacts, such as eutrophication, can result in phase shifts that strongly affect fish diversity.

The highest diversity is found at Molokini (3.0), Kanahena Bay (Āhihi Kīnaʻu) (3.0) Maui, Hanauma Bay (2.5) and Kahe Point, Oʻahu (2.5), and Leleiwi, Hawaiʻi (2.5). Three of these five locations are marine protected areas. The lowest diversity is found at Pelekane Bay (0.25) with few recorded fishes and Puʻuhonua o Honaunau (1.27), Hawaiʻi due to a small sample size and a large school of taʻape recorded in the survey of that site. On the island of Oʻahu, Kaʻalaea (1.1), and Waikīkī (1.2) rank low in diversity. The sand substrate encountered on the majority of the transects at Hulopoʻe, Lānaʻi had few fishes and thus, low diversity (1.1) (Appendix II).

Evenness

The top evenness scores are from Molokini (0.9) and Kanahena Bay (0.9) on Maui. Kamiloloa (0.9) on Molokaʻi, Kaʻapahu (0.9), located on the northwest side of Lānaʻi, and Nualolo Kai (0.8) on the Na Pali coast of Kauaʻi also rank high. The sites with the lowest evenness are Hulopoʻe (0.4) on Lānaʻi, Pelekane Bay (0.4) and Puʻuhonua o Honaunau (0.4) on Hawaiʻi, and Heʻeia (0.5) and Waikīkī (0.5) on Oʻahu (Appendix II).

Abundance

The top five sites with the highest numerical densities are Hulopo'e (26,520/ha) on Lāna'i, Ka'alaea (26,080/ha) and Moku o lo'e (18,560/ha) on O'ahu, Pu'uhonua o Honaunau (20,190/ha) and Kawaihae (19,600/ha) on Hawai'i. These sites have an order of magnitude higher abundance than the sites at the other end of the range (Figure 4.9). In sharp contrast, the 5 sites that have the lowest fish abundance are Waikīkī (3220/ha) on O'ahu, Hanalei (3960/ha) on Kaua'i, Kamiloloa (4640/ha) on Moloka'i, Lehua Island (5000/ha) near Ni'ihau, and Laupāhoehoe (5160/ha) on Hawai'i. Kamiloloa and Waikīkī have high levels of anthropogenic impacts that reduce fish populations, while Lehua and Laupāhoehoe are exposed to high wave energy and have low coral cover (<10%) and spatial complexity (Fig. 4.9, Appendix II).

These factors are all correlated to fish densities. The low biomass of fishes in Hanalei Bay is probably related to station selection and a low sample size that does not represent the bay as a whole. The two stations surveyed are located on the reef flat in close proximity to one another. Friedlander and Parrish (1998) found the lowest biomass to occur on the reef flats.

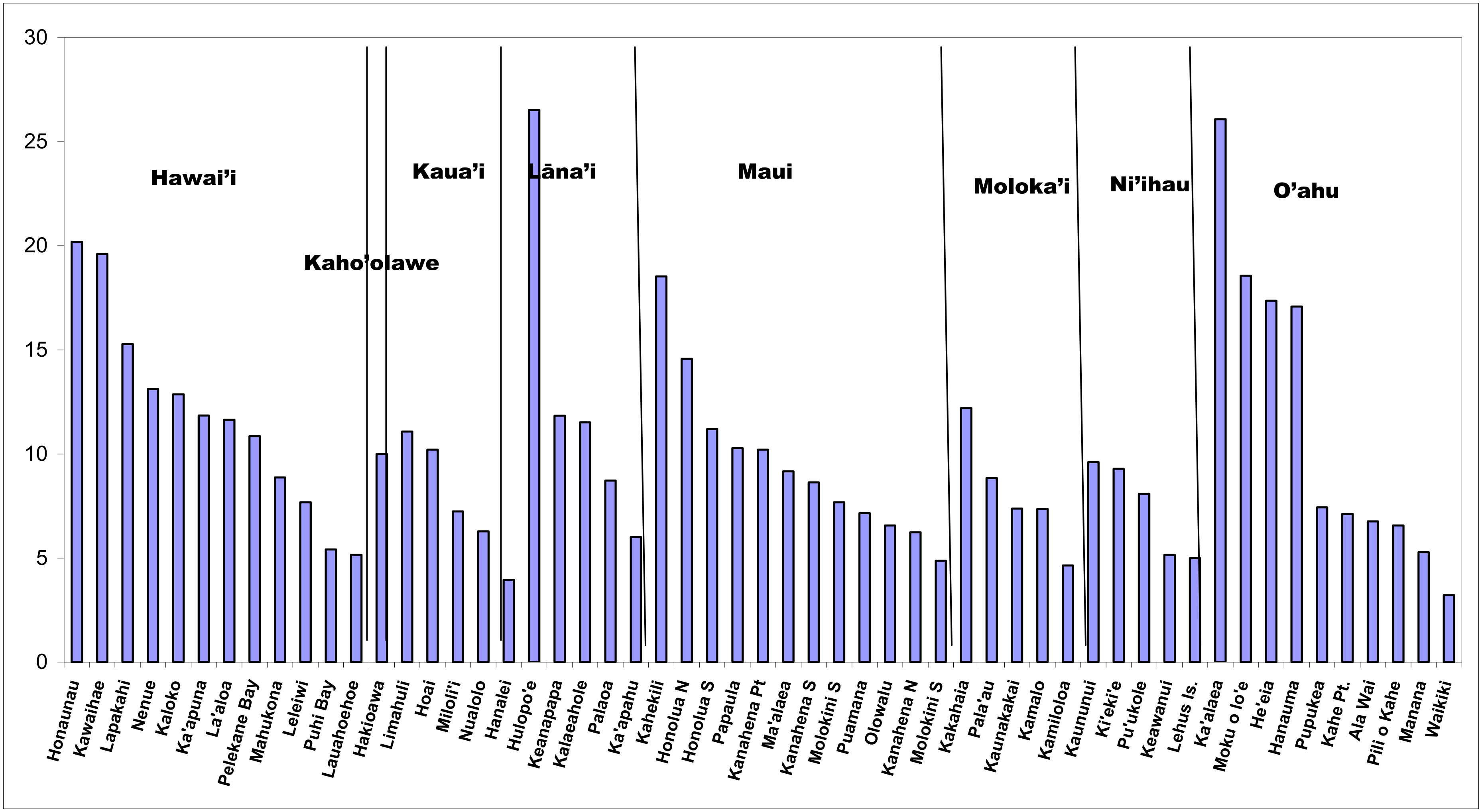


Figure 4.9 Number of fishes (ha x 1000) by location.

Biomass

The sites with the greatest biomass include Molokini Island (2,500 kg/ha), Kakahai'a (2,000 kg/ha) on Moloka'i, Honolua N (1,600 kg/ha) on Maui, Kawaihae (1,500 kg/ha) on Hawai'i, and Ki'eki'e (1,400 kg/ha) on Ni'ihau. These sites have nearly 20 times the biomass of those ranking near the bottom. Sites in the lower end of the range include: Pelekane Bay (54 kg/ha) on Hawai'i, Ma'alaea (127 kg/ha) on Maui, Kamiloloa (127 kg/ha) on Moloka'i, and Ala Wai (145 kg/ha) and Waikīkī (154 kg/ha) on O'ahu (Fig. 4.10, Appendix II).

The sites with the lowest biomass in the state all have historically, or are currently, experiencing strong anthropogenic influences. Dredging (Ma'alaea and Pelekane), sedimentation from runoff (Pelekane and Kamiloloa), and overfishing (Waikīkī and Ala Wai) can have lasting effects on fish populations.

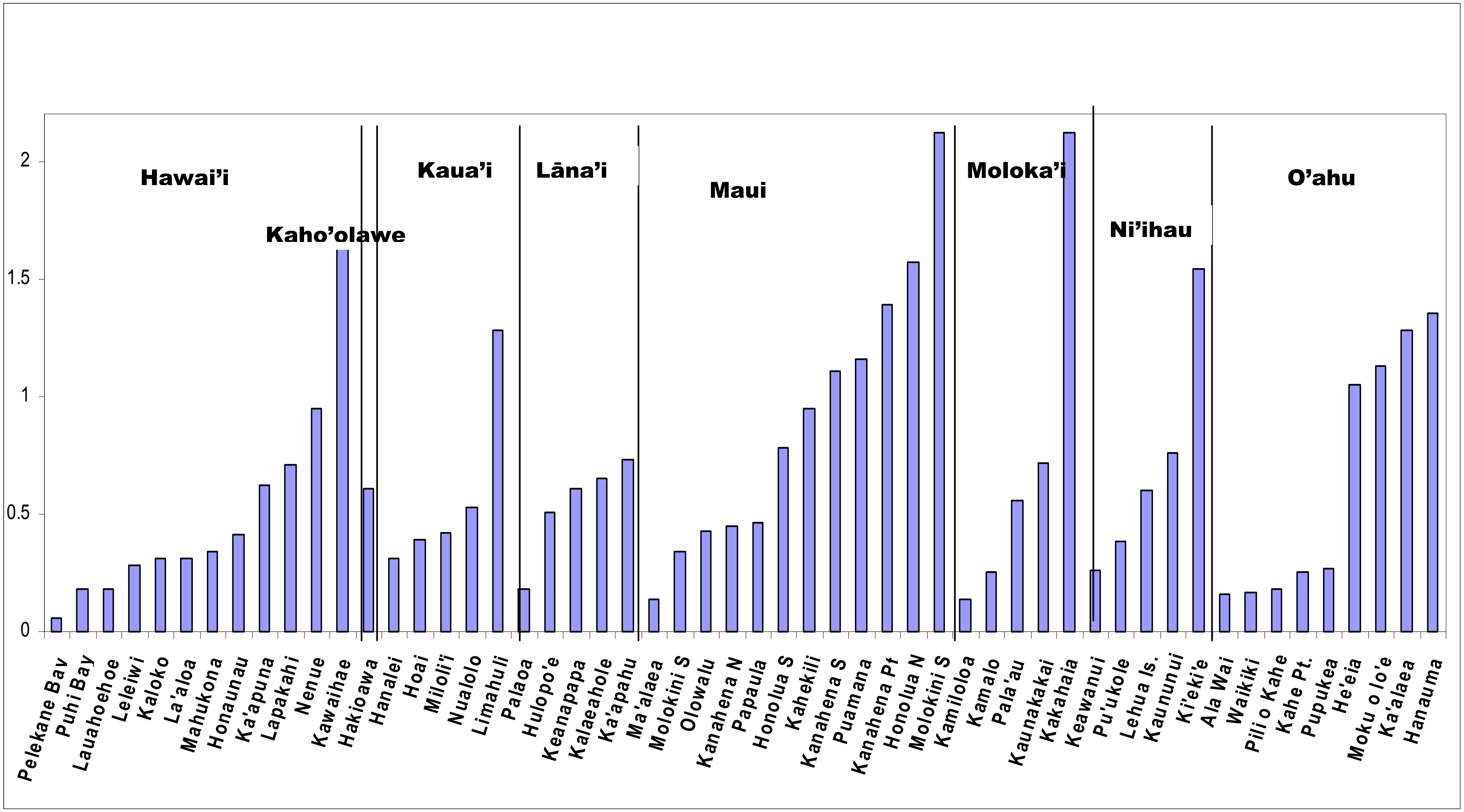


Figure 4.10 Biomass of fishes (Mg/ha) by location

4.1.7 Summary Statistics by Island

The island of Hawai'i has the highest number of fishes per hectare (11.6) (Fig. 4.11). This is due to the high number of *Chromis* species that are particularly abundant on the Kona coast. This may also be attributed to a disproportionate sample size, with the majority of the sites on that island located in West Hawai'i, where fish populations are relatively high.

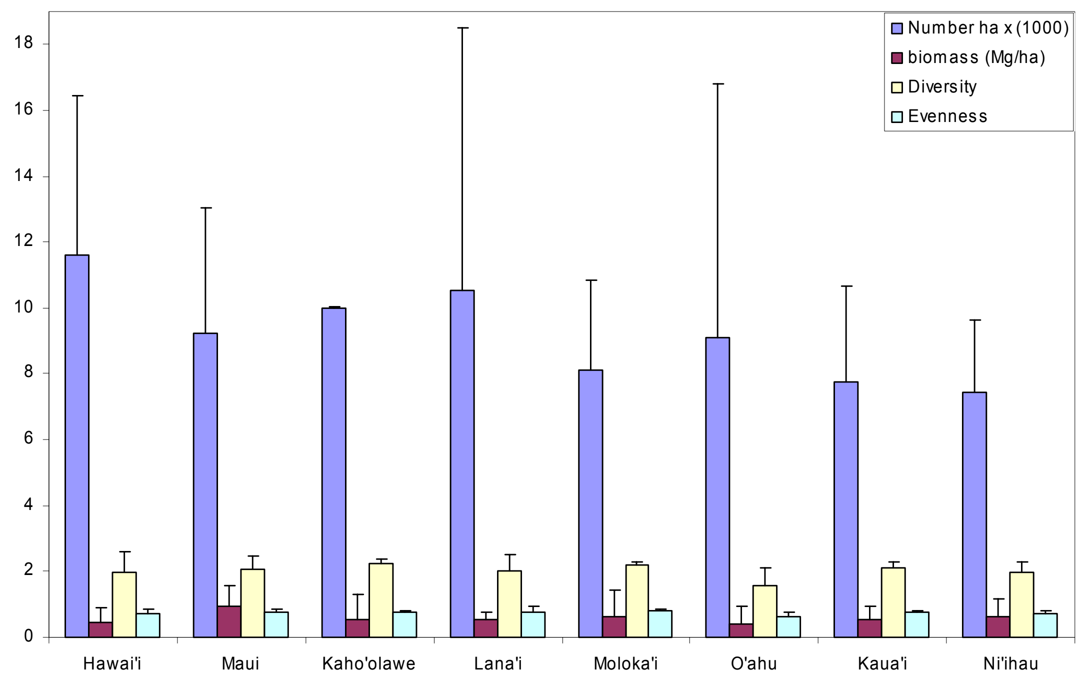


Figure 4.11 Mean summary statistics by island.

Maui has the highest biomass, followed by the more remote islands of Ni'ihau, Moloka'i, and Kaho'olawe. A large sample size and evenly spread distribution of sites may be a factor in Maui's high rating. The islands of Kaho'olawe and Moloka'i also have the high fish diversity (Appendix III).

Although the island of O’ahu ranks fifth in abundance, it is last in order for all other parameters explored, well below state averages for all fish assemblage characteristics (Appendix III). The slightly elevated numerical density rating is in large part due to high numbers of juvenile parrotfishes at the Kāne’ohe Bay sites. Although over half of sites surveyed on O’ahu are marine protected areas (56%), the low biomass (0.43 Mg/ha) attests to the heavy fishing pressure overall compared to the outer islands. O’ahu is also at the bottom of the hierarchy for fish diversity and evenness (Fig. 4.11, Appendix III). Although overfishing is the overwhelming cause of reduced fish populations, other contributing factors include pollution, coastal development, dredging, and sedimentation along with poor management practices.

4.2 Statistical Analyses

4.2.1 Fish Abundance, Biomass, and Diversity

Non-parametric Spearman correlations were used to determine which variables were most strongly correlated with fish assemblage characteristics (Table 4.6).

There is a moderate negative correlation between macroalgae and herbivores (r^2=0.46). Many sites without macroalgae had a high number of herbivores. Over half (62.5%) of the stations had no recorded macroalgae.

Table 4.6 Variables significantly correlated with fish parameters (Spearman's correlations)

Biomass	r_s	r_s^2	Numerical abundance	r_s	r_s^2	Fish diversity	r_s	r_s^2
Stream distance	0.66^s	0.44^s	Stream distance	0.68^s	0.47^s	Stream distance	0.61^s	0.38^s
Coral cover	0.59^s	0.35^s	Calcareous algae	0.63*	0.40*	Coral cover	0.53^s	0.28^s
Rugosity	0.59^s	0.35^s	*Porites lobata*	0.61^s	0.37^s	Macroalgae	-0.53^s	0.28^s
Macroalgae	-0.53^s	0.29^s	Coral cover	0.57^s	0.34^s	*Porites lobata*	0.52^s	0.27^s
Coral richness	0.50*	0.25*	Rugosity	0.53^s	0.28^s	Rugosity	0.49*	0.24*
Porites lobata	0.49*	0.24*	*Pocillopora meandrina*	0.50*	0.24*	Coral richness	0.46*	0.21*
Pocillopora meandrina	0.46*	0.21*	Coral richness	0.49*	0.2*4	*Pocillopora meandrina*	0.45*	0.20*
			Population w/in 10 km	0.4^+	0.16^+			

+=*a*<0.05, *=*a*<0.01, s=*a*<0.001

General linear multiple regression was used to determine the best model for predicting fish biomass, numerical abundance and diversity. To obtain a parsimonious model, many of the variables that made only a small contribution to explaining the variability were excluded. This facilitates ecological interpretation and management application.

The regression model using fish biomass as the response variable was significant among the stations (R^2 (adj)=58.6%, *p*=<0.001). The variation in biomass is best explained by 9 variables: organics, rugosity, calcareous and turf algae, total coral cover and diversity, silt, human population within 5 km, and management status. A negative relationship exists between biomass and human population within 5 km and organics, while all other variables are positively correlated with the response (Table 4.7).

Table 4.7 Statistically significant influential explanatory variables from multiple regression models for fish assemblages (p<0.05). The negative t ratio sign indicates a negative relationship. Blank cells indicate parameters not statistically significant for that dependant variable.

Parameters	**Fish biomass**		**Fish numbers per hectare**		**Fish diversity**	
	t ratio	P^a	*t* ratio	P^a	*t* ratio	P^a
Rugosity	3.5	0.001	3.3	0.001	2.17	0.032
Organics	-4.5	<0.001	-2.3	0.026	-5.7	<0.001
Population within 5 km	-2.3	0.021			-3.2	0.002
Silt	-2.3	0.023				
Calcareous algae	3.9	<0.001	4.3	<0.001	2.0	0.045
Turf algae	2.4	0.016	2.4	0.020	2.8	0.006
Montipora capitata			-3.8	<0.001		
Total coral cover	3.9	<0.001	5.0	<0.001	3.5	0.001
Coral diversity	2.2	0.029	2.7	0.008		
Management status	2.3	0.022	2.2	0.033		
Sand					2.1	0.042
Overall		R^2 (adj) 58.6%		R^2(adj) 54.1%		R^2 (adj) 49.2%

Multiple regression, with numerical abundance of fishes as the response identifies 8 explanatory variables: rugosity, organics, total coral cover and diversity, coralline and turf algae, *Montipora capitata*, and management status. This model was statistically significant (p=<0.001) and explained 54.1% of the variation in fish abundance. All significant variables except organics and *Montipora capitata* are positively correlated with the number of fishes observed (Table 4.7).

The factors that most strongly influence fish diversity are organics, human population, coral cover, wave direction, turf, sand, rugosity, and coralline algae (R^2 (adj)=49.2%, p=<0.001).

Fish populations are strongly related to coral communities. A non-metric multi-dimensional scaling (MDS) plot of 154 stations are ordinated by the fish community factors of biomass, number of individuals, and diversity. Those stations with low fish assemblage values cluster away from the majority of the stations. Total coral cover is superimposed on the fish characteristics to depict a relationship between them, as shown by the gradient of the size of bubbles increasing towards the right (Figure 4.12). Impaired sites are characterized by low fish community characteristics (sites in upper left) and low coral cover (smaller bubble size).

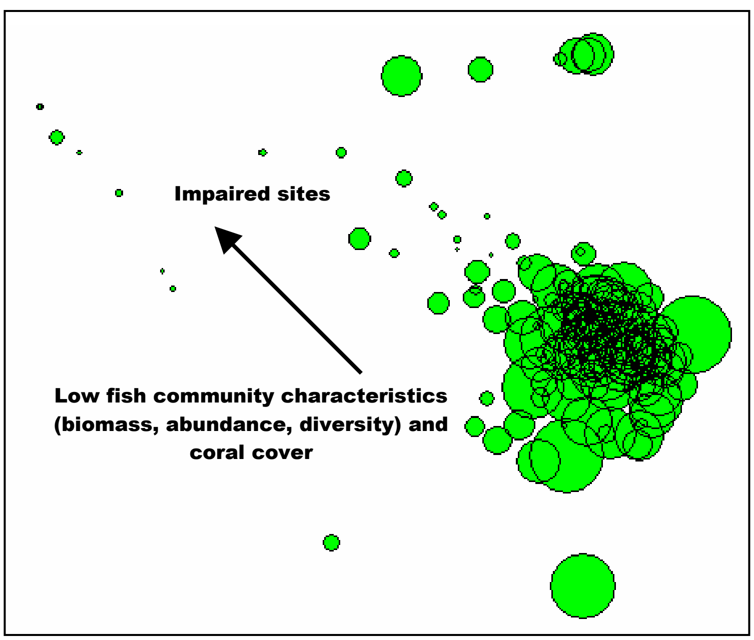


Figure 4.12 Non-metric multi-dimensional scaling (MDS) plot of stations ordinated by fish community factors and showing coral cover gradient.

4.2.2 Fishing Pressure

To determine if fish abundance and/or biomass can determine the degree of overfishing, a Kruskal-Wallis test was used. All species of fishes and select target species that represent popular food fish were used in the analyses. The target species included: surgeonfishes: *palani* and *pualu*, snappers: (*uku* and *wahanui)*, grouper: *roi*, jacks: (*papio*, *opelu* and *kahala)*, parrotfishes: (*uhu)*, squirrel and soldierfishes (*menpachi* and ʻ*ala ʻihi)*, big-eyes: (*ʻāweoweo)*, goatfishes: (*weke, weke ula* and *moano)*, rudderfish: (*nenue)* and unicornfish: (*kala)*. Degree of fishing pressure at each site was based on marine protection status and subjective expert knowledge. Sites were placed into one of three levels of fishing pressure: high, medium, and low.

Fishing pressure and protection status used as categorical variables were statistically significant (p=0.03) for numerical fish abundances although not for fish biomass. This pattern is consistent when using all species of fishes or only selected target species. Post-hoc Mann-Whitney tests found high/low fishing pressure for numerical abundances (p=0.02) and biomass (p=0.03) to be statistically different. The highest level of protection was also found to be statistically different from the lowest level for both numbers of fishes (p=0.03) and biomass (p=0.03). High variability between samples prevents stronger correlations. As sample size increase, this variability will decrease, allowing stronger gradients to be revealed.

4.2.3 Power and Sample Analysis

To determine whether the current sample size is sufficient to detect important differences with high probability in fish assemblage variables, a retrospective examination of statistical test power and sample size was conducted, with Minitab 13.2.

Fish counts ranged from 0 to 638 individuals per transect and biomass ranged from 0 to 14.6 (Mg/ha). Two influential observations were detected for fish biomass. An anomalous school of 500 *Lutjanus kasmira* (ta'ape) were recorded from Kakahai'a, Moloka'i and 400 *Decapterus macarelus* (ōpelu) were recorded from Pelekane Bay on the island of Hawai'i. Eight abundance outliers with counts over 300 included mainly small fishes from the genus *Chromis*.

In testing the power for detecting differences in counts of fishes, the level of significance was set at 0.05, to allow for a 95% chance of detecting an effect if one does exist (Sheppard 1999). The standard deviation was high (7,900), close to the mean of the population (9,800 individuals). At the sample size tested (184), a detection difference of 1,900 individuals per ha or 1/5th of the mean is possible over 90% of the time. This shows some confidence that the sample mean represents the true population mean. This level of confidence is adequate in detecting relative values of fishes to compare between sites, as was done in this study. To quantify absolute values by detecting a difference from the true population mean of 1,000 individual per ha, or 1/10th of the mean, 658 transects would be necessary. At the current sample size of 184, there is only a 40% ability to detect differences correctly at this level.

The level of power in detecting fish biomass is much lower than in detecting numerical abundances. The variability is extremely high, over three times the mean (SD=1.8), with a sample mean of 0.5 Mg/ha. At a sample size of 184 (as used in these analyses) a power value of 0.9 and a level of significance of 0.05, the difference detectable is approximately half the mean. To detect a 0.2 Mg/ha difference, which is one-third of the mean, 431 transects would be necessary.

4.3 Discussion

Fish biomass and abundance are strongly correlated with topographical relief, coral cover and diversity, human population, organics, management status, and coralline and turf algae.

4.3.1 Spatial complexity

In concert with this study, prior research has recognized the importance of topographic relief in the structure of fish assemblages throughout the world (Carpenter 1981; Holbrook et al. 1990) and in Hawai‘i (Friedlander and Parrish 1998a). It is evident that fish populations are highly associated with spatial relief for several reasons.

- Increased substrate provides habitat for benthic invertebrates, which serve as the main diet of many species of fishes, which in turn are utilized at other trophic levels.

