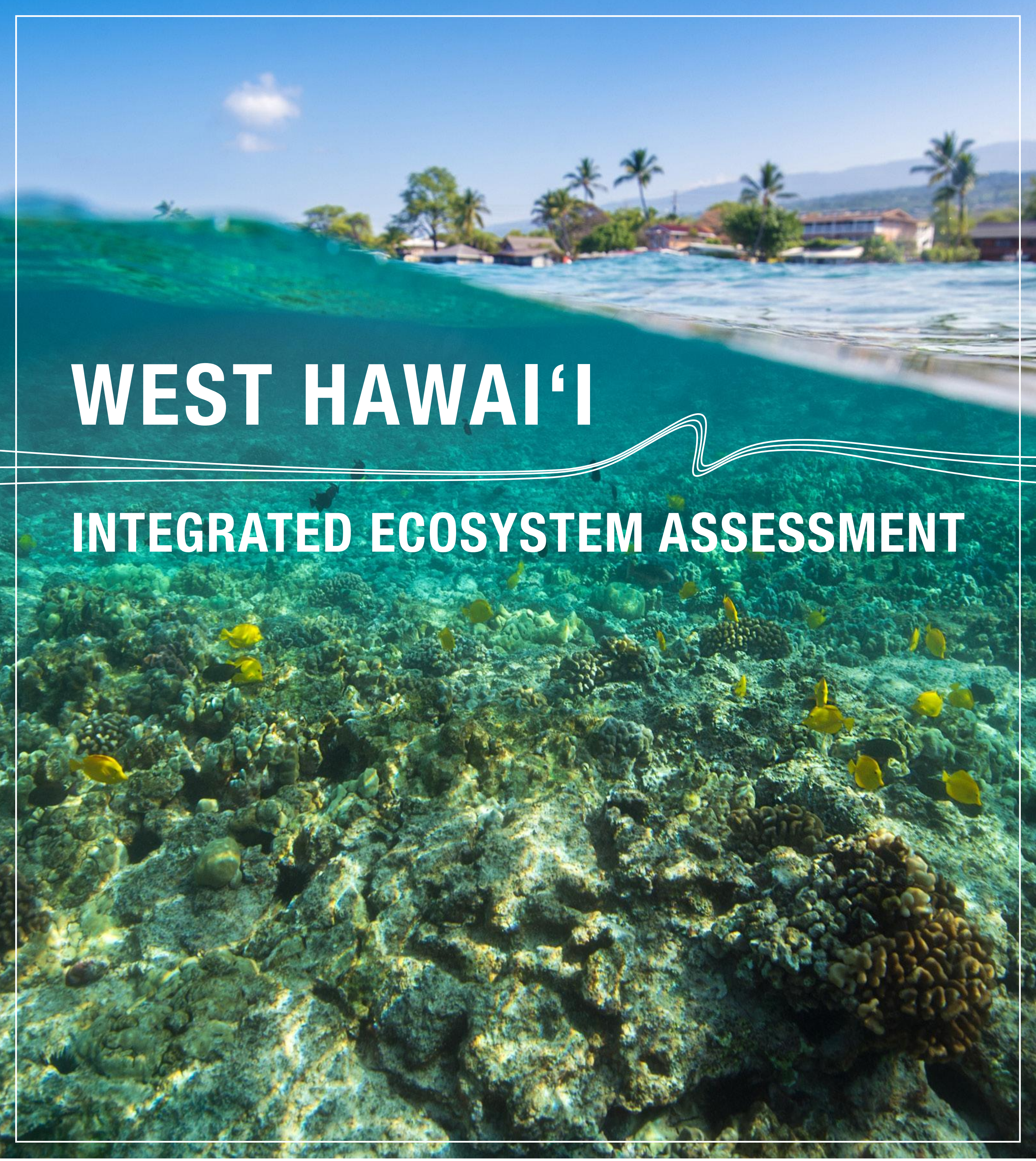

WEST HAWAI‘I

INTEGRATED ECOSYSTEM ASSESSMENT

Ecosystem Trends and Status Report
2016

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

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West Hawai‘i Integrated Ecosystem Assessment:
Ecosystem Trends and Status Report

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SUMMARY OF KEY FINDINGS

Yellow tang (*Zebrasoma flavescens)*

The population of Hawaiʻi Island has increased by 320% in the last 56 years, increasing pressures on the marine environment such as coastal development, habitat degradation, fishing pressure, and nutrient pollution. Human wastewater, for example, is principally disposed via on-site waste disposal systems in West Hawaiʻi. Cesspools – where effluent receives no treatment prior to being released into the environment – comprise 85% of all on-site waste disposal systems in the region. Cesspools leech excess pollution and nutrients into groundwater that flows to the ocean, threatening human health and degrading marine ecosystem integrity. The total number of on-site waste disposal systems in West Hawaiʻi nearly doubled from 1995 to 2010.