- Increase in coral cover associated with rugosity feed obligate corallivores.
- Spatial complexity increases habitat heterogeneity, providing increased areas of refuge for fish populations from predation and competition.
- Topographical relief can expand the availability of resources and their production rate.
- Increased rugosity results in higher heterogeneity, creating habitat complexity that increases fish diversity. Coral diversity, correlated with fish populations, is also probably a direct result of habitat complexity.

Since habitat heterogeneity is important in structuring fish assemblages, an index of fish abundance may be obtained through rugosity measurements. There are clear advantages to this indirect measure of abundance.

A large sample size is necessary due to the high variability among fish populations, many rare, cryptic or mobile species can be under reported, and the power to accurately detect absolute fish abundances can be extremely low. Although the use of a rugosity index can not substitute for fish abundance data, it can serve as a relative indicator of differences between sites over large spatial scales where abbreviated surveys are necessary.

Spatial complexity can be an indicator in determining the distribution of fish size. For optimum protection, fishes select shelter that complements their size, reducing the risk of predation. Size of voids in reef structure are positively correlated to numerical and biomass densities (Hixon and Beets 1989).

Rugosity measurements are heavily influenced by coral cover and diversity, which are also found in this study to be highly correlated with fish populations. Thus, measurements of spatial complexity may prove to be a rapid way to assess both coral and fish communities.

4.3.2 Anthropogenic Impacts

Anthropogenic effects of overfishing of Hawaiian reef fishes have been extensively documented (Shomura 1987; Gulko et al. 2000; Brown et al. 2003; Friedlander et al. 2003). Results from this study determined that heavily populated areas near marine environments appear to have a large, negative effect on near-shore fish stocks on a statewide scale. This was also found to be true for coral community characteristics (see: section 3.1.2).

Organic material, which can be derived from anthropogenic sources, is also negatively correlated with fish populations, while marine protected sites, with reduced human impact, are shown to have the opposite effect.

4.3.3 Wave Energy

Regions sheltered from high wave energy have previously been reported to maintain higher fish populations and exhibited greater species diversity in Hawai‘i (Friedlander and Parrish 1998b; Friedlander et al. 2003). This inverse relationship between wave exposure and fish standing stock is most likely attributed to reduced habitat complexity in high energy environments. The seasonal variability in wave impacts can structure the physiography of reefs, reducing habitat and spatial complexity through a dominance of encrusting coral forms of corals. Although the influence of wave height in this research is related to fish assemblage characteristics, it is not among the most highly correlated factors controlling fish communities.

4.3.4 Herbivorous Association with Algae

No strong correlation between macroalgae and herbivores was found. Large numbers of herbivores were recorded from sites lacking macroalgae. This reflects the fact that most of the *Acanthurids* and *Scarids* which comprise a large percentage of the fishes recorded on the transects do not feed on macroalgae. Many of the fishes in these families feed on turf and filamentous algae. This is supported with statistically significant correlations between turf and fish densities.

4.3.5 Other Associations

Windward and Leeward sides of islands were found to have significant differences in some assemblage characteristics (see section 3.1.5). More fishes in the smallest size class (<5 cm) occur on the Windward sides of islands (K-W test, p=0.009).

Fish abundance and distribution is stratified by depth, making this habitat variable an important measure. Consistent with other research (Friedlander and Parrish 1998b), I found fewer species, but more fishes, at deeper depths. The mean number of fishes observed per transect, and the numerical and biomass densities, are considerably higher at stations >10 m than in shallower waters, while diversity and evenness are statistically similar.

4.3.6 Variability

High variability exists among fish populations. Spurious results from small sample sizes can occur due to the high spatial and temporal variability of fish populations.

The power to detect relative differences between sites for numerical abundance of fishes is sufficient; however, sample size must be substantially increased to confidently determine differences in fish biomass among sites. Thus, confidence in the validity of the formal tests conducted for biomass is low. The power to detect differences in fish biomass in this study is extremely low, due to high variability. The high variability is due to the different substrates selected at each site, which strongly correlate with fish populations. Although this is useful in habitat classification for the development of bioindicators to detect anthropogenic effects, and increases the statistical power in developing reference sites, it substantially reduces the statistical power of other tests conducted by increasing the variance.

To provide data that is truly representative of the average biomass, the sampling design would have to include several hundred more transects. Projected, continued surveys of additional sites will provide the increased statistical power needed to detect important differences in biomass and reduce variability.

The sampling time, effort and cost involved in most surveys is typically restrictive in conducting assessments over large areas, due to the large number of transects necessary to detect differences. It is possible that fewer transects coupled with rugosity measurements can detect relative differences between sites, although intermittent, large schools of fish may provide anomalous outliers that can strongly influence results.

4.4 Conclusions

- Numerical and biomass densities of fishes are strongly correlated with the environmental variables: rugosity, human population, depth, organics, fishing pressure and management status. Biological parameters influencing fish assemblage characteristics include coral cover and diversity and percent coralline and turf algae.
- Since rugosity is highly correlated with fish population parameters, identifying areas of high spatial complexity can assist managers in designing and implementing marine reserves and proposing fishing regulations.
- Extremely high variability exists among fish populations.
- The island of O'ahu ranks lowest among the 8 Main Hawaiian Islands in fish biomass, diversity and evenness. It is also near the bottom of the hierarchy in numerical densities, irrespective of the fact that over half of all sites surveyed are afforded some form of marine protection. This provides

strong evidence for overfishing and other anthropogenic influences tied to human population concentrations.

- Results from analyses of trophic guilds are consistent with the effects of heavy fishing pressure. Piscivores account for only about 1% of numerical abundances and 12% of biomass densities statewide, while approximately half of the total fish recorded are herbivorous. This is consistent with removal of top predators.
- Fish of commercial and recreational importance are visibly absent from the top ten fish species. The only species of relevance to local fisheries are species of juvenile *Scarids,* ranking sixth in abundance. Lack of larger *Scarids* provides evidence to support removal of adults from populations.
- Sites within protected marine reserves are among those with the highest fish densities, while sites with the influence of significant anthropogenic impacts scored consistently low in fish assemblage characteristics among the 56 locations surveyed.
- While the majority of fishes in the Main Hawaiian Islands are indigenous, almost one-fourth of the species recorded are found only in Hawai'i, and a very small percentage of the species quantified are non-native.
- The abundance and biomass of endemic and indigenous fishes decreases with depth, while it increases for introduced fishes.
- Although diversity and evenness are slightly higher in shallow waters (<10 m), numerical and biomass densities are considerably lower.

- The most abundant fish species in the MHI are the Black-finned Chromis, the Lavender Tang and the Saddle Wrasse, while the species with the highest biomass densities are the alien Bluestripe Snapper, the Black Durgon and the Whitebar Surgeonfish.
- The major aquarium species collected in Hawai'i, the Yellow Tang, the Orangespine Unicornfish and the Gold-ring Surgeonfish, are among the species with the highest densities in the state.
- The fish family with the highest density is *Acanthuridae*, with the majority of contributions from two of the twenty species recorded from this family, the Lavender Tang and the Gold-ring Surgeonfish.
- The majority of recorded fishes throughout the state are in the 5-15 cm range.
- There are smaller fishes on the Windward sides and larger populations of detritivores on the Leeward sides of the islands.

CHAPTER 5 SEDIMENTS

5.1 Results

5.1.1 Sediment Grain-size

Many sheltered areas, harbors and bays have low levels of large material and high levels of fine grain sediment. Many sites that have high silt/clay fractions also have high percentages of organics (r_s=0.67).

Five stations were found to have over 50% silt/clay (<63 *μm*). Over 80% of the 91 stations have very small amounts of silt/clay ranging from between 1% and 2% (Figure 5.1).

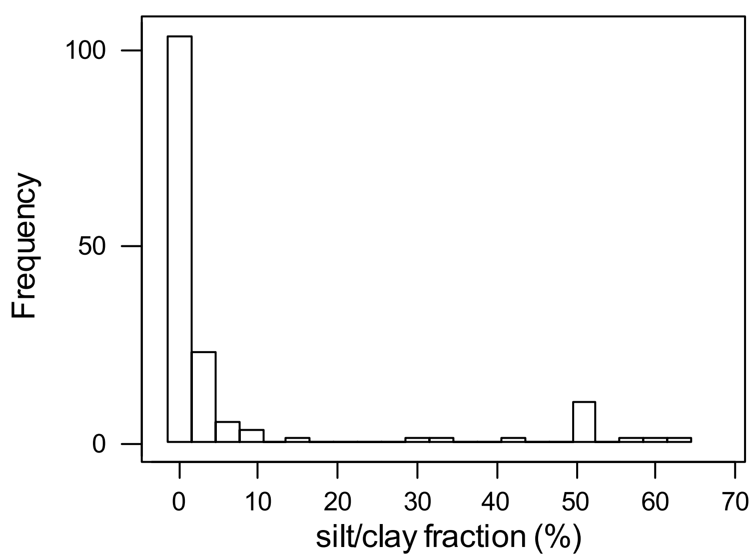


Figure 5.1 Frequency of occurrence of silt/clay fraction for 91 stations (bin size=3%).

Statewide percentages of silt/clay range from 0.1% at Pūpūkea, Oʻahu to 63.1% at Kaʻalaea, Oʻahu (Appendix IV). Wider ranges are exhibited for coarse and very coarse sands (500 *µm*-2.8 mm) and fine and very fine sands (63-250 *µm*). Medium sands comprise the smallest percentage of the total at Hanalei, Kauaʻi (0.4%) (Appendix IV and V) and the highest percentage at Kahe Point, Oʻahu (82.7%) (Appendix IV). Fine and very fine sands are lowest at Pūpūkea, Oʻahu (0.3%) (Appendix IV) and highest at Olowalu, Maui (87.2%) (Appendix IV). Statewide percentages of the largest size fraction (500 *µm* -2.8 mm) range from 0.1% at Hanalei, Kauaʻi to 98.5% at Nualolo Kai, Kauaʻi, exhibiting the widest range of the four grain-sizes (Appendix IV and V)

5.1.2 Sediment Composition

Organic Material (Loss on Ignition (LOI))

Sediments from 91 stations at 50 sites were included in the data analysis (Appendix VI). Statewide percentage of organics range from 0.2% at Ka'apuna, Hawaiʻi to 23.6% at Pelekane Bay, Hawaiʻi. The majority of the MHI stations (86%) have organic percentages between 2% and 5% (Figure 5.2, 5.3, Appendix VI). Several outliers were observed, including Pelekane Bay, Hawaiʻi (Figure 5.4), Kāneʻohe Bay, Oʻahu (Figure 5.5) and Hakioawa, Kahoʻolawe (Figure 5.6). Stations at these sites have organic values that range from 7.4% to 23.6% (Appendix VI).

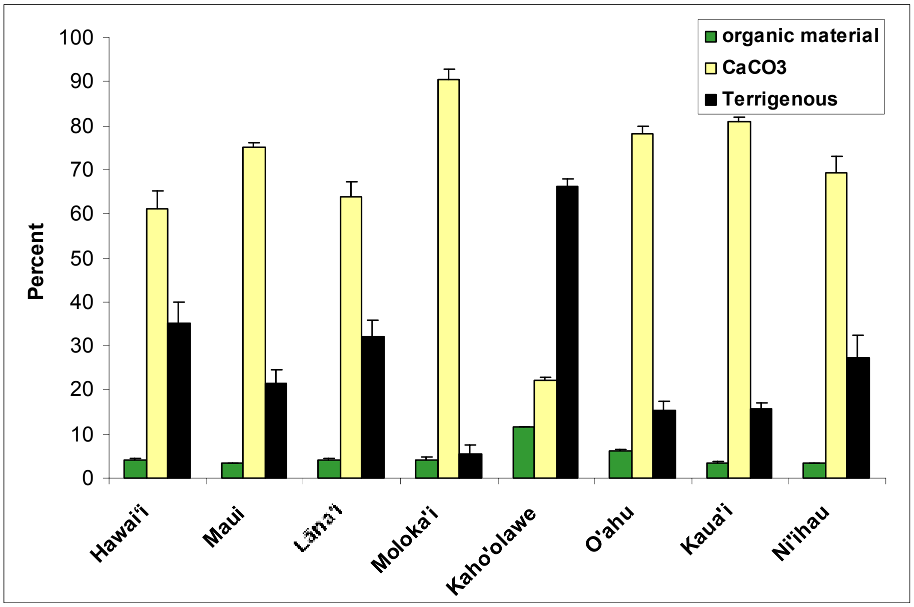


Figure 5.2 Mean summary sediment composition statistics by island (%).

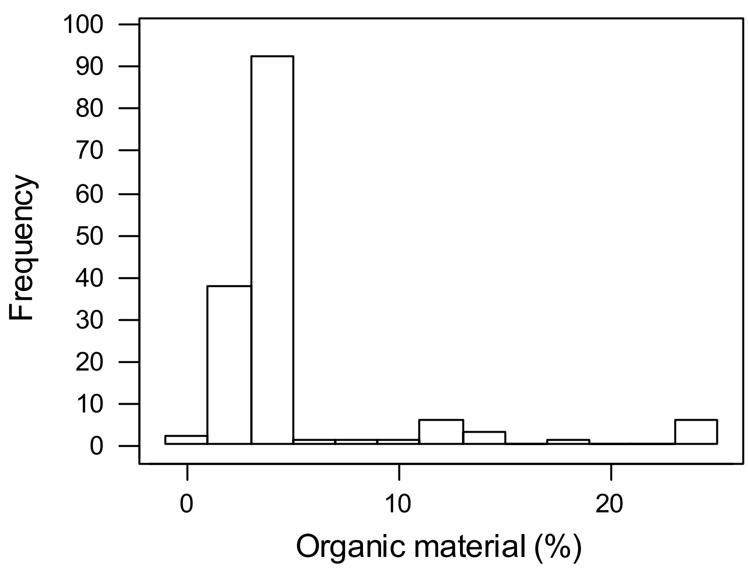


Figure 5.3 Frequency of occurrence of organic material for 91 stations (bin size=2%).

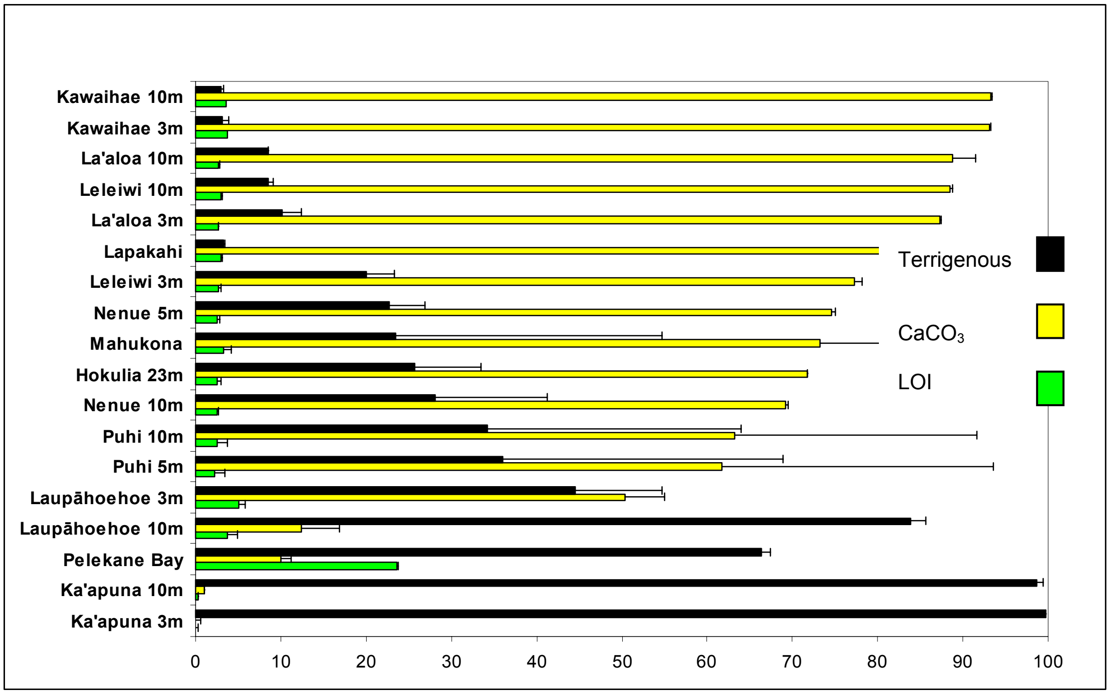


Figure 5.4 Sediment composition (%)-Island of Hawai'i.

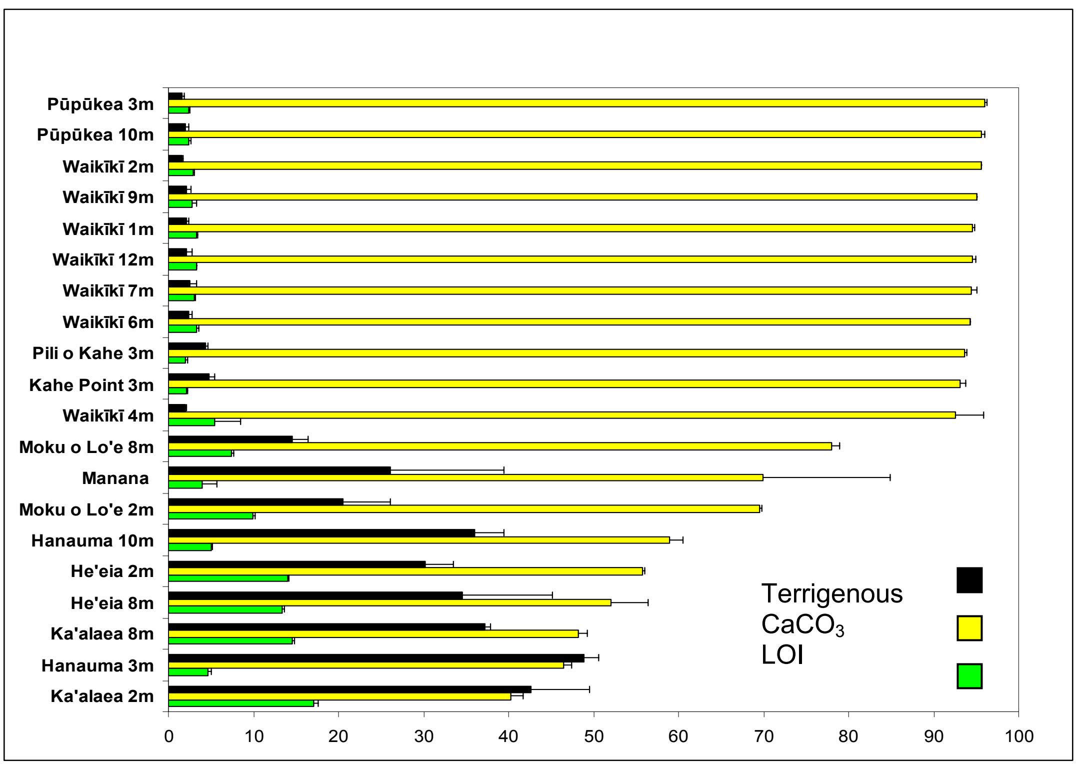


Figure 5.5 Sediment composition Island of O'ahu (%).

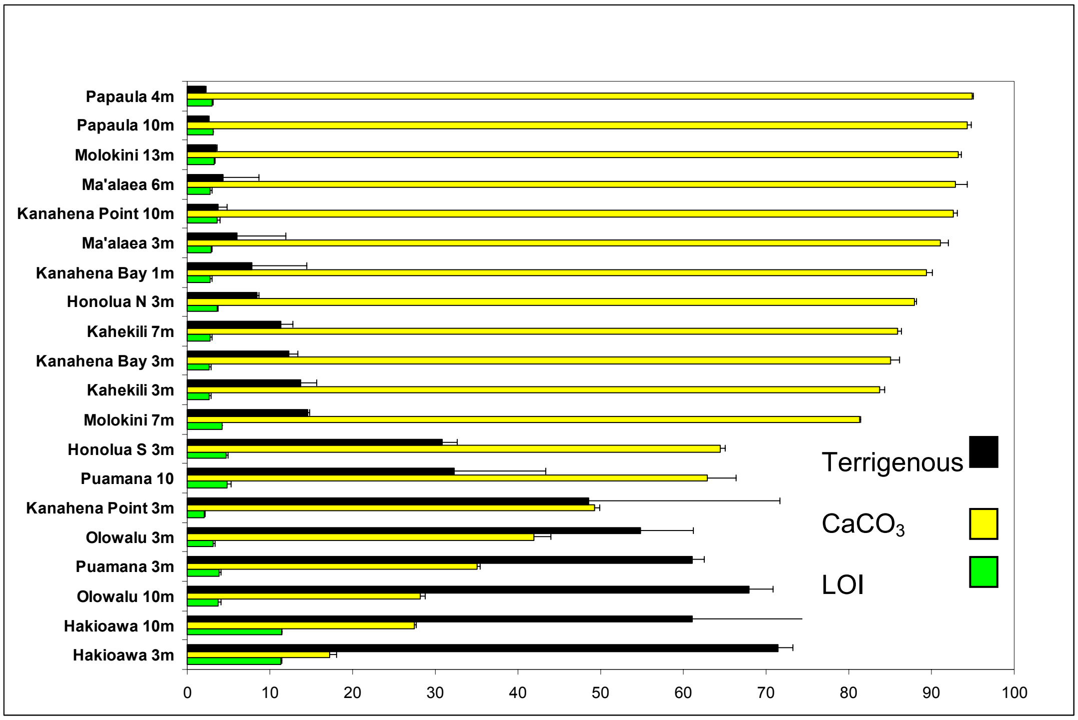


Figure 5.6 Sediment composition-Islands of Maui and Kaho‘olawe (%).

$CaCO_3$

Statewide percentages of $CaCO_3$ range from 1.5% to 96.5% (Figure 5.7, Appendix VI). Ka‘apuna, Hawai‘i (Figure 5.4) is anomalous, having extremely low percentages of $CaCO_3$ (<2%). Sediments from 31 of the 91 stations contain $CaCO_3$ percentages greater than 90%. Sites on all MHI are represented in this group (Appendix IV).

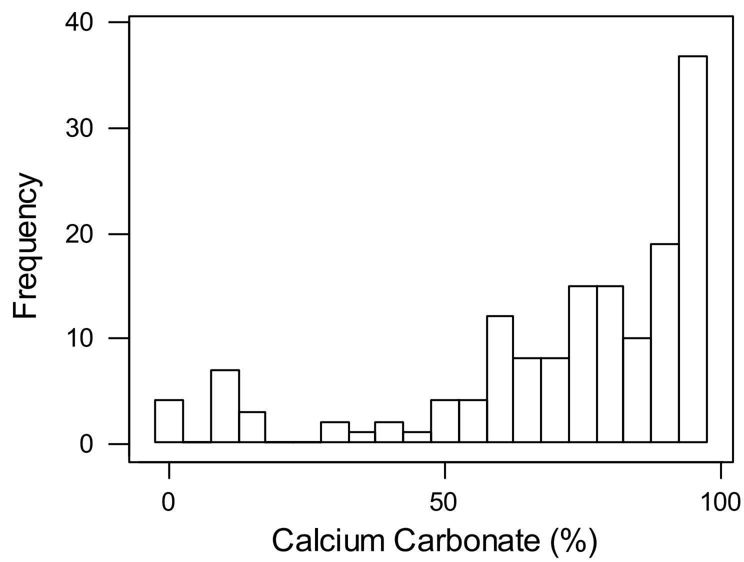


Figure 5.7 Frequency of occurrence of $CaCO_3$ for 91 stations (bin range=5%).

Terrigeneously based materials

Statewide percentages range from 1.4% to 99.7% (Appendix VI). Only 11 of the 91 stations have greater than 50% terrigeneous material. This is composed mainly of basalt or other land-based sediments. All Lānaʻi sites have much larger amounts of terrigenous material than Molokaʻi sites (Figure 5.8). Sites with greater than 75% terrigenous material are found on both the geologically oldest and youngest islands (Figure 5.4, 5.9)

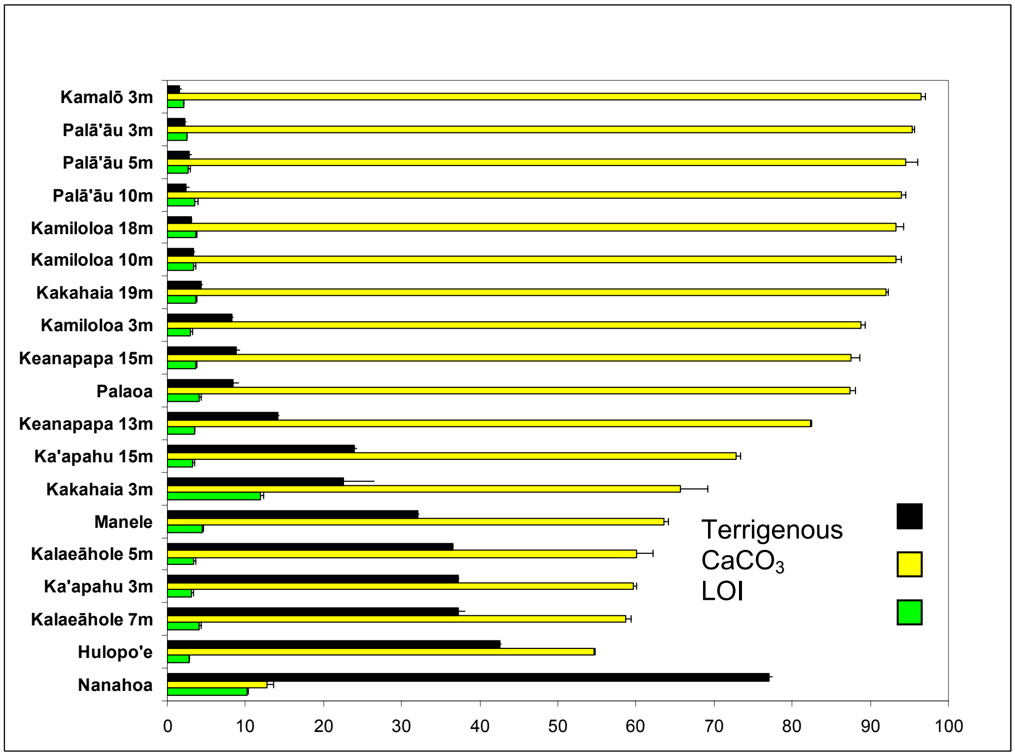


Figure 5.8 Sediment composition-Islands of Moloka‘i and Lāna‘i (%).

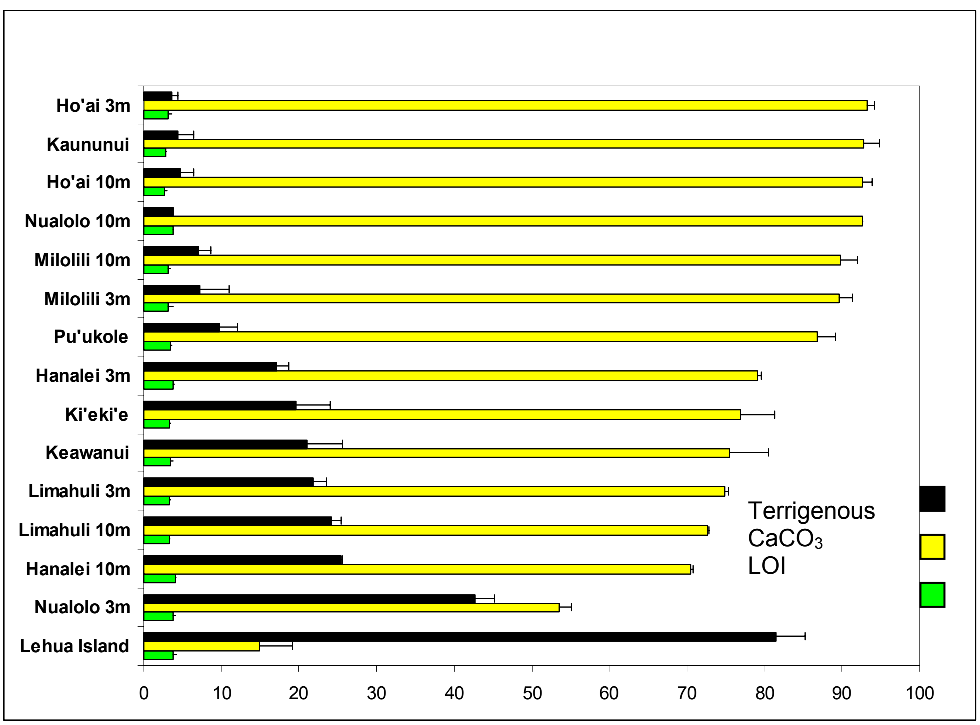


Figure 5.9 Sediment composition-Islands of Kaua‘i and Ni‘ihau (%).

5.1.3 Analyses

Principal components analysis using five variables including three grain-sizes, organic content and $CaCO_3$, revealed three distinctive groupings from the 91 cases (Figure 5.10). In the first three axes, 93% of the variability is accounted for.

Significant positive correlations were found between proportions of organic content and the silt/clay fraction (p=0.0) with a coefficient of determination of 67% (Figure 5.11). Likewise, there is also a significant relationship between $CaCO_3$ and the largest grain-size, coarse and very coarse sand (p=0.01), and $CaCO_3$ and the smallest grain-size, silt/clay (p=0.005).

The geologic age of the islands is significantly correlated with $CaCO_3$ proportions (p=0.005), with older islands showing higher proportions of $CaCO_3$ than younger islands.

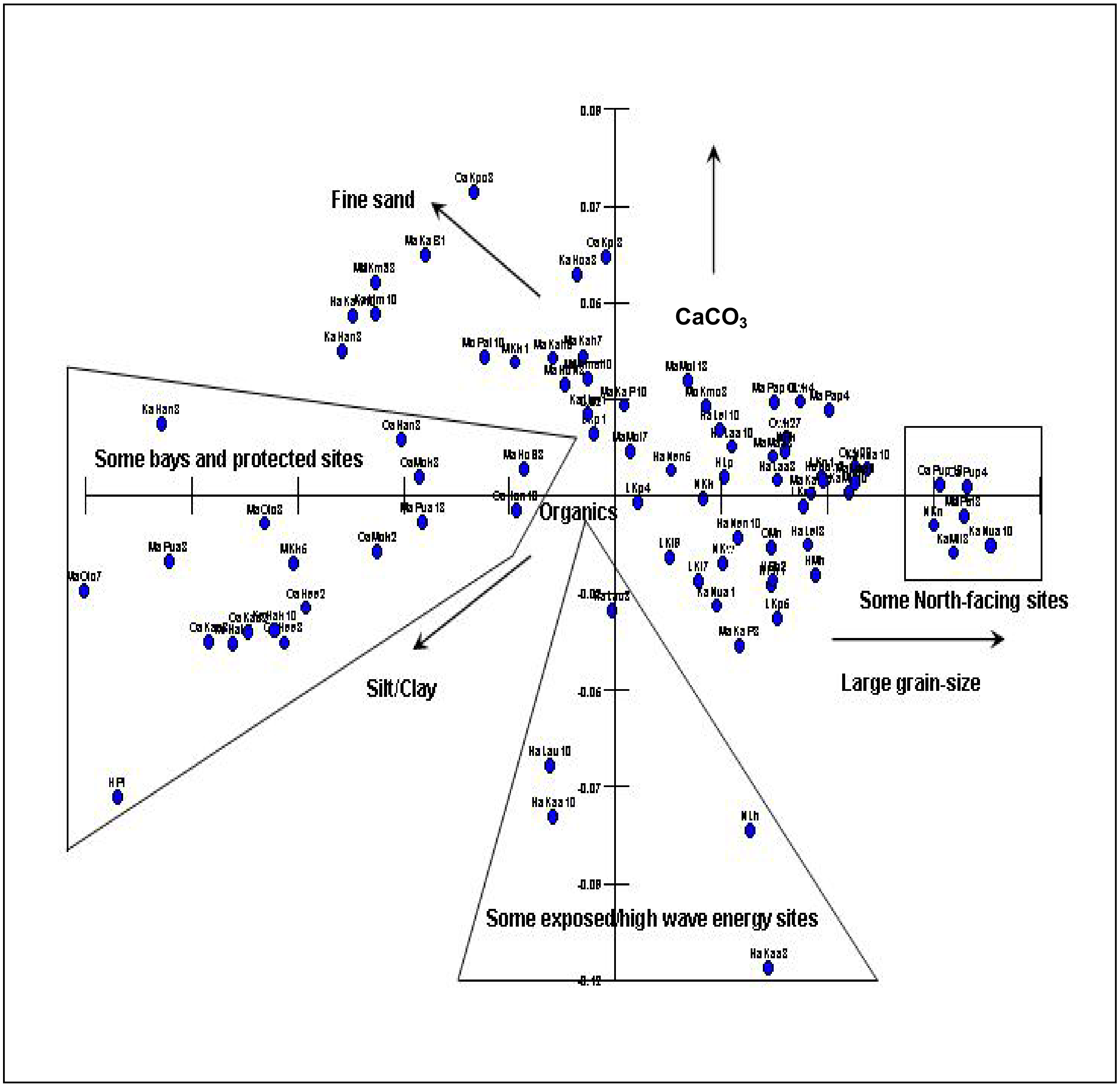


Figure 5.10 Multi-variate analysis of sediment composition and grain-size

Site abbreviations for RAT sites are as follows: 1st letter of island followed by 1st two consonants of site name, followed by transect number if more than one collection was made at a site.
Site abbreviations for CRAMP sites are as follows: 1st two letters of island followed by 1st three letters of site name followed by depth of site.

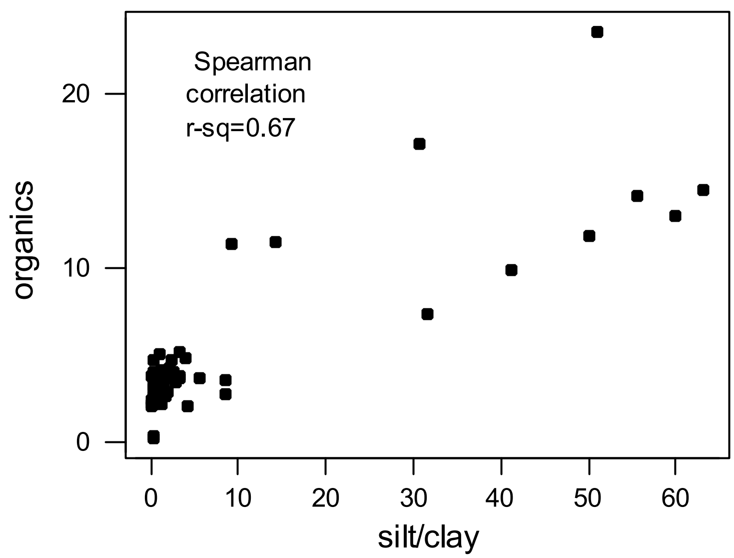


Figure 5.11 Regression analysis of proportions of organic matter and silt/clay fraction (<63 *μm*) (*p*=0.001).

5.2 <u>Discussion</u>

5.2.1 Sediment Composition and Grain-size

High organics and high silt/clay

Sediments containing high levels of organics and small grain-size (silt/clay) are indicative of areas heavily impacted by sedimentation and represent chronic disturbance to coral reefs. Sediment from all stations at both depths at Kāne'ohe Bay, O'ahu, Hakioawa, Kaho'olawe, Pelekane Bay, Hawai'i and the 3 m depth at Kakahai'a, Moloka'i contain a high percentage of organics (7% to 24%) and silt/clay material (9.2% to 63.1%). These 10 outliers are from four sites exhibiting the highest values among the 91 stations from 50 sites throughout the state (Appendix V). All of these sites with the largest proportion of organics and fine grain-size have been heavily impacted by chronic disturbances from sedimentation. Terrigenous organics are derived from land-based biotic material contributed through runoff. Kaho'olawe has a history of sediment loading due to devegetation from feral goats and bombing target practice (Te 2001). Sediment samples from Hakioawa, Kaho'olawe have a high percentage of fine grain particles and organic material, reflecting its past history of terrestrial sediment loading influenced by topography, vegetative cover and soil composition. Contributory anthropogenic stress factors such as sewage discharge and urbanization are not present at this site as they are at the other heavily sedimented sites throughout the state.

South Moloka'i also has a long history of devegetation due to overgrazing (Roberts 2000). Pelekane and Kāne'ohe Bays have limited circulation allowing accumulation and resuspension of sediments. Kāne'ohe Bay has an extensive history of dredging and sewage discharge with considerable urbanization in the surrounding watershed (Jokiel 1991). The main source of terrigenous materials into Pelekane Bay is through Luahine Gulch. Kawaihae harbor, adjacent to Pelekane Bay, has had extensive harbor development and modification that has interrupted long-shore sediment transport.

All stations on the islands of Kaua'i, Lāna'i (except Nanahoa) and Ni'ihau were found to be relatively similar in sediment associated organic content of sediments ranging from 2.7% to 4.0% (Appendix V). Nanahoa, with high organics (10.3%) receives extensive runoff from a denuded watershed during storm events.

High organics and low silt/clay

Sediments with high organics and low silt/clay may indicate anthropogenic stress from nutrification or enhanced fish feeding. Along with terrigenous input, organic contributions can be derived from marine sources such as decomposing algal material or fish detritus. Sites with high organic levels are highly correlated with the silt/clay fraction (<63 *µm*) (Figure 5.11) with the exceptions of Hanauma Bay and Waikīkī, O‘ahu 4 m and Molokini, Maui. These anomalies have organic values close to 5%, ranking in the upper range of the majority of the stations, yet have very low levels of the silt/clay fraction typical of sedimented areas. The Waikīkī sediment was collected from a habitat composed mainly of macroalgae that is typical of a large portion of the inshore habitat in Waikīkī. The following are possible explanations for the high organics and low sitl/clay found at Hanauma Bay and Molokini.

- low contribution of terrigenous material from the surrounding watershed
- past or current history of fish feeding
- high fish biomass

High terrigeneous material

Three sites have a terrigenous sediment component that exceeds 80% (mainly basalt). Not surprisingly, Ka'apuna, Hawai'i, the most recent lava flow, has the highest percentage in the state: 3 m (99.7%) and 10 m (98.6%) (Appendix V). Other sites with high percentages of basalt include Laupāhoehoe, Hawai’i and Lehua Island, Ni‘ihau. While sites on Hawai’i, the youngest island have a sediment composition high in basalt, sites on Kaua’i, the oldest of the MHI have very low levels. Most of the stations (87%) have organic values that range between 2% and 5%.

While 7 of the 50 sites had values higher than this range, only one site exhibited lower values at the other extreme of the spectrum. Ka‘apuna, Hawai‘i has very low organics and carbonate and high terrigenous material. The black basaltic sand found at this site is derived from a recent lava flow in the 1950’s.

High carbonate

Beaches at Waikīkī were artificially replenished with sands imported from Moloka‘i and Kahuku, O‘ahu (Sano 1992). Thus, sediments from Waikīkī stations are all similar in composition and grain-size reflecting the contributing source. These sediments are high in $CaCO_3$ and have a high proportion of coarse grains.

Depth stratification

Of the four grain-sizes processed, only the largest grain-size is statistically different between depths. Although stations <5 m have an average of 8% silt/clay fraction, while those >5 m have considerably lower percentages of fines (5%), this was not found to be statistically different. This trend persists for fine and very fine sands (<5 m=15%, >5 m=14%). Medium sands at shallower depths (23%) are also similar to those at deeper depths (21%). The largest size fraction at depths <5 m (55%) and >5 m (36%) (p<0.001) is the only significantly different grain-size parameter.

In contrast, differences were found between depth categories in most sediment composition parameters. The average organic matter is significantly higher at depths below 5 m (6%) than at depths above 5 m (4%) (p=0.03), while $CaCO_3$ shows an opposite trend. There is a significant difference between $CaCO_3$ at shallower depths (67%) than at deeper depths (76%) (p=0.047). Average percentages of terrigenous material are relatively similar between depths, showing no statistically significant difference (<5 m=27%, >5 m=20%; p=0.08).

5.2.2 Analyses

Most of the sites are relatively similar, consisting of high $CaCO_3$ (>60%) and 2% and 4% organic material. Sites that deviate from this main group are clearly evident and can be predictive of the forcing functions driving the system.

Principle components analysis grouped samples, into three main clusters that deviate from the majority of the stations from sediment composition and grain-size (Figure 5.10). The cluster in the middle left of Figure 5.10, includes sites heavily impacted by sedimentation that are high in silt/clay and/or organics. The sites in this grouping include bays and sheltered sites. High silt/clay fractions are correlated with low coral cover (see section 3.1.2). When fine sediments overwhelm the system, as they do at the sites within this group, sedimentation becomes the dominant forcing function on community structure.

The second cluster, at the bottom of Figure 5.10, includes sites that have high proportions of basalt and low levels of $CaCO_3$ such as Kaʻapuna and Laupāhoehoe, Hawaiʻi and Lehua Island, Niʻihau. Sites with these sediment characteristics have low coral cover and are primarily dominated by *Pocillopora meandrina*, a species found in shallow, high wave energy environments.

The third cluster, in the middle right of Figure 5.10, includes sites that are on exposed, north–facing shores, that are characterized by high proportions of large-grains and low proportions of fines. At sites like these exposed to high storm surf, sediments are reworked and fines winnowed by waves.

As expected, regressions show a carbonate latitudinal gradient across the islands. This stratification is statistically significant (p=0.005), showing a positive relationship between the age of the islands and $CaCO_3$. Older islands have had a longer time for reef development and erosional processes to occur.

5.3 Conclusions

- Sediments containing high levels of organics and high silt/clay are indicative of areas heavily impacted by sedimentation, while those with high organics and low silt/clay may indicate anthropogenic stress from nutrification or enhanced fish feeding.
- When silt/clay overwhelm the system, sedimentation becomes the dominant forcing function on community structure.
- A carbonate latitudinal gradient exists across islands. The older the island, the higher the proportion of $CaCO_3$.
- Sites that have high proportions of basalt and low levels of $CaCO_3$ have low coral cover and are primarily dominated by *Pocillopora meandrina*, a species found in shallow, high wave energy environments.

- Many sites with north-facing exposures have high percentages of large grain sizes. This may be attributed to strong currents and high waves that flush and remove fines.
- Depth stratification of some sediment parameters occurs. Organic matter, $CaCO_3$, and large grain-sizes are stratified by depth, while smaller grain-sizes and terrigenous material are not.
- All Kāne'ohe Bay, O'ahu samples are strong outliers in all sediment characteristics. This region is also anomalous to the rest of the state in coral cover and fish biomass and is likely a function of both natural conditions and several decades of anthropogenic impacts.

CHAPTER 6 MODELING HAWAIIAN CORAL REEF CONDITION

6.1 Introduction

For decades, the search for a measure of “reef health” has engaged managers and scientists alike. Yet this elusive “silver bullet”, which can be used to identify impairments and determine the cause of impacts in marine ecosystems, continues to be evasive. However, there is a clear need for quantitative models or indicators that describe the general ecological condition of a coral reef community. For example, federal agencies conducted two recent workshops in Hawai‘i in order to present their needs to the coral reef research community and elicit their input. Both workshops were directed at promoting the development of techniques that can be used to establish the impact of anthropogenic activity on coral reefs. The first was a joint Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA), United States Geological Survey (USGS) Workshop entitled “Assessing Pollution Stress on Coral Reefs” held in Honolulu on 23-25 August, 2004. A second workshop entitled “Coral Reef Functional Assessment Workshop” was held at the University of Hawai‘i from 31 August to 2 September, 2004 under the auspices of the U. S. Army Corps of Engineers (USACE) with participation by EPA, NOAA, Hawai‘i Department of Health (DOH), Coastal Zone Management (CZM) and a wide range of research units.

Defining and measuring the condition of a coral reef ecosystem is an extremely difficult task. These communities are shaped by complex and highly variable interrelationships between numerous ecological factors. It is unlikely that the condition of a complex coral reef ecosystem can be quantified using a single factor such as abundance of an “indicator species” or through measurements of a physiological process. However, there is a possibility that a combination of key ecological metrics can be used to define the ecological status or “health” of a coral reef. Since factors relate on a large scale, a community or ecosystem approach is superior to a localized focus on a lower level.

An extensive review of the coral reef ecosystem assessment literature concluded that “At this time, sufficient information does not exist to draft biocriteria guidance for coral reef ecosystems” (Jameson et al. 1998). During 1998 the Hawai‘i Coral Reef Assessment and Monitoring Program began an extensive field program to develop the techniques and compile the extensive data required to allow quantitative evaluation of the condition of Hawaiian coral reefs. The original CRAMP experimental design utilized a wide range of easily measured key variables. The present research integrated a compatible Rapid Assessment Technique to expand spatial coverage and incorporate essential environmental and anthropogenic variables for all sites. This investigation was directed at development of models that could be used to evaluate coral reef condition. The first step was to develop the required information in the form of a database. The second step was to quantitatively identify those factors that are reliable metrics for reef condition. The third step was to use these metrics to develop descriptive models. The fourth and final step was to test and evaluate the models.

6.2 Methods

6.2.1 Development of information database

Initial survey sites were selected on the basis of degree of perceived environmental degradation by expert observers, level of management protection, and extent of wave exposure. These selected sites provide a representative cross section of Hawaiian coral reef communities.

Analyses of the initial data (Friedlander et al. 2003) indicated that a much larger spatial array was desirable because the coral reefs of Hawai‘i are diverse and show high variability for many ecological parameters. Thus, the original data were supplemented using a RAT, an abbreviated version of the CRAMP monitoring protocol, using a single 10 m transect to describe benthic cover, rugosity, and sediments. This protocol generates the same biological data (i.e. percent cover, species richness and diversity) and environmental data (e.g. rugosity, depth, sediments, etc.) as the CRAMP monitoring dataset. These transects were stratified on hard substrate in a manner similar to the CRAMP monitoring sites but along a full range of depths (1-25 m). The advantage of the new approach is that it allows for the rapid acquisition of spatial data suitable to describe the variation in communities and the forces controlling these distributions. The RAT is not designed to produce the type of data needed to detect temporal change such as gathered at the CRAMP monitoring sites. An additional 21 RAT sites were added to the 31 CRAMP sites. Experimental design and all biological, physical and environmental data collection methods are described in detail in Chapter 2. These data were entered into MS Access, MS Excel and ESRI ArcView as appropriate.

6.2.2 Identification of Major Factors

To develop a model that includes attributes that respond to anthropogenic impacts, the environmental factors that most strongly influence biotic communities must be identified.

6.2.2a Variable Ranking

A preliminary examination of the data involved a simple ranking based on the range of values from all stations. Variables were sorted in MS Excel to locate the descriptive variables that best relate to coral and fish population parameters. Each environmental factor was paired with one of the following explanatory variables: coral cover or fish numerical or biomass abundance to determine which factors may be useful in statistical analyses (e.g. stations with high levels of silt have low coral cover).

6.2.2b Quantitative Analyses

More detailed quantitative analyses were then undertaken. Data were transformed as described in Chapter 2, as appropriate to meet the assumptions of normality, linearity, and homogeneity of variance required for some of the formal statistical tests performed. Statistical analyses were conducted using Primer© 5.0, MVSP© 3.0, ProStat© 3.01 and Minitab© 13.0 software to examine both univariate and multivariate aspects of the spatial data sets. The data base consists of 61 variables that were measured at 184 stations within 52 sites.

To identify which environmental factors were most important in structuring coral and fish assemblage characteristics and to narrow the field of variables, multiple regression, correspondence analysis, and a non-metric multi-dimensional scaling techniques were used, as described in Chapter 2. Multivariate procedures (BIOENV and SIMPER) were used to link biological data to environmental data to find patterns in coral communities and to determine the contribution of each species to site similarities (see Chapter 3). These results were later used in the development of the final model to determine weights for each factor.

6.2.3 Development of Models

6.2.3a Reference Site Model (RSM)

Most previous studies of coral reef condition have included reference sites. Thus, the initial modeling effort embraced this concept. In general, a "pristine" area is selected by experts to serve as a comparison to the "impacted" reef under study. Reference site selection can be troublesome due to the difficulty in determining optimal reef conditions. Sliding baselines that change over time can make determination of pristine conditions impractical. Without prior comparable historical data, this hypothetical baseline is elusive. A more pragmatic way to measure baseline conditions is to select sites unaffected by anthropogenic disturbances and compare their biological communities to other sites of interest. During the present study, sites remote from human influence or those in marine protected areas with a high degree of protection were qualitatively assumed to be reference areas. Reference sites must be determined qualitatively to avoid a circular argument where the quantified data is used both to select and analyze the sites. Although this provides an external means of defining the reference conditions used to compare against impacted areas, it is highly subjective.

Since depth and wave exposure were found to be highly influential in determining biotic communities, the first attempt at developing a model divided the reference sites into six habitat classes (3 depths and 2 wave exposures) based on these key factors. Considerable overlap between reference sites and non-reference sites prompted the expansion of the model to 12 habitat classes (3 depths and 4 wave exposures) based on depth and direction of wave exposure. The later factor is based on the work of Friedlander et al. (2003) on fish communities.

Reference site analyses

Initially, it was essential to determine if the reference sites were environmentally different from the non-reference sites. A PCA was used to evaluate how well sites were separated.

Next, it was necessary to determine if the reference sites in a given habitat class were different from the reference sites in other classes. Several types of analyses were performed.