Ecosystem indicators compiled for coral reef fishes have shown an overall trend towards a community of smaller, more abundant fishes. From 2003 to 2014, mean fish length, an indicator of adult reef fish size structure, has shown a decreasing trend in both the North and South regions of West Hawaiʻi (Keahole Point serves as the dividing line between regions). Similarly, total fish biomass, an indicator of the entire fish community size, declined by ~20% in the North over the same time frame while in the South, no overall net change was observed. Herbivorous fishes, which are important for coral reef ecosystem resilience, have also declined in biomass across West Hawaiʻi over the past 12 years, while Uhu (e.g., Redlip Parrotfish, *Scarus rubroviolaceus*), a targeted herbivorous fish, is currently (2014) at a level of biomass that is considerably lower compared to the maximum biomass observed in 2007 and 2004 for the North and South regions, respectively. In contrast to the observed declines in the overall size structure of reef fishes in West Hawaii, total fish abundance has shown an increasing trend over the same time period, while juvenile yellow tang, which comprise ~85% of the total aquarium fish catch, increased approximately three- to four-fold and are presently at the highest density levels since monitoring began in 1999.

Ecosystem indicators related to benthic reef community integrity indicate a shift in West Hawaiʻi towards lowered reef accretion and reduced structural complexity. Hard coral cover, an indicator of reef topographic complexity, habitat structure, and reef accretion, decreased from an average of 44% to 31% cover in the North from 2003 to 2014, a decline of roughly one-third in just 12 years. However, over the same time period, hard coral cover remained relatively constant in the South. The ratio between the cover of calcifying to non-calcifying organisms – an indicator of coral reef community dynamics and the extent to which a given system is dominated by organisms that contribute to coral reef development and persistence – declined across West Hawaiʻi since 2003. The North experienced the biggest change in this indicator, with the a calcified:non-calcified ratio decreasing by approximately half to a present value < 1, indicating the benthic community is currently dominated by non-calcifying benthic organisms.

Climate and oceanographic indicators highlight long-term trends and recent anomalous conditions in West Hawaiʻi's natural environment. The El Niño Southern Oscillation (ENSO), an irregular, large-scale climate phenomenon that drives changes in regional oceanic and atmospheric conditions, has shifted over the last four decades towards increased frequency and severity in El Niño conditions, with the recent 2015 El Niño as one of the strongest on record. Rainfall, which can influence salinity, temperature, sediment load, and nutrient concentrations in the marine environment, has been at or below the long-term average over the past 15 years while the intensity of short-term events has increased over the same time period. Long-term sea level, an important indicator for coastal erosion and flooding, is rising by an estimated 3.79 mm/year and is expected to reach 0.48 m higher than present day levels by 2100. Sea surface temperature, an indicator of regional and climatic forcing that is highly influential to myriad ecological processes, was anomalously warm in recent years and reached a record level of thermal stress in September 2015, resulting in widespread and severe coral reef bleaching in West Hawaiʻi.

Coral bleaching in West Hawaiʻi, 2016 (Photographs courtesy of The Nature Conservancy).

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CONTENTS

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INTRODUCTION AND BACKGROUND

West Hawai i is a dynamic ecological region that is home to a diverse group of marine organisms including tropical corals and reef fishes, sea turtles, cetaceans, and manta rays. The marine resources of West Hawai i have long provided sustenance and a venue for cultural practices for local people. In more recent decades, these resources have become central to an expanding tourism industry and provide opportunities for recreational and commercial fishing, in addition to traditional subsistence fisheries (Friedlander et al., 2014b). West Hawai i is also home to the largest expanse of intact and actively growing coral reef in the main Hawaiian Islands (Jokiel et al., 2004). However, in recent decades there is growing concern that the ecological processes supporting the ecosystems in the region are increasingly being altered.

Potter s angelfish (*Centropyge potteri*)

An ecosystem-based management (EBM) approach that recognizes the importance of interacting social and ecological systems is needed to effectively conserve the marine resources and associated ecosystem services in West Hawai i. EBM broadens the focus of management to the entire ecosystem (Kelble et al., 2013) and specifically links the actions of society to the ecological system, seeking to better understand, and therefore manage, how those actions are influencing the multiple services and benefits, and associated values, that society derives from the ecosystem (McLeod & Leslie, 2009; Potschin & Haines-Young, 2011). The West Hawai i Integrated Ecosystem Assessment (IEA; Figures 1 and 2) provides a framework to inform decisions in EBM across multiple sectors and multiple scales in the region. In contrast to more conventional approaches to resource management, an IEA considers interactions among ecosystem components and recognizes that human activities should be guided using collaborative, interdisciplinary, and adaptive methods. As such, the IEA framework recognizes that an understanding of the whole, not simply the individual components, is necessary to conserve marine ecosystems and the services they deliver (Levin et al., 2014).