1) A discriminant analysis was performed to determine if the reference sites fell within their predicted habitat class.

2) A cluster analysis was also conducted to determine if the reference sites in each class grouped together.

3) An analysis of variance was used to determine which variables influenced these reference site similarities and which factors were significantly different between habitat classes.

6.2.3b Ecological Gradient Model (EGM)

There has been recent interest in applying a hydrogeomorphic model (HGM) classification approach to Hawaiian coral reefs (USACE Coral Reef Functional Assessment Workshop 2004). This model has been applied widely to wetlands and places emphasis on abiotic features with three components: (a) geomorphic setting, (b) water source and its transport, and (c) hydrodynamics (Brinson 1993; Brinson and Rheinhardt 1996; Magee 1996). Geomorphic setting is the topographic location of the wetland within the surrounding landscape. The types of water sources can be simplified to precipitation, surface or near-surface flow, and groundwater discharge. The third component (hydrodynamics) refers to the direction of flow and strength of water movement within the wetland. These components are responsible for maintaining many of the functional aspects of wetland ecosystems.

Initial work showed that the reference site concept created difficulties because of its subjective nature so additional models were explored. A classification system based on depth, degree of wave shelter and wave regime, similar to the geomorphology and hydrodynamic characteristics used in the HGM approach, was implemented to define the major habitat classes.

6.2.4 Evaluation and Testing of Models

6.2.4a Reference Site Model (RSM)

It has been suggested that anthropogenic impacts may be established for a site if variables within a habitat class deviate from the established ranges of their reference sites (USACE Coral Reef Functional Assessment Workshop 2004). Two methods were employed in testing this concept.

1. Test sites. Sites not previously surveyed were compared against reference values to identify departures from reference conditions within the appropriate habitat class and to evaluate the RSM's predictive ability to detect degradation. A site perceived to have high anthropogenic impact and a site with low disturbance were selected to test the RSM. These two sites provided an additional 24 stations for use in model evaluation and testing.

2. RSM comparisons. Non-reference sites with known impacts were compared against the reference ranges within the appropriate habitat class to determine if these values can indicate general disturbance and stress specificity. These sites were not used to develop the reference ranges, avoiding a circular argument. Sites were compared against reference standards to determine if the sites with evidence of impact could be detected by the RSM.

6.2.4b Ecological Gradient Model (EGM)

Since the values for most factors follow a continuum with high variability, all stations representing a gradient of degradation from severely impacted to unimpacted conditions were classified into one of twelve environmental groupings based on depth and wave exposure.

A model was created in Microsoft Excel© to identify where a quantified factor lies along a continuum of values. Forty-three physical and biological variables were included in the model. A statewide percent rank and Index of Biotic Integrity (IBI) was generated for the site and for each variable of interest.

6.3 Results

6.3.1 Development of Information Database

The cumulative sampling effort produced information on 61 factors at 184 transect locations at 52 sites.

6.3.2. Identification of Major Factors

6.3.2a Variable Ranking

The parsimonious ranking of values found few single factors that adequately described fish and coral assemblage characteristics. The environmental variables that best described biotic community factors were human population, rugosity, organic composition, and the silt/clay fraction of bulk sediments.

- 80% of stations with higher than average (>4.5 Mg/ha (>0.5 t/ha)) fish biomass have <5,000 people residing within 5 km.
- Almost half the stations with low coral cover (<20%) have high populations (>5,000 people within 5 km), while 92% of stations with high coral cover (>40%) have low populations (<5,000 people within 5 km).
- Over 90% of stations with low coral cover (<20%) have low rugosities (<1.7) while 70% of these stations exhibit rugosities <1.5. In contrast, high

rugosity and high coral cover are strongly correlated. Approximately 85% of stations with high coral cover (>20%) also have high rugosities >1.5, except for the rare stations (2) where large boulders exist. All stations with coral cover greater than 40% have rugosities >1.5.

- Low rugosities are also indicative of low fish biomass. When rugosities are between 1 and 1.5, over 92% of stations have biomass between 0 and 0.9 Mg/ha (1.0 t/ha). With an increase of biomass to 1.4 Mg/ha (1.5 t/ha), 97% of all stations are included.
- Sites with silt/clay > 9% and organics >6% exhibit extremely low coral cover and fish populations.

6.3.2b Quantitative Analyses

Quantitative analyses confirmed the factors found to be important in the variable ranking. Rugosity, organics, depth, human population and wave regimes are influential factors in both coral and fish communities, explaining a considerable portion of the variability. While the distance from a stream is also important to coral variables, fish communities are also influenced by silt, turf, coralline algae and management protection (Table 6.1).

Table 6.1 Summary of statistically significant (p<0.05) environmental variables for biological factors										
	Coral cover		**Coral richness**		**Fish numerical abundance**		**Fish biomass**		**Habitat types**	
Environmental parameters	*t* ratio	*P*	*t* ratio	*P*	*t* ratio	*P*	*t* ratio	*P*	*t* ratio	*P*
Rugosity	8.4	<0.001	2.5	0.037	3.3	0.001	3.5	0.001		
Depth	3.0	0.003								
Silt/Clay							-2.3	0.023	2.5	0.04
LOI			-4.6	<0.001	-2.3	0.026	-4.5	<0.001		
Population	-3.4	0.001	-3.8	<0.001			-2.3	0.021		
Wave height mean	-2.3	0.023	-2.3	0.025						
Wave direction	2.7	0.009	3.9	<0.001					2.4	0.046
Stream distance	2.8	0.006	2.8	0.006						
Turf					2.4	0.020	2.4	0.016	3.2	0.011
Coralline algae					4.3	<0.001	3.9	<0.001	3.3	0.011
Large grain size									4.5	0.001
Sand									6.7	<0.001
Management status					2.2	0.033	2.3	0.022		

6.3.3 Development of Models

6.3.3a Reference Site Model (RSM)

Reference sites analyses

To determine whether the reference stations were different from the non-reference stations, a discriminant analysis was performed. 74% of the stations were correctly classified and 26% misclassified.

PCA was used to evaluate how well separated the undisturbed reference stations were from the disturbed non-reference stations. Although many of the reference stations (blue triangles) cluster together, others exhibit considerable overlap with the non-reference stations (Fig. 6.1).

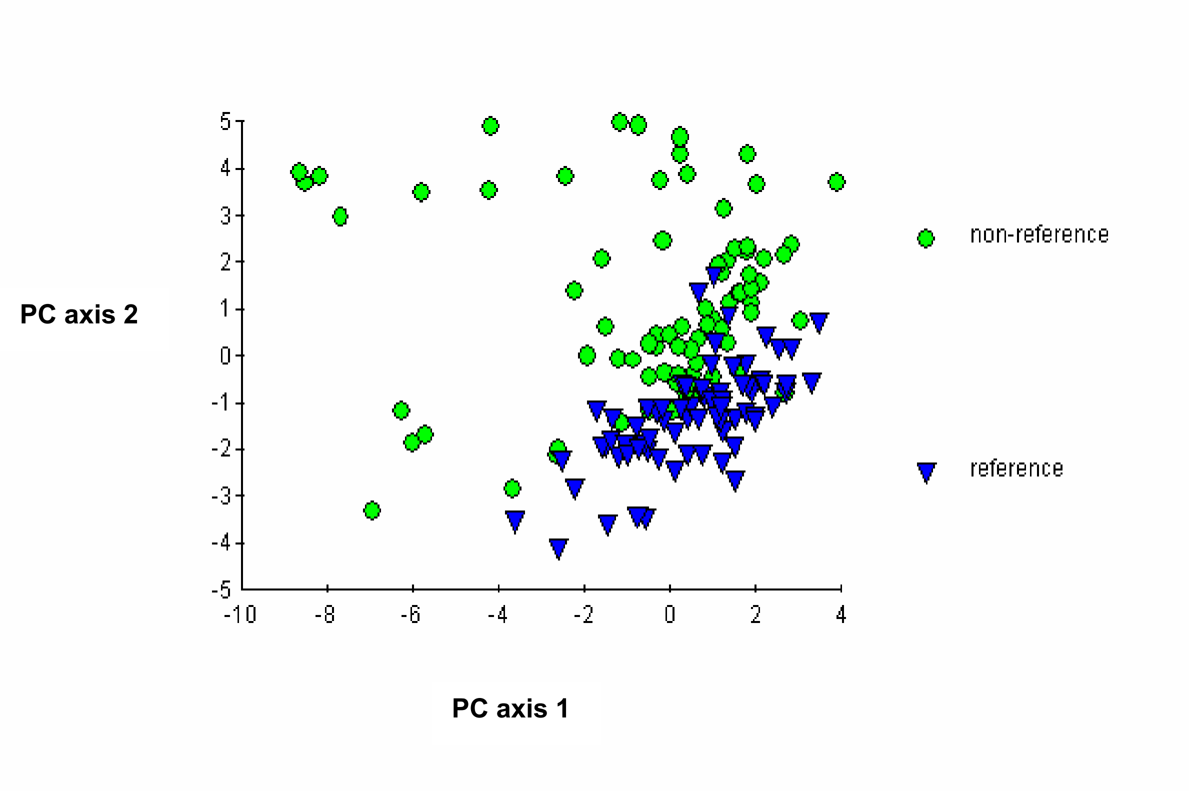


Figure 6.1 Principal components analysis of environmental variables of reference and non-reference sites (n=172)

Since some degree of separation occurred between reference and non-reference sites, next it was critical to determine if the reference sites in each of the six habitat classes were different from one another based on biological and environmental factors.

1) Discriminant analysis

To determine if the reference sites fell within the predicted classification a discriminant analysis was conducted. Of the reference sites, only 43% were in the predicted habitat class. Similar results were obtained when all stations were included (38%). Figure 6.2 shows considerable overlap of reference sites with no consistent pattern between the six habitat classes.

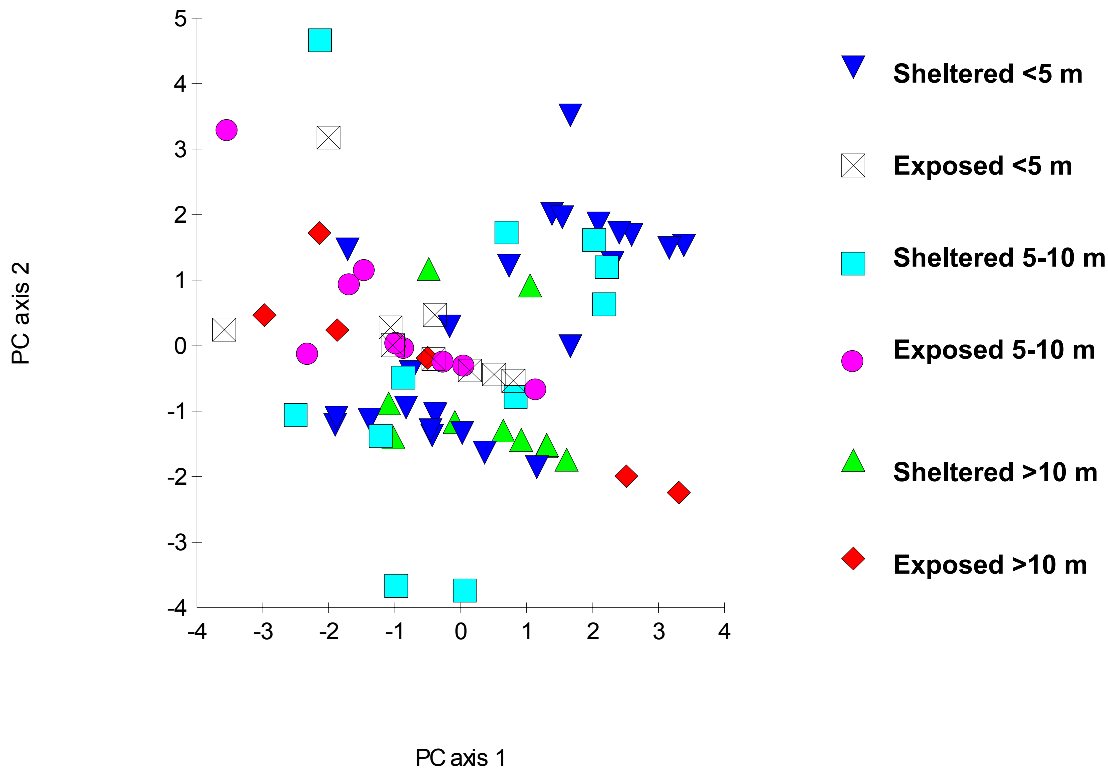


Figure 6.2 Principal components analysis of reference sites by habitat class

3) ANOVA

Most of the habitat classes were not statistically different from one another for the majority of the variables. Nine of the 61 variables showed distinct differences between at least two of the six habitat classes. The distinguishing factors include: sand (F=6.9, p<0.001), *Porites compressa* (F=6.8, p<0.001), very fine sand (F=6.7, p<0.001), medium grain-size (F=4.5, p=0.001), turf algae (F=3.6, p=0.001), calcareous algae (F=2.9, p=0.001), number of fishes (F=2.6, p=0.03), total coral cover (F=2.5, p=0.04) and silt (F=2.5 p=0.04).

6.3.3b Ecological Gradient Model (EGM)

It was demonstrated when identifying major factors that the composition of biological communities is controlled by the physical factors of wave energy and depth zone which define broad ecological habitats. This result suggested an approach similar to the broad HGM classifications for the first tier, in which geomorphology and hydrodynamic characteristics (depth, degree of wave shelter, wave regime) define the major habitat classes. Further, it is necessary to make reef condition comparisons only within each major habitat. For example, low coral coverage may be more indicative of wave regimes and depth than of deteriorated conditions and coral cover was found to be statistically significant between depths (see: Chapter 3 Coral Community Structure).

Habitat classification was expanded from six groups in the RSM to twelve groups in the EGM due to the increase in sample size. The RSM uses only reference sites, while the EGM takes advantage of the entire suite of sites. For the first tier, coastal sites were separated into groups based on major wave regime (North Pacific Swell or South Pacific Swell), degree of exposure (exposed or sheltered) and three depth categories (shallow <5 m, mid-depth 5 - 10 m and deep >10 m). This classification results in 12 major habitats (Table 6.2). An additional category of highly enclosed lagoon reefs (such as Kāneʻohe Bay, Oʻahu) may be added in the future.

Table 6.2 Major habitat classes based on wave exposure and depth				
Dominant Wave Regime	Degree of Exposure	Depth	Depth Range (m)	Code
South Pacific Swell	Exposed	Shallow	<5	SES
South Pacific Swell	Sheltered	Shallow	<5	SSS
North Pacific Swell	Exposed	Shallow	<5	NES
North Pacific Swell	Sheltered	Shallow	<5	NSS
South Pacific Swell	Exposed	Mid-Depth	5-10	SEM
South Pacific Swell	Sheltered	Mid-Depth	5-10	SSM
North Pacific Swell	Exposed	Mid-Depth	5-10	NEM
North Pacific Swell	Sheltered	Mid-Depth	5-10	NSM
South Pacific Swell	Exposed	Deep	>10 to 25	SED
South Pacific Swell	Sheltered	Deep	>10 to 25	SSD
North Pacific Swell	Exposed	Deep	>10 to 25	NED
North Pacific Swell	Sheltered	Deep	>10 to 25	NSD

Metrics for classification within the second tier include biotic measures to define “biological integrity” and environmental measures to identify signs of anthropogenic stress.

6.3.4 Evaluation and Testing of Models

6.3.4a Reference Site Model

Two models have been developed within the HGM classification. The first model RSM defines reef condition within six habitat classes. The RSM relies partially on subjective selection of the so-called pristine control reefs.

1) Test sites

Two test sites were selected to represent the two ends of the spectrum, from minimally impaired to severely impaired. Kaloko/Honokōhau, Hawai‘i is under federal management protection (National Parks Service) and has relatively low anthropogenic influence, while Maunalua Bay, O‘ahu has open access and is perceived as impaired. Variable ranking determined that only three factors have ranges that are narrow enough to describe site condition. The ranges of these factors within their respective habitat classifications were used to compare with the two test sites. The values for coral cover, number of fishes, and silt/clay were expected to fall within the reference range for their respective classification for Kaloko/Honokōhau and below reference ranges for Maunalua Bay. As expected, all stations (17) at Kaloko/Honokōhau exhibited values within the reference ranges, while the majority of the stations (71%) were below reference ranges at Maunalua Bay. Thus, the RSM can sufficiently detect sites that strongly deviate from reference values for select factors in sheltered regions.

The RSM based on classification of reference sites and the use of reference values to detect degradation is effective for use in the evaluation of levels of sedimentation. However, ranges suggest that only severely degraded conditions of coral and fishes for specific habitat classes can be detected. Possible degradation can be detected by values of coral cover outside the lower reference ranges at sites with sheltered wave regimes, but not in exposed regions that typically exhibit low coral cover. Furthermore, only strong deviations of numerical fish abundance can be detected, due to high variability. Other influential factors can not be evaluated with this model.

2) RSM comparisons

Reference comparisons with impacted sites

Following the comparison of test sites against reference values, previously surveyed non-reference sites with evidence of environmental impact were also compared to the range of reference values within each habitat class to test the validity of the model. The variables used for comparison included total coral cover, silt/clay and fish abundances that were previously found to be of merit.

Comparisons indicate that the majority of stations at Waikīkī have values for numerical fish density and coral cover that are outside the reference ranges for each station's habitat class. Coral cover is below reference levels for their respective habitat class for all 11 transects, while the number of fishes is below reference values at over half of the stations. This concurs with the established impacts from overuse and identifies the specific area within the site where disturbance is occurring. Silt values at Waikīkī stations, where bulk sediment samples were collected, are within the reference ranges. This is in concordance with the lack of impact by sedimentation at the stations surveyed.

Sites outside reference ranges for silt/clay

When comparing reference ranges to 99 stations at 26 non-reference sites, the silt/clay fraction is well above the upper range of values for sites predicted to have sedimentation impacts. The sites with established disturbance of sedimentation that far exceed the reference values include: Kakahai'a, Kamiloloa and Pālāʻau, Molokaʻi, Hakioawa, Kahoʻolawe, Pelekane Bay, Hawaiʻi, and Kāneʻohe Bay, Oʻahu. Sites that have silt values slightly higher than reference levels include Puamana Maui, Laupāhoehoe, Hawaiʻi and Kamalō, Molokaʻi. This is in agreement with the US EPA's list of polluted coastal waters showing evidence of degradation by sediments, nutrients, or bacteria. This list, revised in 2002, is based on all available water quality data. The majority of listed sites are near streams with a high level of adjacent urban and agricultural activities. Of the nine sites that fell outside reference ranges, seven are on the EPA list. The sites detected by the reference model but missing from the EPA list are Hakioawa, Kaho‘olawe and Laupāhoehoe, Hawai’i. The island of Kaho‘olawe is not listed in the polluted coastal waters list, but the reefs have been subject to extreme degradation due to siltation. The Laupāhoehoe site receives runoff from a large watershed and is subject to extremely high wave energy from persistent NE Trade Wind waves. This site requires further investigation.

Sites outside reference ranges for fish abundance

In addition to Waikīkī, numerical fish densities are well below reference levels at the majority of stations in Pelekane Bay, Hawai‘i and Kamiloloa, Moloka‘i, and at deeper sites in Kāne‘ohe Bay. One station on the shallow reef flat in Hanalei Bay, Kaua‘i is also outside the lower reference range of values. This is in concert with Friedlander and Parrish (1998a) who found the lowest biomass to occur on the reef flats, compared to other substrate types within Hanalei Bay. All five sites are included in the EPA polluted coastal waters list.

It appears from the low number of sites outside the reference values, that due to high variability, only extreme deviations can be detected. Attempts to quantify the effects of overfishing using numerical and biomass abundance of target food species and size distributions are difficult due to habitat differences and high variability.

Sites outside reference ranges for coral cover

Since exposed habitats may have little or no coral cover, the reference values for these sites are meaningless. Thus only sheltered sites were considered. Eight sheltered sites are outside the lower reference range. These sites where the majority of transects have low coral cover, Puhi Bay and Pelekane Bay, Hawai‘i, Kamiloloa, Moloka‘i, Waikīkī and Kāne’ohe Bay, O‘ahu and Ma‘alaea, Maui are documented to have current or historical anthropogenic impacts that affect coral coverage. Leleiwi, Hawai‘i and Puamana, Maui also deviate from the reference values (Table 6.3). All eight sites are on the EPA polluted coastal waters list.

Table 6.3 Stations with values outside reference ranges, indicating impairment. Reference values based on wave exposure and depth.

site	**silt %**	**reference maximum**	**site**	**Coral cover (%)**	**reference minimum**	**site**	**Number of fish hax1000**	**reference minimum**
Laupāhoehoe 3 m	3.2	2.7	Pelekane Bay 6	0	13.0	Pelekane Bay 1,4,6	0	4.6
Honolua S 3m	2.2	2.7	Pelekane Bay 4	0.2	13.0	Pelekane Bay 5	0.1	4.6
Pelekane Bay	50.9	1.9	Pelekane Bay 1	0	13.0	Pelekane Bay 3	0.2	4.6
Kamiloloa 3m	4.2	1.9	Pelekane Bay 5	3.2	13.0	Kamiloloa 9	4.4	4.6
Hakioawa 3m	9.2	1.9	Pelekane Bay 3	0.6	13.0	Kamiloloa 6	4.6	4.6
Pala’au 1	8.9	1.9	Pelekane Bay 2	4	13.0	Hanalei 3m	1.3	4.6
Kakahai’a 9	50.1	1.9	Kamiloloa 9	6.2	13.0	Kamiloloa 7	1.2	4.7
Laupāhoehoe 10m	3.2	2.5	Kamiloloa 6	1.4	13.0	Kamiloloa 3	4.5	4.7
Kakahai’a 5,8,6	50.1	3.2	Kamiloloa 3m	3.3	13.0	Kamiloloa 10m	4.6	4.7
Kamalō10	4.2	3.2	Kamiloloa 8	10	13.0	Ka’alaea 8m	0.6	4.7
Hakioawa 10m	14.2	3.2	Ma’alaea 3m	5.7	13.0	Moku o lo’e 8m	1.8	4.7
Pālā’au 10m	8.5	3.2	Kamiloloa 7	3.8	21.2	Waikīkī 4	1.6	4.6
Kakahai’a 2	5.6	3.2	Kamiloloa 3	8.6	21.2	Waikīkī 14	0.1	4.6
Puamana13m	3.9	1.0	Kamiloloa 10m	1.3	21.2	Waikīkī 24	0.2	4.6
Kakahai’a 1,3,4,7	5.6	1.0	Ma’alaea 6m	0.9	21.2	Waikīkī 22	0.1	4.6
Kamiloloa 1,2,4,5	2.7	1.0	Leleiwi 10m	20.7	21.2	Waikīkī 42	1.0	4.6
He’eia 2m	55.5	1.9	Puhi Bay 1	14.0	21.2	Waikīkī 31	0.2	0.4
He’eia 8m	59.9	3.2	Puamana 13m	7.8	36.0			
Ka’alaea 2m	30.7	1.9	Puhi Bay 2	34.7	36.0			
Ka’alaea 8m	63.1	3.2	He’eia 8m	5.3	21.2			
Moku o lo’e 2m	41.2	1.9	Ka’alaea 8m	6.5	21.2			
Moku o lo’e 8m	31.7	3.2	Moku o lo’e 2m	12.8	13.0			
			Moku o lo’e 8m	1.6	21.2			
			Waikīkī 4	0.2	13.0			
			Waikīkī 14, 24	0	13.0			
			Waikīkī 22	0.3	13.0			
			Waikīkī 42	1.0	13.0			
			Waikīkī 38	16.8	21.2			
			Waikīkī 33	2.8	21.2			
			Waikīkī 2	3.4	21.2			
			Waikīkī 19, 31	0	36.0			
			Waikīkī 27	12.2	36.0			

6.3.4b Ecological Gradient Model (EGM)

While the RSM is able to detect values that fall outside the reference ranges at highly impaired sites, it is not able to detect marginal degradation because of high variability within reference sites. It also can not determine the degree of impairment or compare to other sites in the state. Only a few select variables can be used to determine impairment due to the high variability.

Since the RSM model cannot be used for other variables that may be linked to specific types of disturbance, a more efficient, parsimonious model was developed. The second approach an “Ecological Gradient Model” recognizes that all ecological factors vary over space and time. This alternative to the RSM is designed to establish reef condition through comparison to the same habitat class in a large number of other Hawaiian reefs in a completely objective manner. Additional stations are included in the model as further data becomes available, so the power and value of this model will increase as the sample size is increased.

An expansion of the EGM design is used to define site impairment. The values for most factors stretch along a continuum with high variability. All stations, representing a gradient of degradation from severely impaired to unimpaired conditions are classified into one of twelve environmental groupings based on depth and wave exposure. Only six environmental groupings were possible with the RSM due to a small sample size of reference sites. A small number of sites can not fully represent the variability among reference sites.