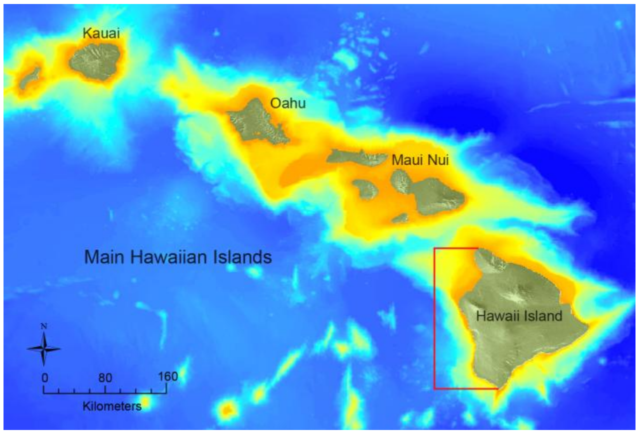

Figure 1. Bathymetric map of the main Hawaiian Islands with the West Hawai i Integrated Ecosystem Assessment geographic extent highlighted in red. Data Source: Hawai i Mapping Research Group, University of Hawai i.

The goal of this report is to summarize our current understanding of key ecosystem components necessary to consider for EBM of West Hawai i s marine ecosystem. We begin by presenting a synthesis from a recent workshop focused on gathering place-based knowledge and expert opinion to help better understand some of the key social-ecological interactions in the region. Community members, scientists, and resource managers came together and developed a consensus of the primary pressures and drivers of coral reef ecosystem state. Informed by the outputs of the collaborative workshop and with current scientific understanding of subtropical marine ecosystems, we then present a series of ecosystem indicators suitable for tracking the status and trends in West Hawai i s marine ecosystem (Table 1). Ecosystem indicators presented herein span a wide range of ecosystem components, from climatic and oceanographic drivers of ecosystem change, to the states of biological and human communities and associated activities. We expect that this interdisciplinary report will serve to elucidate linkages across the different components of West Hawai i s marine ecosystem and that it will provide context as we move toward ecosystem-based management of this highly productive and biologically diverse marine ecosystem.

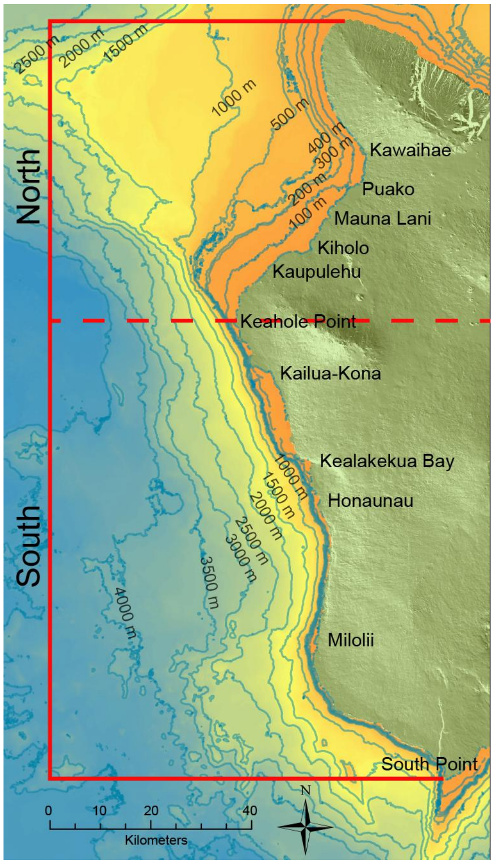

Figure 2. Bathymetric map of West Hawai i highlighting the geographic extent of the West Hawai i IEA (solid red line). The region was subdivided into North and South (dashed red line) at Keahole point for Conceptual Ecosystem Model development. Bathymetric contours (blue lines) are at 100-m intervals up to 500 m and at 500-m intervals thereafter. Data Source: Hawai i Mapping Research Group, University of Hawai i.

CONCEPTUAL ECOSYSTEM MODELING TO SUPPORT ECOSYSTEM-BASED MANAGEMENT

Conceptual ecosystem models (CEMs)–a method of diagramming social-ecological system components and relationships–support EBM in a number of ways. CEMs illustrate the best understanding of system dynamics, key processes, connections between ecosystem components, and highlight social influence and values (Gross, 2003; Kelble et al., 2013). They display the best working hypothesis about the system form and function (Manley et al., 2000) . They help merge existing scientific and community knowledge (Kelble et al., 2013) and collect information and observations from scientists and managers, as well as community members, which is an especially important function when data are scarce for any part of the system (Hohenthal et al., 2015). CEMs help identify gaps in knowledge, while the process of generating the models promotes collaboration and reduces conflicts. CEMs help design and support adaptive management strategies, and assist in assigning appropriate indicators to social or ecological components (Ogden et al., 2005; Nuttle & Fletcher, 2013). CEMS also serve as a scientific framework for monitoring and justification for the choice of indicators (Gross, 2003).

The CEMs developed for West Hawai i follow the Driver-Pressure-State-Impact-Response (DPSIR) framework. The DPSIR framework organizes the components of an ecosystem, including societal actions, in a manner that discovers interactions within the system as well as the intensity of those interactions (Reiter et al., 2013; Gari et al., 2015). Many variations of the DPSIR framework exist (e.g., Kelble et al., 2013; Hohenthal et al., 2015; Yee et al., 2015). We therefore defined each level of the framework as follows: *drivers* are the forces that cause a change in the level of a *pressure*; *pressures* then act as the direct cause of a change to an *ecosystem state*; a change in an *ecosystem state* will result in some *impact* on the services and benefits (and associated values) that society receives from that ecosystem (Potschin & Haines-Young, 2011); and in *response* to these changes, society acts at any level (*driver, pressure, state,* or *impact*) to leverage improvement (see Figure 3).

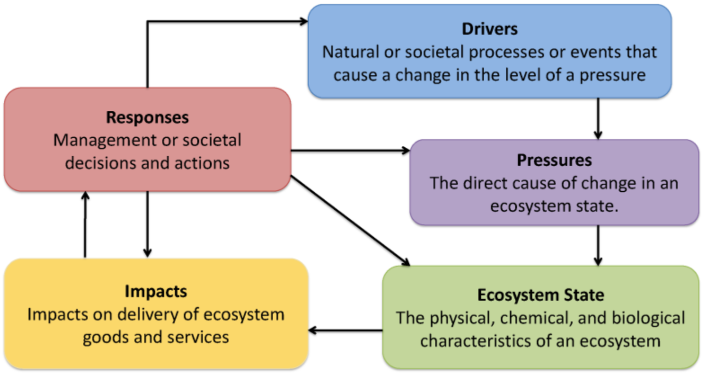

Figure 3. A diagram of the Driver-Pressure-State-Impact-Response (DPSIR) framework, including definitions for each component. Arrows represent the movement from one component to another. Response arrows can be directed to any level of the diagram, as societal responses may be directed toward any or multiple components. Adapted from Hohenthal et al., 2015; Yee et al., 2015; Kelble et al., 2013.

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A social-ecological systems understanding is the foundation of an IEA (Kelble et al., 2013) and the development of CEMs is a pivotal step in building a comprehensive understanding of West Hawai i and clarifying ecological pathways. The results presented here are from Ingram et al., (in prep) and are used to build the North and South CEMs for West Hawai i.

BUILDING THE WEST HAWAI I CONCEPTUAL ECOSYSTEM MODELS

During the Science Symposium on West Hawai i s Marine Ecosystem held in Kailua-Kona, Hawai i, on September 4, 2014, we organized a pilot workshop to collect community and expert knowledge about West Hawai i. Thirty-three community members and representatives participated from a wide variety of organizations and institutions, including, but not limited to, NOAA, National Park Service, University of Hawai i, The Kohala Center, The Nature Conservancy, State of Hawai i s Division of Aquatic Resources, and Conservation International. Participants formed groups based on their knowledge of northern and southern geographic sections of West Hawai i (see Figure 2 for geographic regions), resulting in two North groups and three South groups.

Each group was asked to identify and map existing and potential threats to the coral reef ecosystem state, to identify existing data, and discuss potential indicators. Each group consisted of a facilitator and a note taker to record participant input. The groups were provided with a large map of their focus region (North or South West Hawai i), a large notepad, markers, and icons to label the map. The icons represented pre-selected environmental threats, and blank icons were available for participants to add any suggested threats. Participants attached icons to the map in appropriate areas. In some cases, groups circled the geographical context for particular threats, or identified some regions as uncertain. After placing the icons on the map, the groups discussed indicators that could best monitor the various interactions identified and potential data sources for those indicators. At the conclusion of the workshop, participants filled out a questionnaire asking for comments and potential sources of information for ecosystem indicator development.

We compiled the qualitative data collected through direct observation, photos, notes, and participant information sheets to assemble five CEMs (one per group) using the DPSIR framework. We combined the individual group CEMs into a single model for each region (North and South West Hawai i). We also compiled information on the geographic information, data sources, and potential indicators.

RESULTS

Overarching Findings

The constructed CEMs (Figure 4) represent the current working hypothesis about the structure, processes, and function of this system. They represent the best understanding of the system, which may omit currently unknown factors. To simplify the final CEMs, we subsumed some specific threats into broader driver or pressure categories, (e.g., cattle production was converted to animal production), but noted the processes within the broader label. The presence of a driver or pressure in only one of the models does not necessarily mean it is absent from the other region. The omission of a driver or pressure could be because it does not exist in the region, or it could mean that it was simply not mentioned in the discussion.

After assembling the North and South CEM, we classified the identified threats as distal and proximate drivers according to a framework for coral reef social-ecological systems (Kittinger et al., 2012). We separated distal drivers into environmental (e.g., global climate change and volcanic activity) and socio-economic (e.g., economic and population growth). We found that identified proximal drivers were primarily related to human-use (e.g., land development, recreation, and fishing). Pressures–the direct cause of change in coral reef state–included environmental pressures (e.g., wave forcing and freshwater input), but human use-derived pressures dominated the CEMs (e.g., pollution, extraction of fish). Many drivers and pressures identified in the West Hawai i exercise also emerged in similar CEM exercises done on other coral reef ecosystems adjacent to human societies (Kelble et al., 2013; Yee et al., 2015). However, unique threats and interactions were identified for the West Hawai i region. For example, novel threats not previously reported in the literature include volcanic ash, marine debris, and human disturbance to wild animals.