A total of 43 physical and biological variables were included in the model. They encompass variables on a species, population, community, and ecosystem level (Table 6.4).

Table 6.4 Physical and biological variables incorporated in the ecological gradient model

Physical Factors		**Biological Factors**		
Other variables	**Sediment variables**	**Coral Assemblage Characteristics**	**Fish Assemblage Characteristics**	**Algal Assemblage Characteristics**
Rugosity	Composition Organics $CaCO_3$	Total coral cover	Abundance Numerical Biomass Diversity Evenness	Macroalgae Calcareous Turf
Substrate type (sand, silt)	Grain-sizes Medium sand Fine sand Very fine sand Silt/clay	Species *Porites lobata* *P. compressa* *Montipora capitata* *M. patula* *M. flabellata* *Pocillopora meandrina*	Trophic guild Corallivores Detritivores Herbivores Mobile Invertebrate feeders Sessile Invertebrate feeders Planktivores Zooplanktivores	
Human population within 5 km within 10 km Watershed		Species richness	Size classes <5 cm 5-15 cm >15 cm	
Precipitation Distance from a perennial stream		Species diversity	Endemism status Endemic Indigenous Introduced	

This model, intended as a management tool, was created in Microsoft Excel to evaluate site condition. The operator enters a depth and wave exposure from the list provided (Figure 6.3).

1) Input depth of site in meters **4.9**

2) Select wave exposure **s**

Select one of the following four options:**S, SS, N, NS**

wave exposure options:**S**:location exposed to south swells,**SS**:south facing location sheltered from swell

N:location exposed to north swell, **NS**: north facing location sheltered from swell

3) Input values for parameters of interest under assessment data below

Site Name					Weight 1-10		
transect #	assessment data	RANK	IBI	CRAMP weighted IBI	Operator choice	Operator based IBI	
Organics (LOI)	3.30	0.40	6.00	6.00		0.00	
$CaCO_3$	94.03	0.65	6.50	4.55		0.00	
medium sand	31.69	0.09	0.90	0.63		0.00	Sediment variables
fine sand	27.95	0.86	8.63	3.45		0.00	
very fine sand	31.9	0.86	8.63	6.90		0.00	
silt	8.46	0.95	0.46	0.37		0.00	
Montipora flabellata	5.0	0.95	9.54	2.86		0.00	
Montipora patula	1.7	0.77	7.72	2.32		0.00	
Montipora capitata	4.7	0.86	8.63	2.59		0.00	
Pocillopora meandrina	2.0	0.59	5.90	1.77		0.00	Coral species and assemblage characteristics
Porites compressa	35.2	1.00	10.00	3.00		0.00	
Porites lobata	5.0	0.73	7.27	2.18		0.00	
Total Coral	41.87	1.00	10.00	9.00		0.00	
Species Richness	4	0.60	6.00	3.00		0.00	
Diversity (H')	1.15	0.65	6.50	3.25		0.00	
sand	0.6	0.40	6.00	3.60		0.00	
calcareous algae	8	0.82	8.18	4.91		0.00	
macroalgae	0.9	0.68	3.19	1.91		0.00	Algal functional groups
substrate (turf)	31.1	0.09	9.10	5.46		0.00	
Rugosity	2.07	1.00	10.00	10.00		0.00	
Wave Height (mean)	3.2	0.05	9.55	8.60		0.00	
Wave direction (mean)	175.1	0.36	6.37	3.82		0.00	Environmental parameters
population within 5 km	30	0.14	8.64	7.78		0.00	
population within 10 km	3484	0.23	7.73	4.64		0.00	
population within watershed	2	0.00	10.00	6.00		0.00	
Stream (distance) m	16694.88	0.77	2.28	1.37		0.00	
rain mm	400	0.05	0.45	0.23		0.00	
fish<5cm (%)	7	0.55	5.45	3.27		0.00	Fish size categories
5-15cm (%)	88.6	0.64	6.36	3.82		0.00	
>15cm(%)	11.4	0.91	9.09	5.45		0.00	
Total number of fish	88	0.45	4.54	3.63		0.00	
Biomass	3582.13	0.59	5.90	4.72		0.00	
Number of fish (hax1000)	7.04	0.45	4.54	3.63		0.00	Fish assemblage characteristics
Biomass (tons per hectare)	0.29	0.59	5.90	4.72		0.00	
Fish diversity (H')	2.18	0.86	8.63	4.32		0.00	
Fish evenness	0.81	0.86	8.63	4.32		0.00	
Endemic %	25	0.32	3.18	1.27		0.00	Endemic status
Indigeneous %	75	0.68	6.81	2.72		0.00	
Introduced %	3	1.00	10.00	4.00		0.00	
Corallivores %	10.71	0.95	9.54	3.82		0.00	
Detritivores %	10.71	0.91	9.09	3.64		0.00	
Herbivores %	35.71	0.59	5.90	2.36		0.00	Feeding guilds
Mobile Invertebrate feeders %	32.14	0.36	3.63	1.45		0.00	
Piscivores%	1	0.64	6.36	2.54		0.00	
Sessile Invertebrate feeders %	1	0.77	7.72	3.09		0.00	
Zooplanktivores %	10.71	0.82	8.18	3.27		0.00	
				Total IBI		Total weighted IBI	
		46		7.81		0.00	

Figure 6.3 Main menu of the Ecological gradient model containing data from a station at Palāʻāu, Molokaʻi.

The operator also enters an assessment value for a single factor or a group of factors into the worksheet (Figure 6.3). A statewide percentile for a particular variable of interest is calculated to evaluate that variable relative to all others in a particular class. This main menu draws from data in other worksheets to calculate a statewide percentile rank for the variable of interest. A link to specific types of disturbance may be highlighted in these rankings. For example, a high ranking of silt/clay and organics can be indicative of sedimentation.

In addition to a rank percentile, there is an unweighted IBI and a weighted IBI (Figure 6.3). This CRAMP IBI weighs each factor based on an objective analysis of the primary factors defining reef condition. However, the option is also provided that allows the operator to change the weights to suit a particular management or ecological question.

An overall site IBI is also calculated based on the number of variables input. This IBI is based on a scale of 0 to 10, where zero represents the most impaired site and ten corresponds to the least impaired site. This model is available for use on the CRAMP website: http://cramp.wcc.hawaii.edu.

6.4 Discussion

The major forcing functions on coral reef communities were found to be from both natural and anthropogenic sources. Depth, wave regimes, human population, spatial complexity, organic sediment and fine grain size explained a considerable portion of the variability in coral and fish assemblage characteristics. Results from the identification of these key factors were used in the development of the EGM.

Results of this investigation show the limitations of using a “reference site” or a “control reef” in determining “reef health” or reef condition. The underlying problem is that selection of a reference site is subjective, even by experts. No two reefs are exactly alike in all respects, so agreement on appropriateness of any “control” or “reference” reef cannot be attained in an absolute sense. Therefore, reference site selection is inevitably subjective and may be biased and inaccurate.

The reference paradigm does not hold up under scrutiny when a large number of sites and measured parameters are available for quantitative comparison. Comparisons between a reference site and a site being evaluated can appear to be a reasonable approach if only a single parameter such as coral cover is being compared. For example, a reef with high coral cover is usually taken as a “reference” for comparison to an “impacted” reef with low coral cover. The comparison begins to break down as more measured parameters are added to the analysis. We begin to see that the two reefs are quite different in many fundamental respects. If we begin to increase the number of sites used in the comparison we note a great deal of heterogeneity and overlap between important parameters both within and between sites. There is high spatial and temporal variability that cannot be encompassed by a single reference site or a small number of reference sites.

We can assign different weights to the various factors to produce a quantitative index of biological integrity, and weight them in a manner that will give the “reference reef” the highest score. However, this approach adds yet another dimension of subjectivity to the problem and cannot be defended from an objective quantitative point of view. The reference site model can be useful in a very broad sense as a subjective method of comparison. For example, the sites that ranked at the bottom of the RSM analysis showed good agreement with the EPA “most impaired site” listing. Both listings are somewhat subjective with the EPA listing determined largely by water quality and the RSM calculated in this study being determined largely by ecological conditions other than the EPA criteria.

Multiple variables that have an influence on the biological communities follow overlapping and often dissimilar continuous gradients that confound defining of boundaries. Thus, an alternate to the RSM is to use a large number of sites within each habitat classification and rank the sites along a continuum by purely objective criteria. This alternative, the EGM, defines the condition of a reef in comparison to a wide range of other reefs. The EGM approach compares each site to every other site within its habitat classification. The method continues to grow in power as the number of sites, parameters and classifications are increased. The limitation of the RSM is that it generally has been applied on a one time – one case basis for a particular problem, so has not led to development of a commutative data base that increases in value.

Both the RSM and the EGM provide metrics that can be ranked in relative value to form an index of biological integrity. A low ranking can assist management in identifying degraded areas that may need further investigation or monitoring. A high ranking can identify sites that may be suitable for protection as marine protected areas. Comparing rankings can aid in assessing compatibility of experimental and control sites for use in manipulative field experimentation.

The IBI ranks reef condition based on management priorities. In most cases, biological factors such as coral cover, coral diversity, fish number and fish diversity are given high index values. The EGM IBI, developed in this investigation, assigns weights to various parameters based on objective analysis of the data set. However, the option is provided in the Excel© program that allows the operator to change the index values to suit a particular management or ecological question. For example, one might wish to create an index that assigns the greatest weight to fish biomass, with little or no weight assigned to other factors. An IBI relevant to the question is thereby quickly and easily calculated, and the ranking of sites produced using an objective quantitative process based on a very large data set. This data set will increase as additional sites are evaluated.

Other parameters not measured in the present study due to time and/or cost restraints may prove valuable in refining the model in determining reef ecological condition. These parameters include water quality, coral size frequencies and coral growth. At present there is insufficient water quality data available from our sites to make comparisons. The addition of these and other possibly defining metrics will be included as resources become available.

CHAPTER 7 SUMMARY

7.1 Objectives

The major accomplishments of this investigation include the large-scale description of reefs in the Main Hawaiian Islands, the identification of the key factors that influence coral reef communities, and the compilation of an extensive database consisting of baseline data from 58 sites. From this data a model was developed to describe the condition of Hawaiian reefs.

The primary objective of this research was accomplished, while the five specific objectives were met to varying degrees.

To identify biological and physical factors that accurately describe the condition of Hawaiian coral reef communities with respect to natural and anthropogenic forcing functions.

Many factors combine to influence coral reef communities, but most explain a very small portion of the variability. Both natural factors (rugosity, depth and wave energy) and anthropogenic factors (organics, human population, management protection and distance from a stream) influence biotic assemblage characteristics. Although these factors are the most influential in explaining the observed variability in coral community structure, many other factors combine to varying degrees to influence biological populations (Figure 7.1).

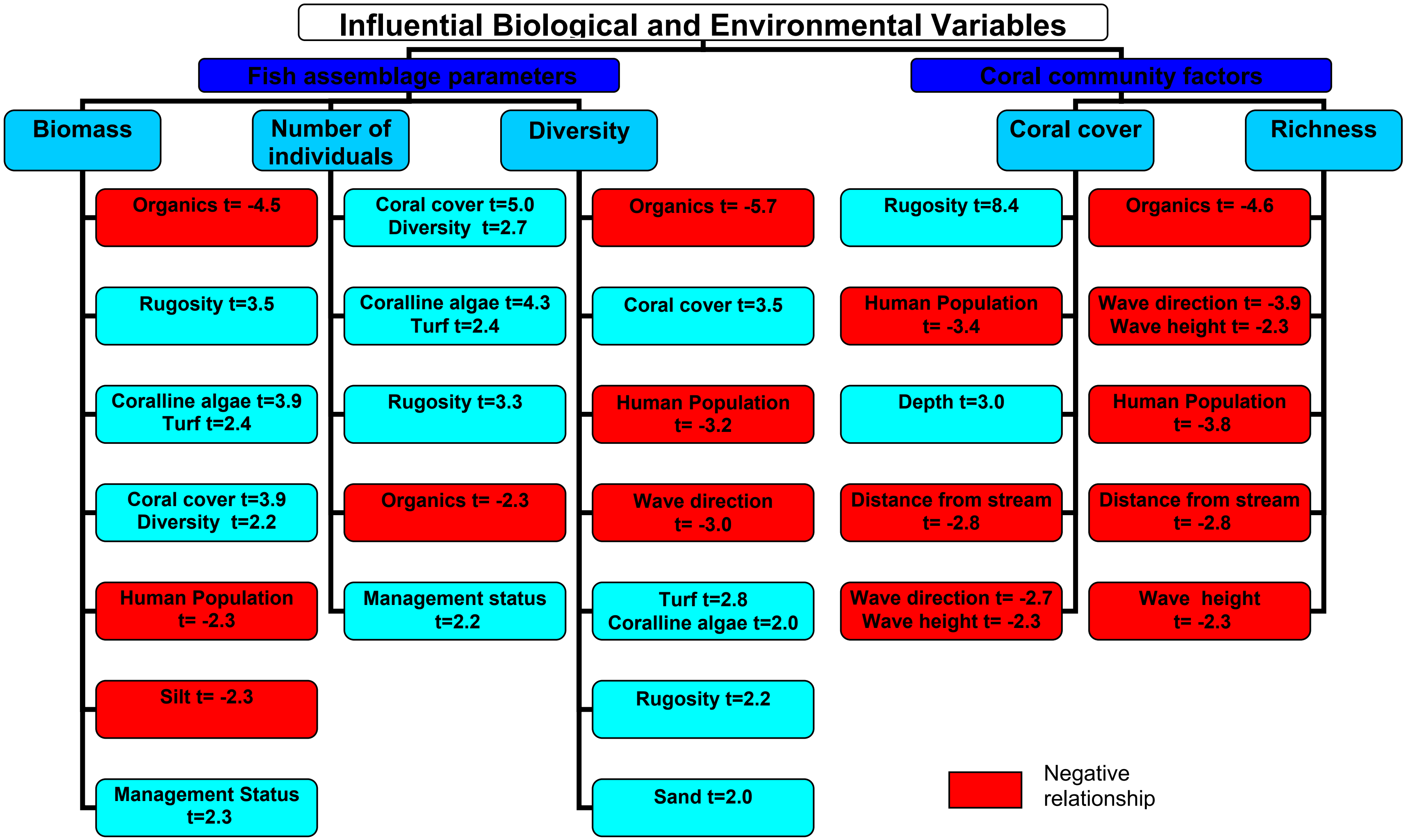


Figure 7.1 Factors that significantly influence biological variables

Different factors affect the habitat classes in a complex manner. Environmental factors that are important in differentiating all habitat classes include benthic community composition and sediment grain-size parameters. Impaired sites show a strong relationship to some factors but not to others. For example, some measures of disturbance (organics and human population) are correlated with all sites, while the level of marine protection influences reference sites alone.

Some of these factors are correlated with anthropogenic impacts and may be applicable in detecting overuse (Figure 7.2).

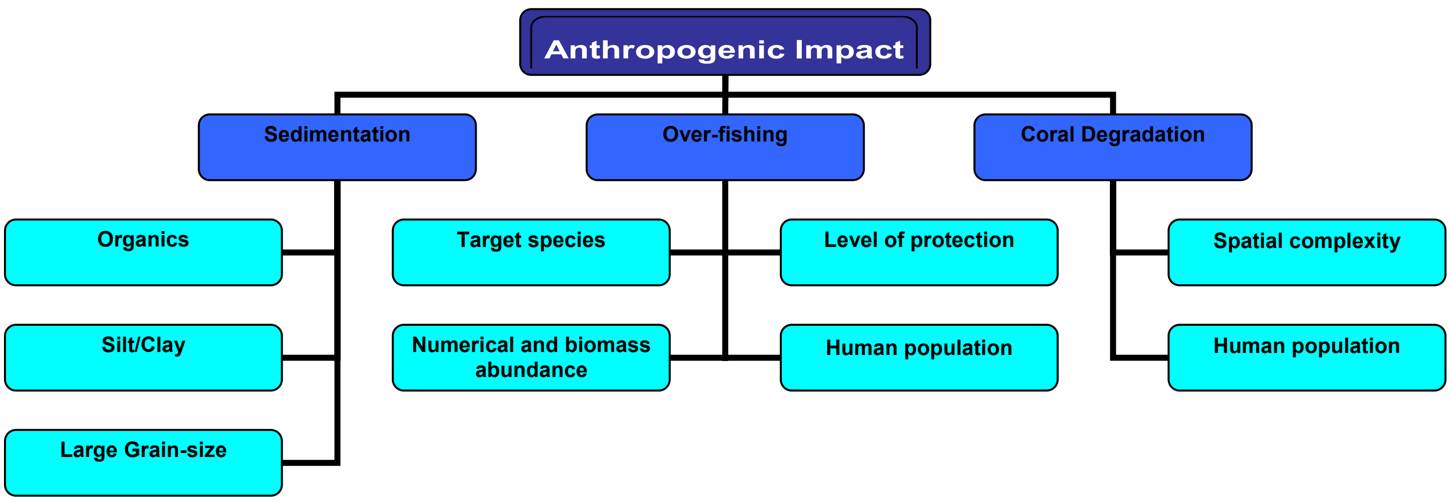


Figure 7.2 Indicators of anthropogenic impact

The following five specific objectives were investigated:

1) To describe spatial variation in Hawaiian coral reef communities in relation to natural and anthropogenic factors.

Spatial biogeographical differences exist within the coral reef ecosystem. Stratification of biological organisms is strongly influenced by physical factors.

Habitat classes, distinguished by depth and wave energy, can be differentiated by their biological variability. Sediment and substrate factors strongly influence these biotic communities.

Natural factors found to influence coral communities in this research are wave energy regimes (wave height and direction), spatial complexity, and depth. Anthropogenic influences include human population, stream distance, and sediments. The forcing functions that affect spatial variability of coral assemblages are difficult to separate. Coral reef heterogeneity is influenced by natural factors on most exposed coastlines. Anthropogenic disturbance can be the overwhelming forcing function when superimposed on natural forces or in wave-sheltered regions.

Coral cover increases with depth and reef complexity. High coral cover and diversity are also related to low wave energy and low levels of silt and organics. Hydraulic stress spatially stratifies coral community structure, evidenced by distinct species distribution in different wave regimes. High coral cover and high coral diversity are related to low human population and increased distance from stream discharge.

Fish assemblages in the MHI are spatially stratified. Fish abundance is positively correlated with degree of legal protection, spatial complexity, and coral cover, while negative effects occur with increased fine sediment, increased organics and higher human population.

2) To identify reference sites for each habitat classification to be used as standards against which impacted regions can be evaluated and anthropogenic effects determined.

The reference site paradigm was not found to be applicable in the Hawaiian marine environment because of the complexity and extreme heterogeneity of coral reef ecosystems. The reference site standard cannot encompass the spatial variability and temporal fluctuations found in the reefs of the MHI.

Stratification of marine organisms is principally influenced by depth, spatial complexity, and wave regimes. This pattern is analogous to terrestrial botanical zonation, which is primarily based on elevation, topography and rainfall. These oceanic, geologic, and meteorological differences created diverse habitats, supporting varied biotic distributions and abundances and makes selection of reference sites difficult. Unlike the attributes used to create the index of biotic integrity for freshwater systems, most marine attributes are not comprised of distinct ranges, but instead follow a continuous gradient.

Although considerable overlap exists for the majority of variables, reference sites can be separated from impacted sites based on a few attributes. Severe degradation and effects of sedimentation are detected by strong deviations from reference values. Reference values could not be derived from the majority of environmental variables due to interactions that influence discriminatory power, habitat complexity and extreme variability. This investigation demonstrated the difficulty in the use of reference values as a standard.

a) The reference sites standard cannot distinguish degree of impairment. The extremes of “severely impaired” and “little or no impact” can be defined, but the high variability in range restricts the ability of reference ranges to discriminate on a finer scale.

b) Reference site values have limited power in detecting disturbance. High variability among most variables prevents identification of specific causes of disturbance. Natural heterogeneity increases reference ranges and decreases the ability of reference sites to detect impaired reef condition. For example, high wave energy environments naturally have extremely low and variable coral cover values that are not related to anthropogenic factors.

c) A small sample of reference sites cannot accurately describe the range of biological integrity encountered among reef communities. When attempting to integrate a large number of reference sites, conditions can overlap substantially with non-reference sites. The high heterogeneity of Hawaiian coral reefs impedes the separation of natural from anthropogenic impacts.

d) Subjective selection of reference sites is flawed. Quantitative analysis showed poor separation between reference and non-reference sites. Determination of optimal reef conditions is obscured by the lack of knowledge of the anthropogenic history of a site and sliding baselines that change over time. The reference concept is defective largely because it does not embrace the diversity of unimpacted reef communities.

e) When only reference sites are used in the evaluation of impairment, comparison of a given site with other sites throughout the state is unattainable.

3) To describe "natural habitat" criteria and establish baseline data for reference sites.

Where no prior baseline data exists, "pristine" conditions can only be defined by present conditions. Baselines change over time and local conditions can fluctuate. Stability can be variable where alternative stable states may exist (Connell 1983). In this research, "natural states" were defined by the present condition of sites with little anthropogenic influence, strong management protection and/or difficult accessibility. These criteria were then used to develop reference values.

The biological and environmental georeferenced baseline data that were established at all assessment sites can be compared to data taken in the future in order to quantify change. Data from these survey sites may provide an important baseline for assessment of the impacts of either catastrophic events or gradual changes. Data from a large number of sites (52) are currently available as a foundation for future research. As this database increases in size so will its value.

4) To identify specific factors or assemblages of organisms that can provide early warning signs of coral reef decline.

Rapid assessments can assist in identification of heavily impacted sites. These sites can be identified by departure from reference values established for a select number of factors with high discriminatory power. However, sites in early stages of decline are more difficult to quantify due to the extreme variability found in coral reef communities. In order to quantify declining conditions, temporal variation must be defined and subsequent surveys with suitable statistical precision must be conducted. Monitoring of sites whose rank is near the endpoints of the entire suite of sites for particular discriminating variables, can be used to quantify the progression of declining conditions.

Among the variables with high discriminatory power are rugosity, human population, sediment associated organics, and silt/clay. These environmental variables encompass both natural (rugosity) and anthropogenic (population and sediments) variability. Values for coral cover, numerical fish abundances and silt/clay that fall outside reference site ranges can also be used to detect impairment. These combined variables can be used to identify degraded sites, or stations within a site where impacts are strongest.

5) To develop a statistical model that for a first approximation is based on physical variables that stratify biological populations (wave regime and depth) to predict biological community condition at these locations. The second approximation is a refinement based on biological and environmental factors subsequently measured at each site. Such a model will allow prediction of reef condition at sites not previously visited and serves as a valid test of model predictive ability.

Two models were developed that utilize the physical factors of wave energy and depth as a first approximation, to separate natural from anthropogenic impacts. Both these models also include a further refinement based on biological and environmental factors.

Although these models have limited capability to predict future reef condition, they have the ability to detect degraded conditions. The subjective Reference Site Model (RSM) can detect severe degradation based on sediment, coral cover and fish abundance, while the objective Ecological Gradient Model (EGM) has the ability to distinguish levels of impairment for numerous variables and make comparisons between sites. In terms of predictability, the models suggest that factors such as increased sedimentation or increased human population will lead to further impairment of reefs.

The RSM and the EGM both provide metrics that can be ranked to form an index of biological integrity (IBI). These models can be used to assist managers in classifying areas of concern or identifying high-quality candidates for marine protection.

The RSM is too subjective in the selection of reference reefs and can only detect severe impairment. Use of this model is restricted to a few key factors due to high variability. The model is not useful for comparisons of a given site to other sites throughout the state. Therefore, a more objective, efficient, and parsimonious model was constructed.

The EGM is a superior alternative to the RSM and is designed to describe reef condition in an objective and quantitative manner along a continuum. Further, the model increases in power as more sites are evaluated and added to the data base. The EGM allows comparisons across a wide range of sites throughout the MHI. The model describes reef condition by ranking a single or a group of factors within a habitat class. A link to specific types of disturbance may be highlighted in the rankings of these variables. The twelve habitat classes, based on the HGM concept of using major natural hydrogeomorphic forcing functions of wave energy and depth, facilitate separation of natural from anthropogenic variability. This model is available for use on the CRAMP website: http://cramp.wcc.hawaii.edu.

7.2 Hypotheses

The following hypotheses outline the predicted outcomes of this research.

- **For biological parameters, quantitative measures of only three groups of reef organisms (coral, macroalgae, reef fish) are sufficient to define the condition of Hawaiian coral reefs.**

Coral, fish and algal assemblage characteristics are strongly influenced by environmental stress. They respond consistently to a wide range of impacts and exhibit high, yet quantifiable levels of variability. These desirable traits make these organisms useful in detecting deteriorating conditions. In this research, many environmental parameters were found to be significantly correlated with coral and fish variables. Impaired conditions in most habitat classifications are strongly associated with low coral coverage and low fish populations. Low levels of macroalgae were found at the majority of sites. Therefore, macroalgae has a lower discriminatory power for these types of assessments.