Drivers

Identified drivers in both CEMs were predominantly human-use related (e.g., animal production, deforestation, land development and urban sprawl, fishing, and recreation). The only naturally occurring drivers were: local climate, reef slope, and volcanic activity. All of the drivers in the North model were also identified in the South model. The drivers that existed only in the South model were reef slope, volcanic activity, agriculture, recreational land use, and aquarium fish collection. Drivers of nutrient-input (an identified pressure) were related to population growth and land development in the North, while in the South, nutrient-input was driven by agriculture and animal production. These differences appear to be representative of the differences in region. Sediment pressure had many generating drivers, with some differences that may be due to region. The South model included recreational land use as a unique driver for sediments. The North model included local climate, and land development and urban sprawl as unique drivers for sediment.

Fishing was specified as commercial and non-commercial fishing. In the North, population growth (distal driver) and land development and urban sprawl (proximal driver) both impacted commercial and non-commercial fishing. In the South, land development and urban sprawl also affected both commercial and non-commercial fishing; however, population growth specifically affected non-commercial fishing.

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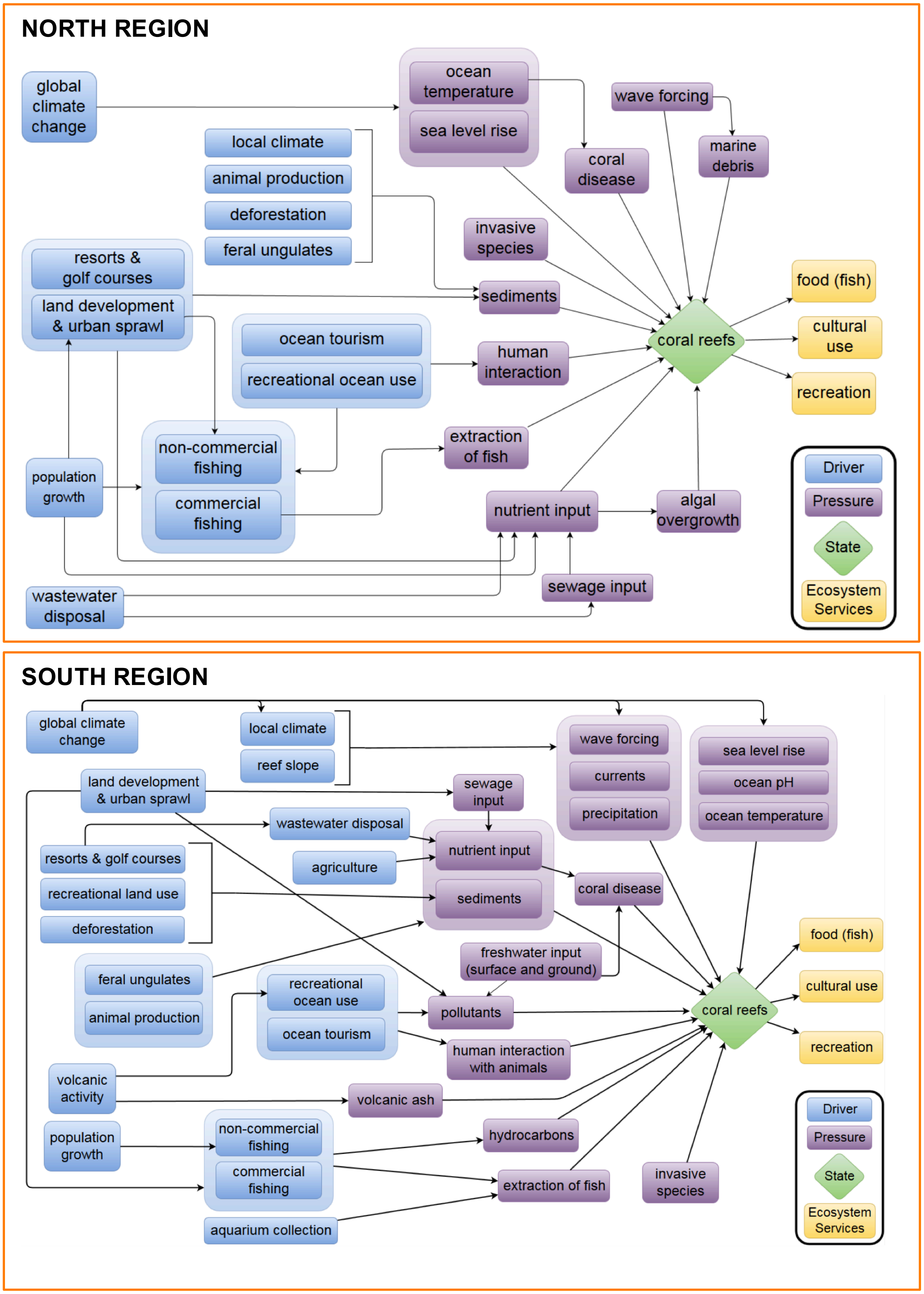

Figure 4. Coral reef Conceptual Ecosystem Models for the North (top) and South (bottom) regions of West Hawai i. (Ingram et al., in prep). Arrows indicate connections between the drivers (blue boxes) and pressures (purple boxes) of coral reef ecosystem state. Yellow boxes represent ecosystem services derived from coral reefs. Please see Figure 2 for a map highlighting the geographic extent of the North and South regions.

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Pressures

The pressures identified as influencing West Hawai i s coral reef ecosystem state in each region (North and South) were relatively similar. Common physical pressures included wave forcing, ocean temperature and sea level rise, while common land-based pressures included sedimentation, sewage, and nutrient input. Coral reef ecosystem state in both regions was also influenced by the extraction of fish, human interaction with animals, coral disease and invasive species. Marine debris and algal overgrowth were the only two pressures identified in the North that were not in the South model; however, the South contained a number of physical pressures that were not identified in the North, including ocean pH, precipitation, ocean currents, freshwater input (surface and ground), and volcanic ash. The pollutants pressure (generated from the drivers recreational ocean use and ocean tourism) consisted of sunscreen and other chemicals that may enter the water through human use of the ocean. This was specifically mentioned in the South, but very likely exists in the North as well.

NEXT STEPS

These pilot results will be used to inform a continuing participatory modeling process. This process designated threats, creating a preliminary list of drivers and pressures that we will use to frame future participatory modeling. We will compare the key components and processes identified in the CEMs to a set of pre-defined indicators, and evaluate the indicators against established criteria (e.g., Loomis et al., 2014). CEMs for all key ecosystem states (e.g., water column and pelagic fishes) will be developed to look closely at individual ecosystem states and examine the relationships that exist between social and ecological components. The development of these models began with a workshop at the Hawai i Conservation Conference on August 3, 2015, which focused on defining relationships and the intensity of those relationships.

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Whitebar surgeonfish (*Acanthurus leucopareius*)

ECOSYSTEM INDICATORS

To achieve sustainable management of any ecosystem, it is necessary to employ indicators which serve to communicate changes in the state of an ecosystem. Indicators are specific, well-defined and measurable variables that have been proven to reflect the status of some component of the ecosystem and provide a practical means to judge changes in ecosystem attributes related to the achievement of management objectives. To aid in the selection of ecosystem indicators, it is often useful to employ a conceptual modeling framework that identifies the focal ecosystem components. Here, CEMs were employed to aid indicator selection. This ensures the indicators that are selected reflect the status of key drivers, pressures, states, ecosystem services, and responses in the ecosystem.

It is important to note that a prerequisite for indicator development is the availability of reliable and robust information at an appropriate spatial and/or temporal scale. Although we have assembled a suite of relevant ecological indicators to help track the status and trends in key ecological processes in West Hawai i (Table 1), many gaps remain. For example, we present geographic differences in a number of human activities (e.g., recent development, non-commercial fishing) that provide important context for present-day ecological state. However, our ability to evaluate the extent to which historical changes in human activities and governance (e.g., changes in agricultural practices and land permitting) have influenced ecological state through time is, in many cases, limited. Additionally, our understanding of ecosystem dynamics and the myriad social-ecological interactions occurring in the region continues to expand and evolve. As such, the evaluation and synthesis of information and development of ecosystem indicators is an adaptive and continual process.

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Table 1. Summary of indicators for tracking the trends and status of West Hawai i s marine ecosystem. Indicators are divided into three broad categories – Social, Ecological, Climate & Ocean – based on the ecological pressure or ecological attribute they represent. Indicators were selected based on information in the peer-reviewed literature and results from the Conceptual Ecosystem Modeling (CEM) work, as identified in the *Justification* column.

Ecological Pressure or Attribute	Indicator	Definition and Rational	Justification	Data Availability
SOCIAL				
Human Activities	Population Growth	Changes in annual population of Hawai i Island. Human-related pressures on ecosystem state such as coastal development, habitat degradation, new coastal development, and fishing pressure are based on human activities, and thus the ultimate driver behind many of these pressures is human population growth.	CEM	1959-2014
	Number of Visitors	The total number of visitors by air serves as an indicator of increased tourism associated use of the marine environment. Tourism expenditures represent the single largest source of economic activity in Hawai i. Moreover, beach and water sports, such as swimming, snorkeling, and scuba diving, are by far the most popular recreational activities among visitors.	CEM	1990-2014
Physical Human Impact	Shoreline Modification	Shoreline modification in coastal areas describes the alteration or removal of geomorphic structure as a result of human use. Similar to land development, modification often affects sedimentation and runoff that can impact coastal water quality.	CEM	2010
	New Development	All new development that occurred between 2005 and 2010. Development on land can affect nearshore coastal environments by exposing soil and increasing sediment runoff. When development paves over natural land, the resulting impervious surfaces increase the rate of pollution runoff from streets and sidewalks into the nearby ocean.	CEM	2005-2010
Nutrient and Wastewater Input	On-Site Disposal Systems: Total Effluent and Nitrogen Flux	Locations of On-Site Disposal Systems (OSDS) and associated effluent leakage and nitrogen flux. Much of Hawai i still uses OSDS (e.g., cesspools and septic tanks) that leech excess pollution and nutrients (e.g., nitrogen) into groundwater that flows to the ocean. This runoff from land can result in algae blooms, fish kills, and potential disease threats to humans.	CEM, (Anderson et al., 2002; Ault et al., 2014)	2014
	On-Site Disposal Systems: Total Number	Number of On-Site Disposal Systems. Changes in the number of OSDS in West Hawai i serves as a proxy for historical changes in sewage and other wastewater leakage into nearshore ecosystems.	CEM, (Smith et al., 1999; Anderson et al., 2002)	1992-2010