- **For habitat-scale physical parameters, five quantitative measures of bulk sediment deposit composition, (e.g. wave regime, depth, substrate, and rugosity) can be used to define Hawaiian coral reef condition.**

The physical factors that explain a considerable amount of the variability in biotic reef communities can be used to evaluate the condition of reefs. The factors most strongly influencing coral and fish community structure are rugosity, depth, bulk sediment associated organic material, fine grain-size, wave height and direction.

This hypothesis was quantitatively substantiated. Topographical relief as measured by rugosity is the environmental variable most influential in explaining both fish and coral community structure in all statistical analyses (see: Chapters 3 and 4). Wave regimes and depth (associated with light and temperature), are also highly influential in stratification of marine organisms. They explain a considerable amount of the variability surrounding fish and coral assemblages.

Sediment composition and grain-size can provide a good indication of land-based sediment input and levels of impact. High levels of organics and small grain size are indicative of areas strongly influenced by sedimentation of anthropogenic origin. Organic components above 6% and silt/clay fractions above 9% define sites that are heavily impacted by sedimentation and represent a chronic disturbance to coral reefs.

General water circulation can be described through examination of grain-sizes. Sites with high percentages of coarse grains and low levels of fines are associated with north facing exposures and coastlines with strong water circulation. This is mainly attributed to strong currents and high waves that flush and remove fines. Bays, harbors and sheltered areas with longer residency times and poorer water circulation contain larger percentages of organics and fine grain-sizes (see: Chapter 5 Sediments).

- **At a local scale, factors such as proximity to perennial streams and proximity of human population are sufficient to define the condition of Hawaiian coral reefs.**

These two measures of disturbance were found to be highly influential in defining reef condition. The relationship between biological parameters (coral cover, fish biomass and number) and stream distance at all sites was evaluated using the RELATE procedure in PRIMER 5.0. A disruption in the serial pattern along a natural gradient (stream distance) was detected. The disruption in the seriation of this linear, spatial sequence can characterize anthropogenic disturbance. This was substantiated with multiple linear regression where a negative relationship between coral community factors and stream distance was found.

Human population also clearly influences fish biomass, fish diversity, coral cover and coral richness. Human population within 5 km of a site has an inverse relationship with most coral and fish assemblage characteristics.

- **The degree of impact from anthropogenic activity can be quantified by the departure of coral reef communities from their natural states.**

Although degraded conditions can be detected by values from select attributes that deviate from natural conditions, the evaluation of the degree of impact must encompass a wider range of variables. Sites range along biological and environmental gradients with no distinct breaks that would indicate intensity of degradation. Including the entire range of sites from unimpacted to severely impacted allows a comparison to the entire spectrum of conditions. The degree of impact is defined in “shades of grey” rather than “black and white”.

- **The degree of over-fishing can be determined through comparison of abundance and biomass data for select fish species.**

This hypothesis was confirmed through statistical analyses of quantitative fish community characteristics and semi-quantitative levels of fishing pressure and management protection status for both select target species and all species of fishes. As expected, fish biomass is negatively correlated with fishing pressure and positively correlated to management protection status. Numerical abundances are also influenced by fishing pressure. This result is consistent with results of multivariate analyses linking human population with fish community characteristics. The consequences of over-fishing can be shown by decreased biomass and numerical abundances of fishes. However at this point estimates are limited to general, categorical values of high, medium, and low impact. In the future increased sample size and decreased variability may allow further quantification and refinement of these values.

7.3 Research Summary

7.3.1 Coral Reef Community Structure

Hawaiian reef communities can be characterized as “*Porites* reefs”, structured mainly by wave energy and anthropogenic factors. Coral cover in the

MHI is approximately 22%, with corals of the genus *Porites* comprising half of the coverage. Three species of *Montipora* and *Pocillopora meandrina* comprise the overwhelming majority of the remainder.

No single factor accounts for the variation observed in coral cover and diversity, but several parameters are highly correlated with coral assemblages. Sites with high coral cover and diversity are characterized by low wave regimes and low levels of silt and human population. Topographical complexity and distance from streams are equally important in explaining coral reef variability.

Corals are stratified by depth and degree of hydraulic stress, with higher coral cover found at deeper sites with lower wave regimes. High wave energy and circulation showed inverse correlation with levels of silt. Silt is winnowed out of sediments by high wave energy.

7.3.2 Reef Fish Community Structure

The extremely high spatial variability that exists among fish populations can be attributed in part to their schooling behavior and acute mobility. A large sample size can help reduce the effects of this variability.

Fish community structure in the MHI can be characterized as follows. The mean value is nearly 10,000 fishes per hectare, weighing 2,640 kg with most fish ranging in size between 5 and 15 cm. Smaller fishes are found on the windward sides of the islands. An average of 17 species were recorded per 25 m transect, with the Saddle Wrasse, *Thalassoma duperrey* (hīnālea), observed most frequently. The vast majority of species recorded are either indigenous or endemic, with relatively few introduced fish species. The density of non-native species is higher in shallower waters, contrary to overall fish densities that increase with depth. Only a few alien fish species occur in Hawai'i, yet the introduced Bluestripe Snapper, *Lutjanus kasmira* (ta'ape) has been very successful and shows the highest biomass of any reef species in the state.

Some of the most popular fish species in the aquarium trade, the Yellow Tang, *Zebrasoma flavescens* (lauīpala), the Orangespine Unicornfish, *Naso lituratus* (umaumalei) and the Gold-ring Surgeonfish*, Ctenochaetus strigosus* (kole), are among those with the highest densities statewide.

A strong anthropogenic influence was shown by the negative correlation of fish assemblage characteristics with parameters linked with human impact. Along with sediment organics from land-based sources, the impacts of over-fishing and human population pressure can be seen in declining fish assemblage characteristics. The size structure of fish communities is a strong indicator of over-fishing. The low number of individuals in the largest size class is clearly evident. Fishing pressure can also be detected by changes in abundance of populations of popular food fish as well as overall fish populations. The effect of fishing is also reflected by higher fish abundances in areas with stronger management protection. Sites within marine reserves are among those with the highest fish densities in the state. In sharp contrast, sites with heavy anthropogenic impacts exhibit consistently low fish populations. Over-fishing is visible in the absence of fishes of recreational and commercial value from the upper hierarchy of dominant species. The trophic structure also relates to over-fishing. Extremely few piscivorous fishes are found in the MHI relative to the

Northwestern Hawaiian Islands (NWHI), where fishing pressure is minimal (Friedlander and DeMartini 2002).

Other evidence that declines are associated with anthropogenic influence is the low rank of O'ahu compared to the other MHI in fish assemblage characteristics. This strong link to human population density is evident regardless of the high number of marine protected sites surveyed on this island.

Fish populations are strongly influenced by biological and physical factors. As in the case of coral communities, fish populations are stratified by depth and heavily influenced by topographical relief. Coral cover and richness and coralline and turf algae explain a portion of the variability in fish assemblage characteristics (see: Chapter 4 Nearshore Reef Fish Community Structure).

7.3.3 Sediments

Heavy terrigenous input is strongly associated with high levels of organic material and fine grains in the bulk sediment samples. Sites with limited water circulation are most heavily impacted. Silt and clay that overwhelm the system can become the dominant forcing function on community structure, strongly influencing both coral and fish populations. Coral settlement can be blocked at sites containing large amounts of sand that can be mobilized by waves and currents. Sites that contain sediments with high levels of basalt and low levels of carbonates appear to be less impacted by sedimentation. These sites tend to be shallow, high wave energy habitats on exposed coastlines that are primarily dominated by successionist coral species such as the rose or cauliflower coral, *Pocillopora meandrina*. Both a vertical and horizontal stratification of sediment composition and grain-size is apparent for some parameters. Organics and large grain-sizes decrease, while $CaCO_3$ increases with depth. A horizontal carbonate gradient is characterized by increases in carbonate fraction of bulk sediment with increasing latitude, reflecting the greater coral reef development of the older islands.

Other signs of anthropogenic stress may result from artificial fish feeding or eutrophication. These can be characterized by high levels of organic compounds accompanied by low proportions of silt and clay (see: Chapter 5 Sediments).

7.4 Conclusions

7.4.1 Applications of Research

This investigation contributes substantially to the marine research community as follows:

1) The work describes Hawaiian coral reef communities on a broad geographic scale.
2) Results of the analysis identify key factors influential in explaining distribution of biotic populations and those linked to impaired conditions.
3) This investigation produced an extensive baseline database for future research and comparisons.
4) A model is available to the marine community for evaluation of site condition, for use in identification of areas of concern, for detection of

specific anthropogenic factors and for identification of possible marine protected area candidates.

Educational value

As global impacts continue to increase, baseline data as amassed in this investigation will be extremely valuable in determining deteriorating conditions. Coral bleaching and degradation of reef communities is accelerating at an alarming rate and is expected to continue. Identifying trends and patterns in the factors influencing the biota may prove to be important in minimizing the effects of this stress. Dissemination of information through educational sources, to work towards mitigation of damages and to explore viable solutions, will be vital. Statistically sound data will serve as the foundation to develop educational programs to keep the public informed and to educate the next generation of scientists.

Marine protected areas (MPAs)

Successful implementation of marine protected networks requires quantitative data on the environmental, ecological, and anthropogenic impacts to the biota. Understanding of the location, its biotic distribution and habitat types is essential to the development of functioning marine protected areas (Dugan and Davis 1993). Marine reserves would more fully meet their objectives if distributed along certain important environmental gradients. Depth and habitat complexity must be considered to protect as wide a spectrum of fish, coral, and invertebrate species as possible and to conserve representative species of recreational and commercial importance. Careful consideration should also be made to incorporate relevant ecological parameters including trophic guilds, endemism, and diversity. Yet, even MPAs with restricted fishing and high diversity that encompass a wide variety of habitats, can be ineffective with poor management.

Impacts from anthropogenic activities can influence ecological communities and thereby reduce the effectiveness of MPAs. Even no-take regions can be negatively impacted due to environmental degradation. Direct and indirect impacts result from increased tourist use of marine resources. Changes in diversity and abundance of fish populations can result from artificial feeding. Habitat destruction from trampling can affect fish nurseries, habitat for flora and fauna, recruitment sites and coral populations.

Friedlander et al. (2003) advocate MPAs that consist of high rugosity and moderate wave exposure with a high percentage of branching or lobate corals. Sheltered regions and areas of high spatial complexity have larger fish assemblages and are therefore worthy of greater consideration. Habitats of branching coral provide structural relief on a local scale and shelter large numbers of juvenile fishes. These important juvenile habitats, which provide greater connectivity with adult environments, deserve incorporation into reserve designs.

MPAs that have become areas of concern for management include the marine life conservation districts of Hanauma Bay and Waikīkī. Studies on carrying capacities have induced growing concern for the resources in these areas. These regions have been successfully marketed by all facets of the tourism industry. These protected areas have been sold as a wildlife encounter that must be experienced. Ecotourism has expanded into more pristine and less accessible regions. MPAs have become an open invitation to the tourist industry. The Hawaii Visitors Bureau and the tourist industry promote protected areas without financially supporting their sustainability. Different management strategies have been used to address a plethora of problems related to these types of impacts. These include spatial and temporal solutions as well as socio-economic factors. A preventative approach to selecting MPAs may prove more effective and lessen future management problems.

Preventative management

Interest in coral reefs as a recreational resource has increased, yet inadequate data can result in faulty decisions. The effectiveness of MPAs has been scientifically substantiated and is growing in popularity among managers. Extensive survey of all sites considered for MPA designation is usually prohibitive in time and cost. Baseline data provided by temporal CRAMP monitoring and spatial RAT assessments are available to managers to assist in evaluating possible MPAs. These biological baselines provide a foundation from which to compare any future transitions and elucidate patterns of decline that may require management protection. These baselines may also prove useful in evaluating existing programs.

In these rapidly changing times, a preventative approach to site selection must also include environmental factors that correlate with coral bleaching. The susceptibility of reefs to mortality related bleaching is influenced by some predictable environmental determinants. Resistance factors can mitigate the effects of temperature stress and create conditions favorable to recovery. These include habitats pre-exposed to stress, where corals have adapted to unfavorable conditions such as higher temperatures, areas with good water motion, protection from solar radiation, and proximity to cooler, deeper waters. Topography, turbidity, slope and cloud cover may also affect bleaching events.

Rapid assessments can distinguish candidates to set aside for protection and identify sites that are most susceptible to temperature stress. Fish and coral populations, rugosity, depth, habitat classification and sediment composition quantified by RATs, are among parameters listed to be measured for their potential in assessing coral bleaching impacts (The Nature Conservancy 2001).

Operative design of MPAs includes both spatial and temporal monitoring to track changes and assess effectiveness. Assessment data and background variability from this research are accessible to managers to compare to future conditions.

Application to science

The existing database can be used and expanded in future investigations of coral reef condition throughout the State of Hawaii. The statistical applications will be strengthened with the addition of further sites. The database is expanding with the addition of research conducted at CRAMP sites. These sites have been selected by marine scientists for the existing spatial and temporal data that can be used to further their research interests. Sites have been used to determine distribution and abundance of introduced organisms, (Coles in press), and alien algae (Smith et al. 1998). They are also currently being utilized to assess the extent of coral disease in the MHI (Aeby unpublished). Data on current fish populations are being compared to a terrestrial archeological site to contrast fish communities (Graves unpublished), to facilitate management decisions (Natural Area Reserves, Division of Aquatic Resources, Environmental Protection Agency, Kahoʻolawe Island Reserve Council, National Oceanic and Atmospheric Administration, Fish and Wildlife, US Dept. of Agriculture), and to further educational research (UH: biometry, zoology, botany, anthropology, Boise Forestry Science, Reefbase). Data has been requested to support legal cases (Hokulia and Pila'a), prepare environmental impact statements (artificial reefs, mooring pins and harbor modification), assist in permitting ('Āhihi Kina'u), and to incorporate into state and federal "state of the reef" reports. Requests for specific site information by State and Federal managers, non-governmental organizations, scientists from diverse fields and the general public have been numerous.

These initial assessment data can be used in the future to estimate impact of major environmental events such as storm waves or bleaching events. These data can be used to test the effectiveness of each parameter in predicting coral resistance and recovery. Such results can be utilized in strengthening the MPA selection process, evaluating existing management protocol, and designing future monitoring programs. The value of this database will continue to increase over time and will be highly influential to marine science.

Recent times have seen the rapid acceleration of environmental degradation of marine ecosystems. Anthropogenic impacts have resulted in an irreversible loss of biodiversity on a global scale, at an alarming rate. Unprecedented over-harvest has depleted marine stocks worldwide. Hawai‘i’s unique biota has not been exempt. As rapidly shifting baselines attest to this time of uncertainty, it is imperative to preserve Hawai‘i’s natural legacy through joint scientific and management efforts. To protect what resources remain, we must initially identify and evaluate our marine inventory through assessment and monitoring efforts to recognize indicators that can distinguish anthropogenic from natural impacts. The survival of our seas depends on statistically sound scientific data to identify and interpret the trends and patterns that lead to degradation. Research must take the lead in safeguarding our oceans. We must either embrace surmounting problems to uncover solutions or risk the devastating effects of environmental collapse.

Appendix I: Summary statistics of fish assemblage characteristics by transect for the Main Hawaiian Islands

Island	Location	Transect	Depth (m)	Number of Species	Total count	Total Biomass (g)	Number ha x (1000)	Biomass (Mg/ha)	Diversity
Hawai'i	Honaunau	1	13	15	193	5905	15	0.43	1.38
Hawai'i	Honaunau	2	12.1	17	293	5101	23	0.37	1.17
Hawai'i	Honaunau	3	12.7	22	271	4318	22	0.32	1.26
Hawai'i	Kaloko	1	11.8	17	312	3669	25	0.26	0.85
Hawai'i	Kaloko	2	13.3	18	106	3497	8	0.25	2.27
Hawai'i	Kaloko	3	12.1	21	266	3157	21	0.23	1.20
Hawai'i	Kaloko	4	11.5	20	103	7561	8	0.54	2.10
Hawai'i	Kaloko	5	8.2	13	24	2484	2	0.18	2.42
Hawai'i	Kaloko	6	12.4	21	156	4615	12	0.34	1.84
Hawai'i	Kaloko	7	17.3	16	142	2665	11	0.19	1.79
Hawai'i	Kaloko	8	15.5	14	111	3823	9	0.28	1.87
Hawai'i	Kaloko	9	14.5	16	121	4168	10	0.30	1.76
Hawai'i	Kaloko	10	13.9	21	168	4467	13	0.33	2.06
Hawai'i	Kaloko	11	7	22	147	4476	12	0.33	2.33
Hawai'i	Kaloko	12	18.2	19	470	3210	38	0.24	1.09
Hawai'i	Kaloko	13	18.2	21	138	2390	11	0.17	1.95
Hawai'i	Kaloko	14	12.1	10	97	2242	8	0.16	1.65
Hawai'i	Kaloko	15	3.9	17	119	4157	10	0.30	1.95
Hawai'i	Kaloko	16	5.5	16	124	4797	10	0.34	1.99
Hawai'i	Kaloko	17	2.7	15	128	4680	10	0.34	1.98
Hawai'i	Lapakahi	1	15.2	33	171	8527	14	0.62	2.39
Hawai'i	Lapakahi	2	5.8	20	116	4751	9	0.34	2.25
Hawai'i	Lapakahi	3	9.4	20	219	3439	18	0.25	1.43
Hawai'i	Lapakahi	4	9.4	21	119	3207	10	0.24	1.80
Hawai'i	Lapakahi	5	2.7	33	247	12269	20	0.89	2.34
Hawai'i	Lapakahi	6	17.3	26	394	24926	32	1.81	1.96
Hawai'i	Lapakahi	7	5.2	10	71	4656	6	0.34	1.87
Hawai'i	Mahukona	1	5.8	17	126	5808	10	0.42	2.02
Hawai'i	Mahukona	2	10.3	20	121	2982	10	0.22	2.35
Hawai'i	Mahukona	3	5.5	18	57	3089	5	0.23	2.48
Hawai'i	Mahukona	4	9.1	22	91	3785	7	0.27	2.54
Hawai'i	Mahukona	5	4.5	19	128	2813	10	0.21	1.80
Hawai'i	Mahukona	6	3.6	22	142	6654	11	0.48	2.43
Hawai'i	Puhi Bay	1	5.2	18	79	1863	6	0.14	2.14
Hawai'i	Puhi Bay	1	10.6	15	46	1735	4	0.13	2.06
Hawai'i	Puhi Bay	2	5.2	13	61	1826	5	0.14	1.66
Hawai'i	Puhi Bay	2	10.6	15	71	2397	6	0.17	1.95
Hawai'i	Puhi Bay	3	5.2	17	53	2030	4	0.15	2.46
Hawai'i	Puhi Bay	3	10.6	14	82	2305	7	0.16	1.71
Hawai'i	Puhi Bay	4	5.2	13	73	2932	6	0.21	1.96
Hawai'i	Puhi Bay	4	10.6	14	76	3162	6	0.23	2.02
Hawai'i	Pelekane Bay	2	1.3	2	404	2119	32	0.15	0.06
Hawai'i	Pelekane Bay	3	1.3	2	2	20	0	0.00	0.69
Hawai'i	Pelekane Bay	5	2	1	1	0	0	0.00	0.00

Appendix I: continued

Island	Location	Transect	Depth (m)	Number of Species	Total count	Total Biomass (g)	Number ha x (1000)	Biomass (Mg/ha)	Diversity
Hawai’i	Ka’apuna	1	3	14	219	11567	18	0.84	1.41
Hawai’i	Ka’apuna	1	10	14	77	3827	6	0.28	2.08
Hawai’i	Kawaihae	1	10	24	168	16013	13	1.16	2.65
Hawai’i	Kawaihae	1	3	19	322	25336	26	1.84	2.13
Hawai’i	La’aloa	1	3	15	166	3556	13	0.25	1.51
Hawai’i	La’aloa	1	10	19	125	4224	10	0.31	2.24
Hawai’i	Laupāhoehoe	1	3	16	81	2656	6	0.19	2.15
Hawai’i	Laupāhoehoe	1	10	15	48	1934	4	0.14	2.34
Hawai’i	Leleiwi	1	3	19	103	3024	8	0.22	2.34
Hawai’i	Leleiwi	1	10	25	89	3981	7	0.29	2.63
Hawai’i	Nenue	1	3	26	170	17753	14	1.29	2.55
Hawai’i	Nenue	1	10	24	158	5922	13	0.43	2.03
Kaho’olawe	Hakioawa	1	3	19	149	9249	12	0.67	2.34
Kaho’olawe	Hakioawa	1	10	16	101	6069	8	0.44	2.10
Kaua’i	Hanalei	1	3	6	16	213	1	0.02	1.51
Kaua’i	Hanalei	1	10	24	83	7447	7	0.54	2.55
Kaua’i	Hoai	1	3	22	87	3399	7	0.24	2.52
Kaua’i	Hoai	1	10	22	168	6433	13	0.46	1.96
Kaua’i	Limahuli	1	3	8	60	1029	5	0.07	1.46
Kaua’i	Limahuli	1	10	31	217	30920	17	2.24	2.60
Kaua’i	Miloli’i	1	3	11	102	1351	8	0.10	1.73
Kaua’i	Miloli’i	1	10	20	79	9247	6	0.67	2.17
Kaua’i	Nualolo	1	3	16	94	5591	8	0.41	2.18
Kaua’i	Nualolo	1	10	16	63	7586	5	0.55	2.46
Lana’i	Hulopo’e	1	8.5	21	280	3643	22	0.26	1.00
Lana’i	Hulopo’e	2	5.8	22	383	9070	31	0.66	1.15
Lana’i	Kalaeahole	7	9.9	19	74	4459	6	0.33	2.59
Lana’i	Kalaeahole	8	9.9	20	216	14868	17	1.08	1.59
Lana’i	Kalaeahole	9	5.2	31	158	9662	13	0.70	2.68
Lana’i	Kalaeahole	10	6.4	16	128	3618	10	0.26	1.75
Lana’i	Keanapapa	1	14.6	16	76	2520	6	0.18	2.16
Lana’i	Keanapapa	2	13	26	157	7047	13	0.51	2.13
Lana’i	Keanapapa	3	4.8	18	177	5540	14	0.40	1.78
Lana’i	Keanapapa	4	11.5	22	186	6843	15	0.50	1.59
Lana’i	Keanapapa	5	2.9	26	129	9471	10	0.69	2.60
Lana’i	Keanapapa	6	3	27	162	14650	13	1.06	2.55
Lana’i	Ka’apahu	11	13.45	9	18	235	1	0.02	2.00
Lana’i	Ka’apahu	12	13.45	16	28	2026	2	0.15	2.47
Lana’i	Ka’apahu	13	13.3	5	9	288	1	0.02	1.52
Lana’i	Ka’apahu	14	13.3	5	8	225	1	0.02	1.49
Lana’i	Ka’apahu	15	3.15	25	148	21809	12	1.58	2.77
Lana’i	Ka’apahu	16	2.7	25	112	14824	9	1.08	2.70
Lana’i	Ka’apahu	17	3	33	193	17404	15	1.26	2.60
Lana’i	Ka’apahu	18	3	20	86	16567	7	1.21	2.65
Lana’i	Palaoa	1	20.9	10	35	656	3	0.05	2.05
Lana’i	Palaoa	2	3	15	90	5074	7	0.37	2.33