Invasive species	Invasive Algae	Invasive algae are a threat to coral reef ecosystems as they can spread rapidly, smother coral, out-compete other organisms for space and resources, and thus significantly alter ecosystem structure and function.	CEM	2000-2013
	Introduced Fish	Introduced fish can have large impacts on ecosystem biodiversity and fisheries. The following introduced species has been identified along West Hawai i: Peacock Grouper (*Cephalopholis argus*, roi) and Bluestripe and Blacktail Snappers (*Lutjanus kasmiara*, ta ape, *Lutjanus fulvus*, to au).	CEM	2000-2013
Nearshore Fisheries Extraction	Commercial & Non-Commercial Fishing Pressure	Nearshore fisheries in the main Hawaiian Islands target a diverse set of species in which multiple gear types are used to harvest reef finfish, estuarine species, and schooling coastal pelagics. Communities in Hawai i often depend on these fisheries for the economic, social and cultural services they provide, including supporting livelihoods, providing a direct source of food, and contributing to cultural practices, customs and traditions.	CEM, (Friedlander & DeMartini, 2002; Friedlander et al., 2014b; Kittinger et al., 2015)	2004-2013
ECOLOGICAL				
Reef Fish Community Integrity	Total Fish Abundance	The total number of reef fish standardized by the unit area of reef. Fish density is a major factor determining the influence reef fishes have in a coral reef ecosystem. Fish abundance varies by habitat quality, environmental variability, and its influence on population demography (i.e., recruitment and natural mortality) and fishing pressure.	(Friedlander & DeMartini, 2002; Sale, 2004; Feary et al., 2007; Guillemot et al., 2014)	2003-2014
	Total Fish Biomass	The total weight of the entire fish assemblage per unit area. It is useful to consider biomass, in addition to abundance because the ecological impact of fishes on a reef is often related to the size of fishes and the status of the fishery is more directly related to fish population biomass rather than solely on the number of fish.	(Guillemot et al., 2014)	2003-2014
	Mean Adult Fish Length	Coral reef fisheries are typically multi-species. The mean length of adult fishes (calculated here as those above 40% of their expected maximum length) provides an indication of the size structure of the entire adult reef fish community.	CEM, (Ault et al., 2014; Guillemot et al., 2014; Nadon et al., 2015)	2003-2014
	Species Richness	Total number of species recorded per survey. Biodiversity is intrinsically linked to ecosystem function and greater species richness supports more productive fisheries. Furthermore, species richness is linked to diversity in responses to environmental change amongst species that perform similar ecosystem functions on a reef, and as such is considered a critical aspect of ecosystem resilience.	(Moberg & Folke, 1999; McClanahan et al., 2011)	2003-2014

	Herbivore Biomass	Herbivores, i.e., species for which plant material makes up a majority of their diet, are a key component and indicator of coral reef ecosystem resilience, that is, the ability of a reef to maintain or recover to a coral dominated state following disturbance, and avoid a phase-shift into algal dominance compromise. Herbivores are a large part of the fish community assemblage, making up ~ 1/3 of species landed by coastal fishing in West Hawai i, with the majority being kept for home consumption.	CEM, (Green & Bellwood, 2009; Kittinger et al., 2015; Williams et al., 2015b)	2003-2014
	Target Fish Biomass	Uhu (Redlip Parrotfish, *Scarus rubroviolaceus*) is one of the main target species within the parrotfish complex in Hawai i. Uhu can prevent problem algae from becoming established as well as open up new settlement sites for coral recruitment. Based on the dual importance of this species, in terms of fisheries and functional importance, its biomass can be indicative of two things: fishing pressure and reef resilience.	(Lokrantz et al., 2008; Sabater & Carroll, 2009;Houk et al., 2011; Bejarano Chavarro et al., 2013)	2003-2014
Aquarium Target Fish	Juvenile Yellow Tang	The majority of the State s aquarium trade sources fish from West Hawai i; approximately 70% of the fish caught in the State are from West Hawai i with juvenile yellow tang (*Zebrasoma flavescens*) comprising ~ 85% of the total catch.	CEM, (Walsh et al., 2003; Williams et al., 2009; Walsh et al., 2013)	2003-2014
Benthic Reef Community Integrity	Hard coral cover	The percent cover of hard coral in a given area reflects the amount of reef topographic complexity, habitat structure, reef accretion, and diversity and abundance of coral-dependent species.	(Walsh, 1984; McClanahan et al., 2011)	2003- 2014
	Macroalgae Cover	The percent cover of fleshy macroalgae serves as an indicator for benthic community organization and health. Macroalgae can grow rapidly and potentially inhibit coral recruitment and growth, and reduce coral survival. Tracking the abundance of macroalgae can also indicate other important processes occurring within coral reef ecosystems, including nutrient enrichment and herbivory intensity.	CEM, (McClanahan et al., 2002; Hughes et al., 2007; McClanahan et al., 2011)	2003-2014
	Ratio of Calcifying: Noncalcifying	The ratio between calcified to non-calcified organisms represents the combined cover of reef building hard corals (Scleractinian) and calcifying algae (crustose coralline algae and *Halimeda*) to the combined cover of turf and fleshy macroalgae. Tracking the calcified to non-calcified ratio of benthic organisms serves as an important indicator of coral reef community dynamics and the extent to which a given system is dominated by reef accreting versus non-accreting benthic organisms.	(Cinner et al., 2013; Williams et al., 2013)	2003-2014
	Coral Disease	The percent of diseased coral. Coral disease has been linked to the compounding effects of climate change, local anthropogenic inputs and	CEM, (Harvell et al., 2007; Couch et	2010-2011