Appendix I: continued

Island	Location	Transect	Depth (m)	Number of Species	Total count	Total Biomass (g)	Number ha x (1000)	Biomass (Mg/ha)	Diversity
Lana'i	Palaoa	3	4.5	22	306	3012	24	0.22	1.23
Lana'i	Palaoa	4	25.2	4	5	19	0	0.00	1.33
Maui	Honolua N	1	3	27	182	19679	15	1.42	2.32
Maui	Honolua S	1	3	19	140	9771	11	0.71	2.37
Maui	Kanahena B N	1	3	28	78	5680	6	0.41	2.96
Maui	Kanahena B S	1	3	21	108	13936	9	1.01	2.46
Maui	Kahekili	1	3	25	298	19576	24	1.42	2.34
Maui	Kahekili	1	10	25	165	4283	13	0.31	2.14
Maui	Kanahena Pt N	1	3	19	196	30518	16	2.21	1.64
Maui	Kanahena Pt S	1	10	20	59	4298	5	0.31	2.49
Maui	Ma'alaea	1	3	14	144	1940	12	0.15	1.76
Maui	Ma'alaea	1	10	15	85	1543	7	0.11	1.77
Maui	Molokini	1	10	18	61	4227	5	0.31	2.73
Maui	Molokini	1	10	28	96	26516	8	1.92	2.99
Maui	Olowalu	1	10	19	100	6923	8	0.50	2.39
Maui	Olowalu	1	3	12	64	3824	5	0.28	1.89
Maui	Papaula	1	3	21	151	9934	12	0.72	2.16
Maui	Papaula	1	10	11	106	1637	8	0.12	1.64
Maui	Puamana	1	3	19	132	27933	11	2.02	2.13
Maui	Puamana	1	10	19	47	1037	4	0.07	2.63
Moloka'i	Kakahaia	1	19	25	117	9295	9	0.67	2.45
Moloka'i	Kakahaia	2	9.4	22	126	5711	10	0.42	2.47
Moloka'i	Kakahaia	3	19	21	588	201477	47	14.62	0.80
Moloka'i	Kakahaia	4	10.6	16	105	5283	8	0.38	1.97
Moloka'i	Kakahaia	5	4.5	20	107	5386	9	0.39	2.42
Moloka'i	Kakahaia	6	3.3	13	79	3180	6	0.23	2.05
Moloka'i	Kakahaia	7	4.5	22	74	3453	6	0.25	2.35
Moloka'i	Kakahaia	8	8.2	15	82	3061	7	0.22	1.78
Moloka'i	Kakahaia	9	3.5	21	94	1728	8	0.13	2.57
Moloka'i	Kamiloloa	1	18	17	173	10170	14	0.73	2.00
Moloka'i	Kamiloloa	2	18	19	132	9542	11	0.69	2.24
Moloka'i	Kamiloloa	3	9	18	56	5901	4	0.43	2.45
Moloka'i	Kamiloloa	4	18	19	129	8889	10	0.64	2.05
Moloka'i	Kamiloloa	5	10	17	156	3663	12	0.26	1.40
Moloka'i	Kamiloloa	6	3.5	16	57	1366	5	0.10	2.21
Moloka'i	Kamiloloa	7	9	7	15	1501	1	0.11	1.78
Moloka'i	Kamiloloa	8	3.5	18	76	1789	6	0.13	2.10
Moloka'i	Kamiloloa	9	3.5	10	55	364	4	0.03	1.60
Moloka'i	Kaunakakai	1	3	18	68	8190	5	0.60	2.57
Moloka'i	Kaunakakai	2	3	19	117	8585	9	0.63	2.27
Moloka'i	Kaunakakai	3	3	17	81	6891	6	0.50	2.21
Moloka'i	Kaunakakai	4	3	20	103	12456	8	0.91	2.39
Moloka'i	Pālā'au	1	3	17	90	4683	7	0.34	2.16
Moloka'i	Pālā'au	2	3	15	113	10085	9	0.73	1.95
Moloka'i	Pālā'au	3	3	15	88	3892	7	0.28	1.95
Moloka'i	Pālā'au	4	3	13	118	6655	9	0.48	1.91

Appendix I: continued

Island	Location	Transect	Depth (m)	Number of Species	Total count	Total Biomass (g)	Number ha x (1000)	Biomass (Mg/ha)	Diversity
Moloka'i	Kamiloloa	1	3	14	58	1460	5	0.11	2.21
Moloka'i	Kamiloloa	1	10	13	58	2052	5	0.15	2.41
Moloka'i	Kamalō	1	3	18	87	2433	7	0.17	2.39
Moloka'i	Kamalō	1	10	13	97	3891	8	0.28	2.14
Moloka'i	Pālā'au	1	3	21	133	10407	11	0.75	2.35
Moloka'i	Pālā'au	1	10	15	88	3582	7	0.26	2.18
Ni'ihau	Ki'eki'e	1	4	24	213	38260	17	2.78	1.96
Ni'ihau	Ki'eki'e	2	6.4	7	19	327	2	0.03	1.51
Ni'ihau	Kaununui	3	5	19	110	16136	9	1.17	2.27
Ni'ihau	Kaununui	4	7	11	130	2867	10	0.21	1.04
Ni'ihau	Keawanui	5	10	27	83	4803	7	0.34	2.72
Ni'ihau	Keawanui	6	10.6	9	46	1710	4	0.13	1.79
Ni'ihau	Lehua Is.	9	2.9	20	94	14645	8	1.06	1.80
Ni'ihau	Lehua Is.	10	6.1	9	31	458	2	0.04	1.59
Ni'ihau	Pu'ukole Pt.	7	9.1	21	102	8672	8	0.63	2.48
Ni'ihau	Pu'ukole Pt.	8	9.4	18	100	942	8	0.07	2.29
O'ahu	Manana	1	4.7	7	56	216	4	0.02	1.35
O'ahu	Manana	2	4.2	15	133	2523	11	0.18	2.09
O'ahu	Manana	3	1.7	9	49	677	4	0.05	1.67
O'ahu	Manana	4	3	16	47	771	4	0.05	2.10
O'ahu	Manana	5	1.8	11	104	3718	8	0.27	1.50
O'ahu	Manana	6	5.2	5	7	70	1	0.01	1.55
O'ahu	Waikīkī	2	7.6	15	60	1493	5	0.11	2.01
O'ahu	Waikīkī	4	1.8	7	20	226	2	0.02	1.64
O'ahu	Waikīkī	14	0.9	1	1	2	0	0.00	0.00
O'ahu	Waikīkī	17	19.1	3	3	232	0	0.02	1.10
O'ahu	Waikīkī	19	12.1	9	19	841	2	0.06	1.66
O'ahu	Waikīkī	22	1	1	1	19	0	0.00	0.00
O'ahu	Waikīkī	24	1	1	2	187	0	0.01	0.00
O'ahu	Waikīkī	27	11.35	18	94	1687	8	0.12	2.21
O'ahu	Waikīkī	31	12.1	1	3	246	0	0.02	0.00
O'ahu	Waikīkī	33	5.45	23	138	14938	11	1.09	2.36
O'ahu	Waikīkī	38	6.36	22	130	4812	10	0.34	2.47
O'ahu	Waikīkī	42	4.54	4	12	300	1	0.02	0.98
O'ahu	Ala Wai	1	3	10	84	1884	7	0.14	1.09
O'ahu	Ala Wai	1	10	14	85	2120	7	0.15	1.68
O'ahu	Hanauma	1	3	25	154	13893	12	1.01	2.58
O'ahu	Hanauma	1	10	30	273	19912	22	1.44	2.38
O'ahu	He'eia	1	3	22	293	21357	23	1.55	1.72
O'ahu	He'eia	1	10	7	141	4783	11	0.34	0.85
O'ahu	Pili o Kahe	1	3	19	82	2221	7	0.16	2.33
O'ahu	Kahe Pt.	1	3	20	89	3084	7	0.23	2.45
O'ahu	Moku o lo'e	1	3	21	441	26743	35	1.94	1.87
O'ahu	Moku o lo'e	1	10	7	23	1577	2	0.12	1.37
O'ahu	Pūpūkea	1	3	10	60	1568	5	0.12	1.66
O'ahu	Pūpūkea	1	10	21	126	5193	10	0.38	2.27

Appendix I: continued

Island	Location	Transect	Depth (m)	Number of Species	Total count	Total Biomass (g)	Number ha x (1000)	Biomass (Mg/ha)	Diversity
O'ahu	Ka'alaea	1	3	16	638	31377	51	2.28	1.30
O'ahu	Ka'alaea	1	10	3	14	542	1	0.04	0.80

Appendix II: Summary statistics of fish assemblage characteristics by location for the MHI

Island	Location	Number of Species	Total count	Total Biomass (g)	Number ha x (1000)	Biomass (Mg/ha)	Diversity
Hawai'i	Honaunau	18	252	5108	20.2	0.37	1.27
Hawai'i	Kaloko	17	161	3886	12.9	0.28	1.83
Hawai'i	Lapakahi	23	191	8825	15.3	0.64	2.01
Hawai'i	Mahukona	20	111	4188	8.9	0.31	2.27
Hawai'i	Puhi Bay	15	68	2281	5.4	0.16	1.99
Hawai'i	Pelekane	2	136	713	10.9	0.05	0.25
Hawai'i	Ka'apuna	14	148	7697	11.8	0.56	1.75
Hawai'i	Kawaihae	22	245	20674	19.6	1.50	2.39
Hawai'i	La'aloa	17	146	3890	11.6	0.28	1.88
Hawai'i	Laupāhoehoe	16	65	2295	5.2	0.16	2.25
Hawai'i	Leleiwi	22	96	3503	7.7	0.25	2.49
Hawai'i	Nenue Point	25	164	11837	13.1	0.86	2.29
Kaua'i	Hanalei Bay	15	50	3830	4.0	0.28	2.03
Kaua'i	Ho'ai	22	128	4916	10.2	0.35	2.24
Kaua'i	Limahuli	20	139	15974	11.1	1.16	2.03
Kaua'i	Miloli'i	16	91	5299	7.2	0.38	1.95
Kaua'i	Nualolo Kai	16	79	6589	6.3	0.48	2.32
Kaho'olawe	Hakioawa	18	125	7659	10.0	0.55	2.22
Lāna'i	Hulopo'e	22	332	6356	26.5	0.46	1.08
Lāna'i	Kalaeāhole	22	144	8152	11.5	0.59	2.15
Lāna'i	Keanapapa	23	148	7678	11.8	0.55	2.14
Lāna'i	Ka'apahu	17	75	9172	6.0	0.66	2.28
Lāna'i	Palaoa	13	109	2190	8.7	0.16	1.74
Maui	Honolua N	27	182	19679	14.6	1.42	2.32
Maui	Honolua S	19	140	9771	11.2	0.71	2.37
Maui	Kanahena	28	78	5680	6.2	0.41	2.96
Maui	Kanahena S.	21	108	13936	8.6	1.01	2.46
Maui	Kahekili	25	232	11929	18.5	0.86	2.24
Maui	Kanahena Pt.	20	128	17408	10.2	1.26	2.07
Maui	Ma'alaea	15	115	1742	9.2	0.13	1.76
Maui	Molokini	18	61	4227	4.9	0.31	2.73
Maui	Molokini S.	28	96	26516	7.7	1.92	2.99
Maui	Olowalu	16	82	5374	6.6	0.39	2.14
Maui	Papaula	16	129	5785	10.3	0.42	1.90
Maui	Puamana	19	90	14485	7.2	1.05	2.38
Moloka'i	Kakahai'a	19	152	26508	12.2	1.92	2.10
Moloka'i	Kamiloloa	15	152	6554	6.1	0.24	2.15
Moloka'i	Kaunakakai	19	92	9031	7.4	0.65	2.36
Moloka'i	Pala'au	17	213	13323	8.5	0.49	2.13
Moloka'i	Kamalō	16	92	3162	7.4	0.23	2.27
Ni'ihau	Ki'eki'e	16	116	19293	9.3	1.40	1.74
Ni'ihau	Kaununui	15	120	9501	9.6	0.69	1.66
Ni'ihau	Keawanui	18	65	3256	5.2	0.24	2.26
Ni'ihau	Lehua Island	15	63	7552	5.0	0.54	1.70

Appendix II: continued

Island	Location	Number of Species	Total count	Total Biomass (g)	Number ha x (1000)	Biomass (Mg/ha)	Diversity
Ni'ihau	Pu'ukole Pt.	20	101	4807	8.1	0.34	2.39
O'ahu	Manana	11	66	1329	5.3	0.10	1.71
O'ahu	Waikīkī	9	40	2082	3.2	0.15	1.20
O'ahu	Ala Wai	12	85	2002	6.8	0.15	1.39
O'ahu	Hanauma	28	214	16903	17.1	1.22	2.48
O'ahu	He'eia	15	217	13070	17.4	0.95	1.29
O'ahu	Pili o Kahe	19	82	2221	6.6	0.16	2.33
O'ahu	Kahe Pt.	20	89	3084	7.1	0.23	2.45
O'ahu	Moku o lo'e	14	232	14160	18.6	1.03	1.62
O'ahu	Pūpūkea	16	93	3381	7.4	0.24	1.97
O'ahu	Ka'alaea	10	326	15960	26.1	1.16	1.05

Appendix III: Summary statistics of fish assemblage characteristics overall and by island

Island	Number (ha x 1000)	SD	biomass (Mg/ha)	SD	Diversity	Evenness
Hawai'i	11.6	7.8	0.46	0.37	1.99	0.70
Maui	9.2	3.8	0.96	0.54	2.08	0.74
Kaho'olawe	10.0	2.7	0.55	0.16	2.22	0.78
Lana'i	10.6	7.9	0.53	0.46	2.03	0.74
Moloka'i	8.2	2.3	0.63	2.81	2.18	0.79
O'ahu	9.1	7.6	0.43	0.48	1.55	0.64
Kaua'i	7.8	4.6	0.54	0.64	2.11	0.77
Ni'ihau	7.4	4.4	0.64	0.86	1.95	0.72

Avg Count of species	Avg number ha x (1000)	Avg of biomass (Mg/ha)	overall average diversity
16.9 ± 6.8	9.8 ± 7.9	0.5 ± 1.2	1.94 ± 0.6

Appendix IV: Sediment grain-sizes (%) for sites in the Main Hawaiian Islands

HAWAI'I	Coarse and very coarse sand	sd	medium sand	sd	Fine and very sand	sd	silt/clay	sd
Ka'apuna 4m	95.9	4.1	3.1	3.0	0.8	1.0	0.2	0.1
Ka'apuna 10m	66.6	4.6	27.2	4.5	5.8	0.2	0.3	0.1
Hokulia 23m	87.8	1.3	9.9	1.2	1.9	0.1	0.4	0.1
Nenue 5m	63.5	21.7	30.5	18.2	5.9	3.7	0.3	0.1
Nenue 10m	76.5	23.1	19.5	18.3	3.5	4.4	0.5	0.5
Kawaihae 3m	85.4	2.2	5.9	2.4	8.0	4.0	0.7	0.6
Kawaihae10m	12.4	10.8	29.2	0.9	55.8	13.7	2.6	2.0
La'aloa 3m	79.2	4.2	14.6	2.3	4.7	2.2	1.5	0.2
La'aloa 10m	72.3	4.4	18.7	1.0	8.3	3.0	0.8	1.8
Laupahoehoe 3m	66.3	16.4	17.2	9.1	13.3	6.8	3.2	0.5
Leleiwi 3m	85.4	1.3	10.9	1.0	3.2	0.3	0.6	0.0
Leleiwi 10m	69.0	39.8	23.4	30.5	7.1	9.0	0.4	0.2
Puhi Bay	82.3	10.3	15.3	10.3	2.1	0.0	0.3	0.1
Lapakahi	72.1	1.3	21.3	18.3	5.5	3.0	1.0	0.1
Mahukona	87.7	2.1	8.5	1.7	3.1	0.4	0.7	0.0
Pelekane	3.4	0.2	4.1	1.2	41.6	4.3	50.9	3.3
MAUI								
Honolua N 3m	44.9	11.4	33.4	2.1	20.3	13.6	1.4	0.2
Honolua S 3m	42.6	3.2	42.3	3.9	12.8	0.3	2.2	1.0
Kahekili 3m	38.6	8.8	50.4	4.1	10.5	4.6	0.6	0.1
Kahekili 7m	42.4	20.2	49.4	15.3	7.5	4.6	0.8	0.3
Maalaea 3m	78.3	1.2	13.3	1.9	7.7	0.8	0.7	0.1
Maalaea 6m	88.0	8.7	7.2	5.9	3.8	2.6	1.0	0.2
Molokini 8m	58.5	1.8	27.4	0.5	12.0	0.2	2.1	1.1
Molokini 13m	61.8	20.0	28.5	13.7	8.9	6.0	0.8	0.3
Olowalu 3m	11.7	8.4	29.1	13.4	58.8	21.8	0.4	0.0
Olowalu 7m	0.6	0.1	11.4	1.0	87.2	1.0	0.9	0.0
Papaula 4m	79.3	21.8	19.7	21.6	0.7	0.3	0.3	0.0
Papaula 10m	73.7	9.5	22.3	7.0	3.5	2.5	0.4	0.0
Puamana 3m	4.5	6.3	17.6	23.2	77.3	29.8	0.6	0.3
Puamana 13m	33.6	12.8	18.1	0.8	44.4	12.1	3.9	1.6
Kanahena Bay 1m	14.3	4.5	70.8	0.9	13.0	5.0	1.9	0.3
Kanahena Bay 3m	82.5	17.8	14.9	18.1	1.7	0.1	1.0	0.2
Kanahena Pt 3m	82.8	11.3	11.9	7.0	4.1	3.6	1.2	0.7
Kanahena Pt 10m	56.0	22.2	20.4	6.8	20.4	13.9	3.2	1.4
KAHO'OLAWE								
Hakioawa 3m	14.1	13.4	34.7	1.9	42.0	13.8	9.2	1.4
Hakioawa 10m	18.3	2.9	27.4	2.5	40.2	10.5	14.2	5.1
LĀNA'I								
Ka'apahu 13	48.4	3.9	45.3	6.3	4.9	2.1	1.4	0.3
Ka'apahu 16	85.5	5.6	10.4	7.8	3.0	2.2	1.1	0.1
Ka'apahu 14	58.9	5.7	36.7	5.5	3.1	0.0	1.3	0.2

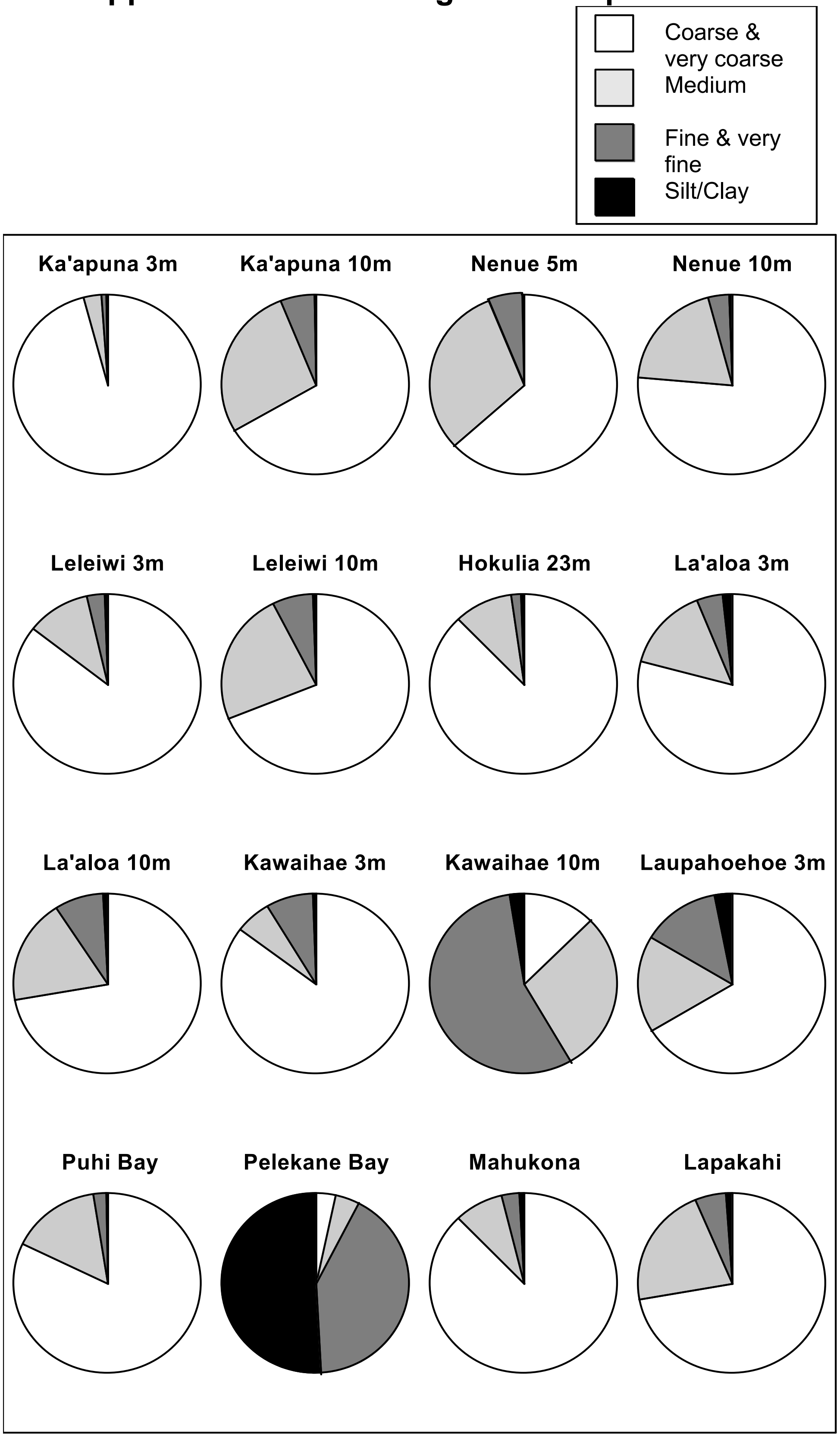
Appendix IV: continued

LĀNA'I	Coarse and very coarse sand	sd	medium sand	sd	Fine and very sand	sd	silt/clay	sd
Kalaeahole 10	73.8	10.8	20.3	8.0	3.3	1.7	2.5	1.0
Kalaeahole 9	68.6	19.7	24.6	14.9	2.7	3.2	2.7	1.7
Keanapapa 2	82.5	2.4	14.8	1.8	2.1	0.5	0.6	0.2
Keanapapa 1	82.5	2.3	16.0	2.2	1.1	0.1	0.5	0.1
Manele Bay	7.7	1.0	20.9	4.5	60.7	2.1	4.8	3.4
Hulopo'e Bay	26.3	5.1	57.1	2.3	15.3	1.8	1.3	0.9
Palaoa Point	96.2	0.5	2.8	0.7	0.4	0.1	0.7	0.2
MOLOKA'I								
Kamalo 3m	67.3	5.1	14.6	3.1	14.0	2.0	4.2	0.0
Kamiloloa 3m	11.6	6.9	54.1	12.0	33.7	5.1	0.6	0.1
Kamiloloa 10m	48.8	16.0	25.1	7.3	23.4	9.4	2.7	0.7
Palaau 3m	96.6	0.2	1.6	0.4	0.7	0.1	1.1	0.3
Palaau 10m	31.7	5.9	28.0	1.6	31.9	5.9	8.5	1.7
Kakaha'ia 9	11.0	0.3	9.9	0.3	29.1	3.9	50.1	4.5
Kakaha'ia 7	36.4	9.9	32.5	2.0	25.5	5.2	5.6	2.7
O'AHU								
Kahe Point 3m	13.9	6.9	82.7	6.6	3.3	0.3	0.1	0.0
Pili o Kahe 3m	33.1	16.3	66.3	16.3	0.5	0.0	0.1	0.0
Pupukea 4m	95.8	1.6	3.8	1.2	0.3	0.3	0.1	0.1
Pupukea 8m	94.4	0.0	4.4	0.7	0.9	0.5	0.3	0.2
Ka'alaea 2m	12.9	4.4	12.4	3.4	44.0	5.5	30.7	4.5
Ka'alaea 8m	3.8	1.9	5.1	2.3	28.0	7.1	63.1	9.0
He'eia 2m	13.4	2.7	10.7	8.4	20.4	8.1	55.5	19.2
He'eia 8m	11.3	4.4	5.1	2.7	23.7	10.2	59.9	17.3
Moku o lo'e 2m	22.2	1.8	11.8	2.8	24.8	0.2	41.2	1.2
Moku o lo'e 9m	25.3	1.2	23.9	20.7	19.1	6.7	31.7	15.3
Hanauma 3m	20.4	4.0	68.6	2.8	10.8	1.2	0.2	0.0
Hanauma 10m	45.6	11.9	31.9	4.5	21.5	7.1	1.0	0.2
Waikiki 4	76.2	8.6	21.1	8.0	1.7	0.4	1.0	0.2
Waikiki 27	79.0	2.7	12.4	0.9	7.7	2.0	0.9	0.2
Waikiki 22	87.6	5.2	7.2	1.9	4.8	3.2	0.5	0.1
Manana	80.5		17.1		2.1		0.3	
KAUA'I								
Limahuli 1m	46.6	10.1	46.2	10.2	6.7	0.8	0.5	0.1
Limahuli 10m	11.1	4.1	74.9	2.4	13.2	1.2	0.8	0.5
Ho'ai 3m	34.3	0.8	60.6	0.3	5.0	0.4	0.2	0.1
Ho'ai 10m	88.3	3.7	10.8	2.9	2.0	0.8	0.3	0.2
Nualolo 3m	77.6	5.6	18.0	8.6	3.4	2.1	1.0	0.9
Nualolo 10m	98.5	0.4	0.8	0.1	0.6	0.2	0.1	0.1
Miloli'i 3m	97.2	1.7	1.6	1.1	1.1	0.8	0.2	0.1
Miloli'i 10m	87.6	5.2	8.8	3.4	3.1	1.6	0.5	0.2
Hanalei 3m		0.4		0.8		0.7		0.1
Hanalei 10m		0.1		0.4		1.1		0.1

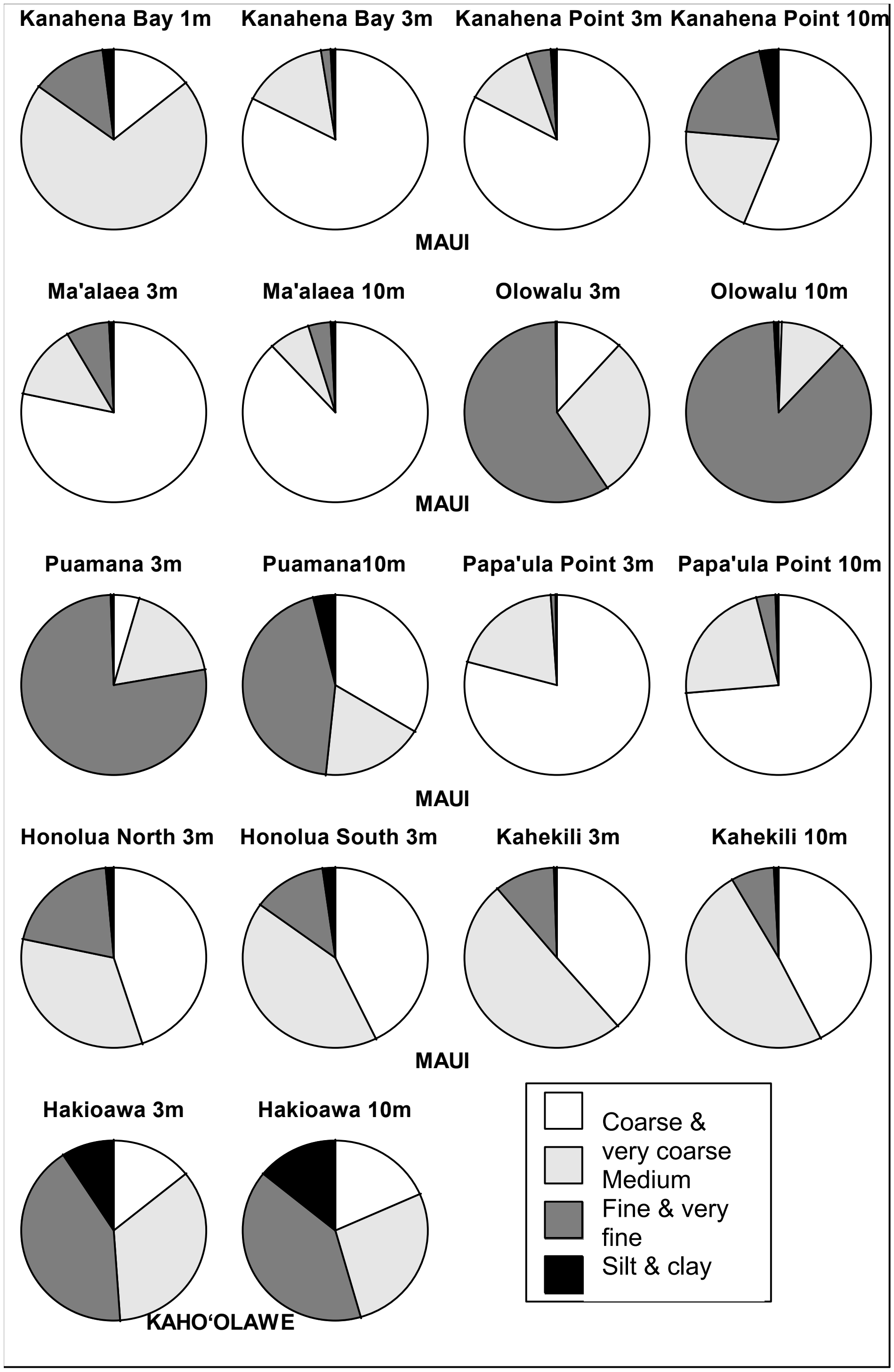
Appendix IV: continued

NI'IHAU	**Coarse and very coarse sand**	**sd**	**medium sand**	**sd**	**Fine and very sand**	**sd**	**silt/clay**	**sd**
Ki'eki'e 1	71.2	9.8	20.1	7.5	8.0	2.4	0.7	0.1
Keawanui Bay 5	78.0	9.3	5.2	1.3	15.9	7.8	0.9	0.2
Kaununui 3	95.2	1.1	2.4	0.2	1.3	0.8	1.1	0.2
Pu'ukole Pt. 7	75.9	8.2	22.8	7.2	0.9	0.9	0.4	0.1
Lehua Island 9	91.2	1.7	4.9	1.6	2.2	0.2	1.8	0.1

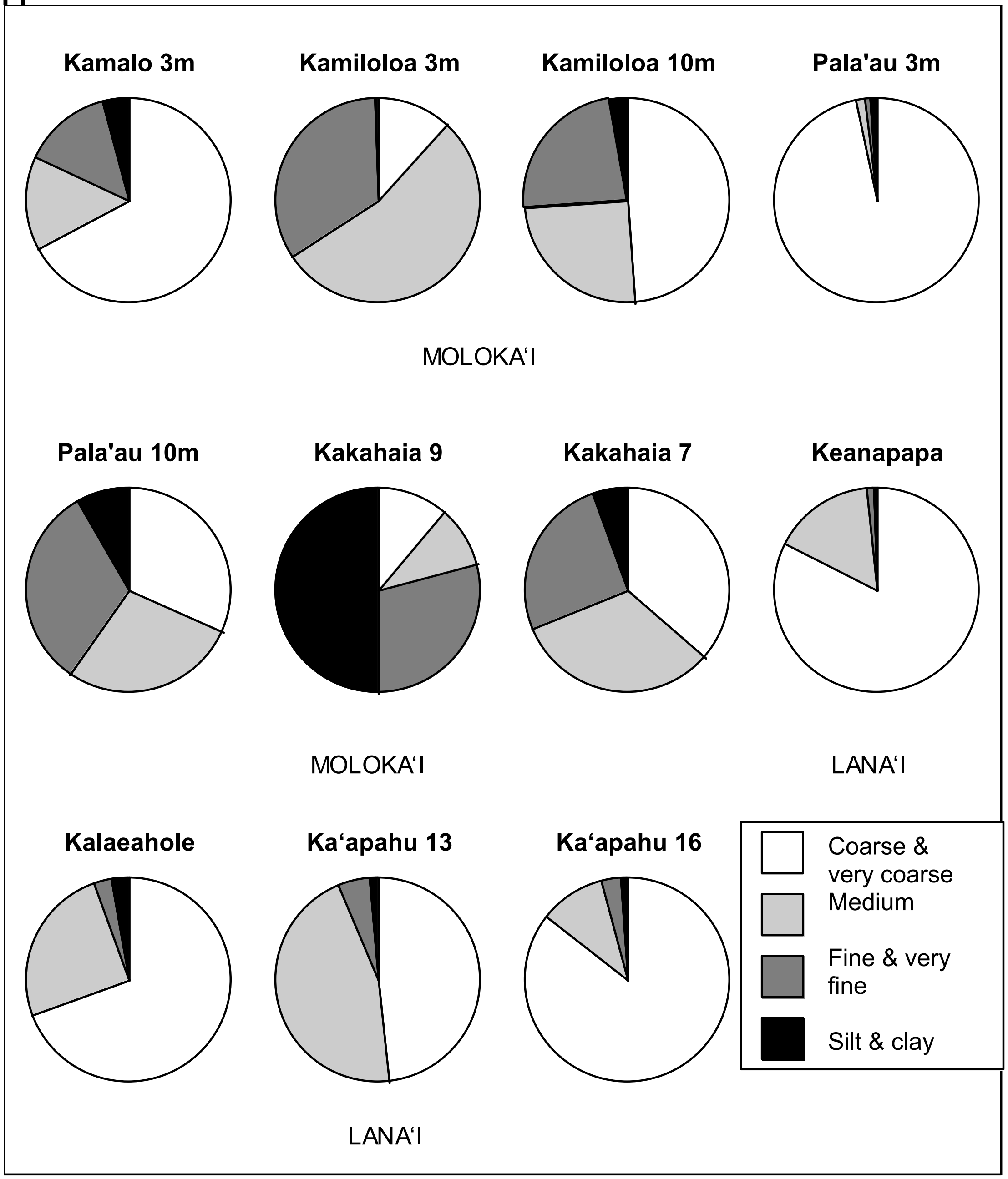
Appendix V: Sediment grain-size: pie charts



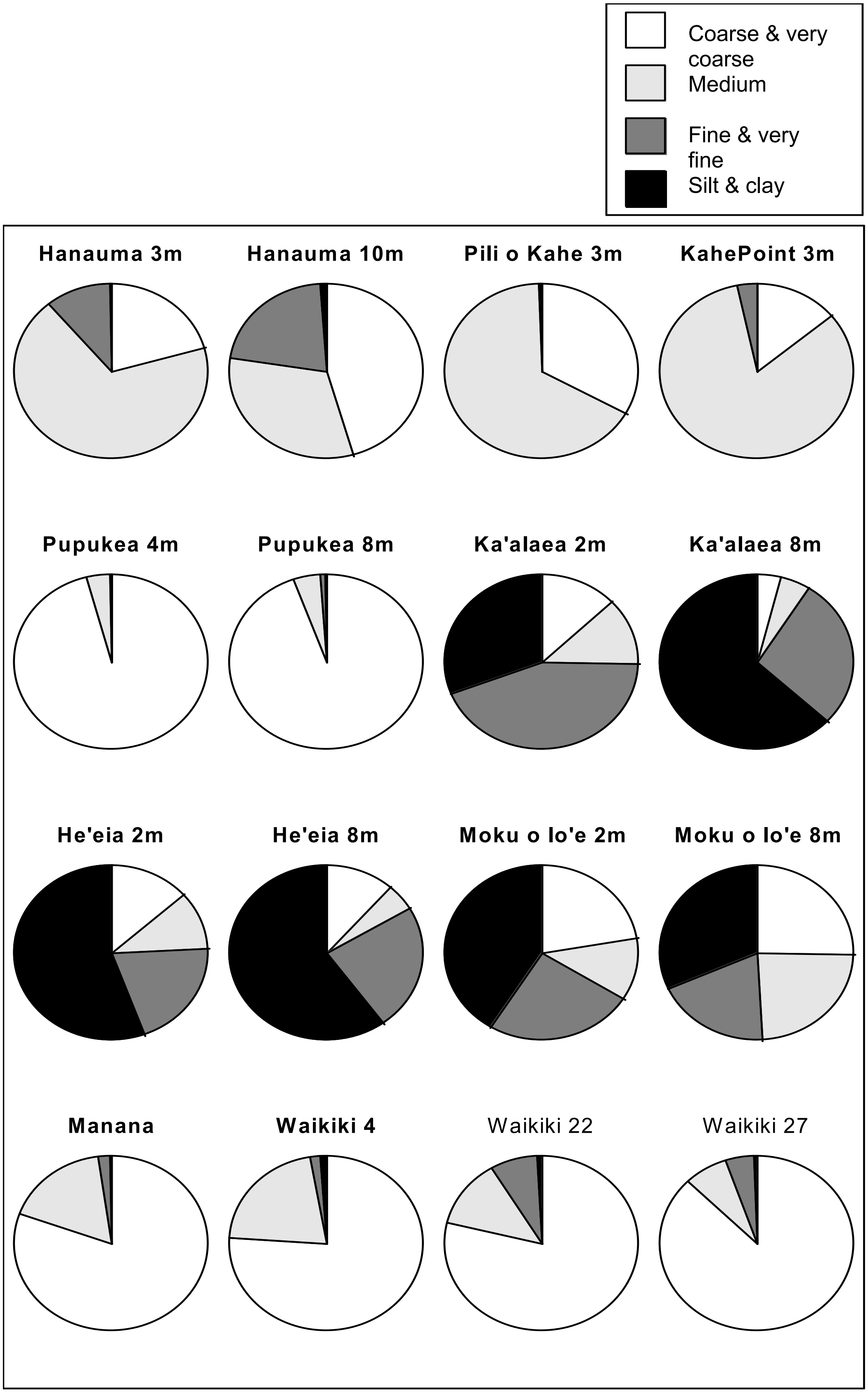
Appendix V: continued



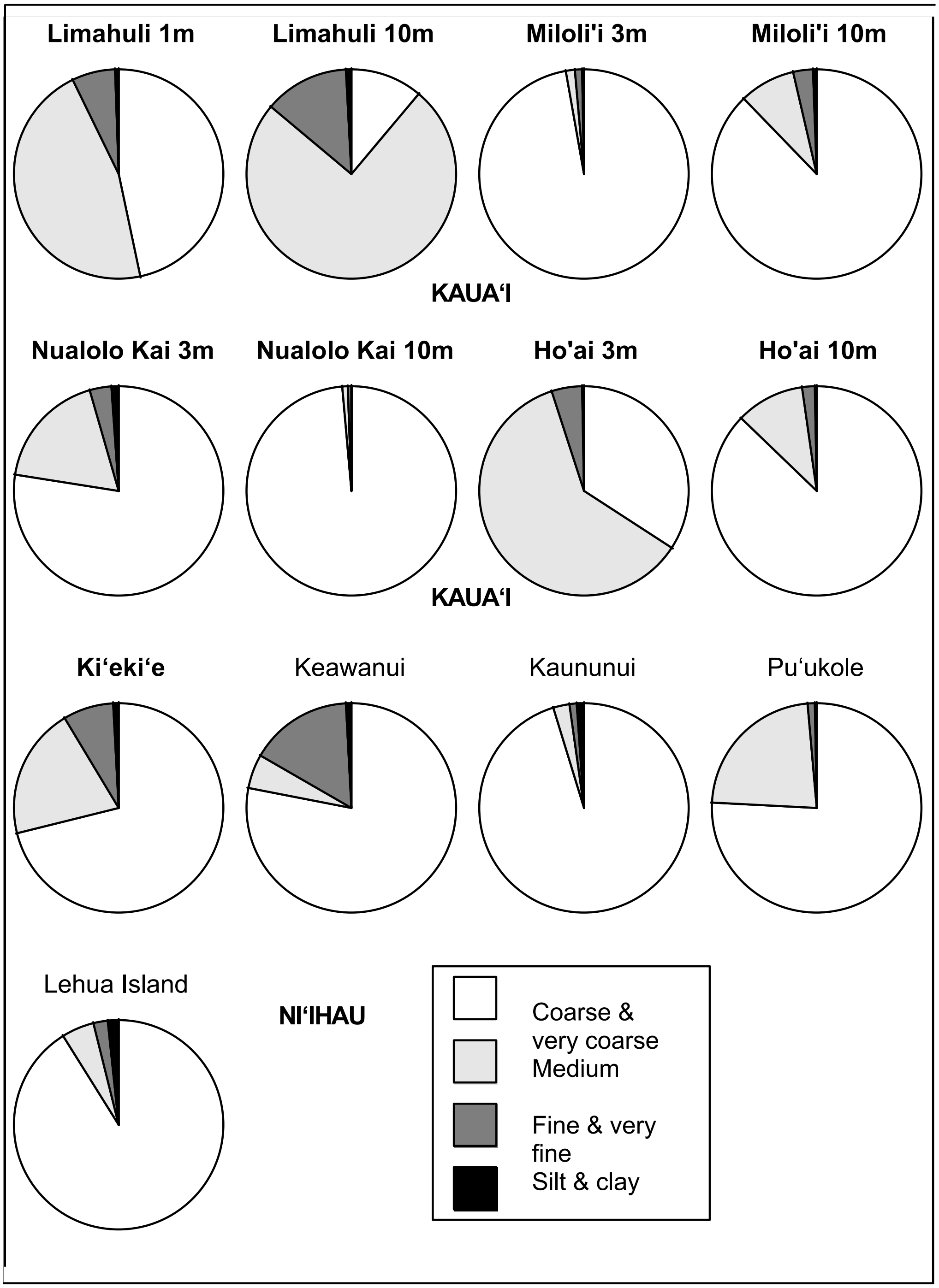
Appendix V: continued



Appendix V: continued



Appendix V: continued



Appendix VI: Sediment composition for sites in the Main Hawaiian Islands

Site	LOI (%)		$CaCO_3$ (%)		Terrigenous (%)	
HAWAI'I	mean	sd.	mean	sd	mean	sd
Ka'apuna 3m	0.2	0.1	0.2	0.5	99.7	0.4
Ka'apuna 10m	0.3	0.0	1.1	0.0	98.6	0.6
Hokulia 23m	2.6	0.4	71.7	0.1	25.7	6.4
Nenue Point 5m	2.6	0.2	74.6	0.4	22.8	3.4
Nenue Point 10m	2.6	0.1	69.3	0.3	27.8	10.7
La'aloa 3m	2.6	0.1	87.3	0.2	10.1	2.0
La'aloa 10m	2.8	0.1	88.7	2.7	8.5	2.3
Kawaihae 3m	3.8	0.5	93.1	1.3	3.1	1.1
Kawaihae 10m	3.6	0.2	93.3	0.7	3.1	0.5
Laupāhoehoe 3m	5.1	0.7	50.3	4.8	44.6	9.4
Laupāhoehoe 10m	3.8	1.1	12.4	4.5	83.9	4.9
Leleiwi 3m	2.8	0.2	77.3	0.9	20.0	2.9
Leleiwi 10m	3.0	0.2	88.5	0.4	8.6	0.6
Pelekane	23.6	0.2	10.0	1.2	66.4	1.4
Lapakahi	3.0	0.1	81.9	3.3	15.1	7.3
Mahukona	3.4	0.8	73.2	26.8	23.5	26.8
Puhi Bay 5m	2.3	1.1	61.6	1.6	36.0	1.0
Puhi Bay 10m	2.6	1.2	63.2	28.4	34.3	2.5
MAUI						
Kanahena Bay 1m	2.8	0.2	89.5	0.7	7.8	5.5
Kanahena Bay 3m	2.7	0.2	85.1	1.1	12.3	1.1
Kanahena Point 3m	2.1	0.1	49.3	0.6	48.6	18.9
Kanahena Point 10m	3.6	0.4	92.6	0.5	3.8	0.8
Mā'alaea 3m	2.9	0.1	91.1	0.9	6.0	1.1
Mā'alaea 10m	2.8	0.2	92.9	1.4	4.3	1.3
Olowalu 3m	3.2	0.2	42.0	2.1	54.9	5.5
Olowalu 10m	3.8	0.3	28.2	0.6	68.0	2.3
Puamana 3m	3.9	0.2	35.1	0.4	61.0	1.6
Puamana 10m	4.8	0.4	62.9	3.6	32.3	9.6
Papa'ula Point 3m	3.0	0.2	94.9	0.2	2.1	0.1
Papa'ula Point 10m	3.2	0.0	94.3	0.5	2.5	0.5
Honolua North 3m	3.6	0.2	87.9	0.3	8.5	0.3
Honolua South 3m	4.7	0.3	64.5	0.6	30.8	1.5
Kahekili 3m	2.6	0.3	83.7	0.6	13.7	1.7
Kahekili 10m	2.8	0.2	85.9	0.5	11.4	1.2
Molokini 8m	4.2	0.0	81.3	0.2	14.5	0.3
Molokini 13m	3.3	0.1	93.2	0.3	3.5	0.3
LĀNA'I						
Ka'apahu 13	3.2	0.3	72.8	7.7	24.0	7.3
Ka'apahu 14	3.1	0.2	63.1	0.0	33.8	0.2
Ka'apahu 16	3.1	0.0	59.7	1.3	37.3	1.4
Kalaeahole 9	3.4	0.1	60.1	7.0	36.5	5.8
Kalaeahole 10	4.0	0.9	58.7	3.6	37.2	3.0
Keanapapa 1	3.6	0.3	87.5	0.4	8.9	0.6
Keanapapa 2	3.5	0.2	82.3	8.9	14.1	12.0
Nanahoa	10.3	0.5	12.7	0.3	77.0	0.4
Manele Bay	4.4	0.2	63.5	0.4	32.0	
Hulopo'e Bay	2.8	0.1	54.6	3.8	42.6	
Palaoa Point	4.1	0.7	87.5	2.3	8.5	

Appendix VI: continued

	LOI (%)		$CaCO_3$ (%)		Terrigenous (%)	
MOLOKAʻI	mean	sd.	mean	sd	mean	sd
Kamalō 3m	2.1	0.3	96.5	0.6	1.4	0.4
Kamiloloa 3m	3.0	0.1	88.8	8.5	8.2	11.4
Kamiloloa 10m	3.4	0.2	93.3	0.8	3.3	0.7
Kamiloloa 1	3.6	0.1	93.3	0.9	3.1	0.7
Pālā ʻau 3m	2.5	0.1	95.3	0.5	2.2	0.7
Pālā ʻau 10m	3.5	0.4	94.0	3.1	2.4	1.1
Pālā ʻau 1	2.7	0.4	94.6	0.2	2.7	0.5
Kakahai'a 7	3.6	3.9	92.0	0.2	4.4	0.3
Kakahai'a 9	11.9	0.4	65.6	6.0	22.5	1.9
KAHOʻOLAWE						
Hakioawa 3m	11.4	0.0	17.2	0.9	71.4	1.6
Hakioawa 10m	11.5	0.0	27.5	0.2	61.0	1.5
OʻAHU						
Hanauma 3m	4.7	0.3	46.5	0.9	48.8	1.7
Hanauma 10m	5.0	0.1	59.0	1.5	36.1	3.2
Pili o Kahe 3m	2.0	0.3	93.6	0.3	4.4	0.4
Kahe Point 3m	2.1	0.2	93.1	0.6	4.8	0.6
Pūpūkea 3m	2.3	0.1	96.0	0.2	1.6	0.2
Pūpūkea 10m	2.3	0.3	95.7	0.4	2.0	0.3
Kaʻalaea 2m	17.1	0.5	40.3	1.4	42.6	5.7
Kaʻalaea 8m	14.5	0.3	48.2	1.0	37.3	0.8
Heʻeia 2m	14.1	0.1	55.7	0.3	30.2	2.7
Heʻeia 8m	14.6	0.7	39.0	8.3	34.6	10.0
Moku o loʻe 2m	9.9	0.2	69.5	0.3	20.6	4.5
Moku o Loʻe 8m	7.4	0.3	78.1	1.0	14.6	1.7
Waikiki 4	2.9	0.1	95.6	0.1	1.5	0.4
Waikiki 5	3.3	0.3	94.3	0.0	2.4	0.4
Waikiki 7	5.4	3.0	92.6	3.2	2.0	0.3
Waikiki 8	3.1	0.1	94.4	0.7	2.5	0.7
Waikiki 9	2.8	0.4	95.1	0.1	2.1	0.5
Waikiki 12	3.2	0.1	94.8	0.3	2.1	0.4
Waikiki 22	3.4	0.0	94.6	0.2	2.1	0.3
Waikiki 27	3.3	0.1	94.6	0.5	2.2	0.8
Manana Island	4.0	1.7	69.9	15.0	26.1	11.7
Maunalua Bay 12m	3.7	0.9	92.3	2.4	4.0	1.6
Maunalua Bay 6m	3.2	0.3	94.1	0.6	2.7	0.5
KAUAʻI						
Limahuli 1m	3.3	0.2	74.8	0.5	21.9	1.4
Limahuli 10m	3.3	0.1	72.6	0.3	24.1	1.1
Miloliʻi 3m	3.2	0.6	89.7	1.8	7.2	3.2
Miloliʻi 10m	3.1	0.3	89.9	2.1	7.0	2.1
Nualolo Kai 3m	3.8	0.3	53.5	1.6	42.7	2.6
Nualolo Kai 10m	3.7	0.0	92.6	0.0	3.7	0.0
Hoʻai 3m	3.1	0.5	93.2	1.0	3.7	0.8
Hoʻai 10m	2.6	0.4	92.6	1.3	4.7	1.7
Hanalei 3m	3.8	0.2	79.1	0.5	17.1	1.3
Hanalei 10m	4.1	0.1	70.4	0.3	25.5	0.3
NIʻIHAU						
Ki'eki'e	3.4	0.0	77.0	4.4	19.7	7.5
Kaununui	2.8	0.0	92.8	2.0	4.4	3.2
Keawanui	3.4	0.3	75.6	5.0	21.0	3.9
Pu'ukole	3.5	0.1	86.8	2.4	9.8	1.9

Appendix VI: continued						
	LOI (%)		**$CaCO_3$ (%)**		**Terrigenous**	
NI‘IHAU	mean	sd.	mean	sd	mean	sd
Lehua Island	3.7	0.6	14.9	4.4	81.4	9.8

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