		distribution of susceptible host populations. Coral disease is therefore a useful early indicator of changing reef ecosystem integrity.	al., 2014a; Williams et al., 2014)	
CLIMATE AND OCEAN				
Large-Scale Climate Forcing	Pacific Decadal Oscillation	The Pacific Decadal Oscillation (PDO) is often described as a long-lived El Niño-like pattern of Pacific climate variability. Extremes in the PDO pattern are marked by widespread variations in the Pacific that can drive prolonged (years to decades) changes in sea surface temperature, ocean mixing and biological productivity. When a positive phase of PDO is coincident with a positive phase of ENSO (i.e., El Niño), an increase in hurricane activity in Hawaiʻi can occur during the summer months (as observed in 2015).	CEM, (Polovina et al., 1994; Bond & Harrison, 2000;Rooney et al., 2008)	1950-2015
	Multivariate ENSO Index	The Multivariate ENSO Index (MEI) is an indicator of the El Niño Southern Oscillation (ENSO): an irregular, large-scale ocean-atmosphere climate phenomenon. El Niño represents the warm phase of the ENSO cycle, characterized by weakening of the trade winds across much of the Pacific and warming of ocean temperatures in the Equatorial Pacific. La Niña represents the cool phase and is associated with stronger than normal trade winds and anomalously cool ocean temperatures.	CEM, (Philander, 1990)	1950-2015
Precipitation	Rainfall	Changes in rainfall dictate the amount and intensity of ground water and surface water transport to the marine environment, which can influence nearshore salinity and temperature as well as suspended sediment and nutrient concentrations.	CEM, (Giambelluca et al., 2012)	1950-2012
Sea Level Rise	Coastal Sea Level	Tracking the status and trends in sea level is important for coastal communities and nearshore marine ecosystems. Over long time periods, sea level rise can lead to chronic coastal erosion, coastal flooding, and drainage problems and can exacerbate short-term fluctuations in coastal sea level driven by waves, storms and extreme tides.	CEM, (Fletcher, 2010)	1990-2015
Mesoscale Processes	Eddy Kinetic Energy (EKE)	The combination of prevailing northeasterly tradewinds and island topography results in the formation of vigorous mesoscale (~100 km) eddies in the lee of Hawaiʻi Island. Eddies can upwell cool, nutrient rich water that influences ocean temperatures and fuels a localized increase in phytoplankton production.	(Seki et al., 2002)	1992-2015
Temperature Variability	Sea Surface Temperature	Sea surface temperature (SST) plays an important role in a number of ecological processes and varies over a broad range of temporal scales. SST can vary in response diurnal, intra-seasonal (e.g., mesoscale eddies),	CEM	1985-2015

		seasonal, interannual (e.g., ENSO) and decadal (e.g., PDO) forcing.		
	Thermal Stress HotSpot	Thermal Stress Hotspot is an indicator of increased SST that exceeds typical maximum summertime temperatures resulting in stress-inducing HotSpots for coral reef ecosystems. Coral bleaching–the loss of corals photosynthetic symbionts–can result if HotSpots are > 1 C above the maximum summertime temperatures and sustained for extended periods of time.	CEM, (Hoegh-Guldberg, 1999; Liu et al., 2014)	1985-2015
Wave Forcing	Wave Power	Wave forcing is a major environmental forcing mechanism in marine ecosystems. Variations in wave forcing can influence important ecological processes such as coral reef development, spatiotemporal patterning in benthic and reef fish communities, sediment transport and resuspension, and shoreline and beach morphology.	CEM, (Dollar, 1982; Storlazzi et al., 2004; Rooney & Fletcher, 2005)	1979-2013
Ocean Productivity	Chlorophyll-a (proxy for phytoplankton biomass)	Phytoplankton production is an essential source of energy in the marine environment, influencing the trophic-structure of entire marine ecosystems and the distribution and production of fisheries. However, if artificially elevated via human-activates, eutrophication, hypoxia, and other negative ecosystem consequences can occur.	(Smith et al., 1999; Anderson et al., 2002; Chassot et al., 2010)	2002-2015

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SOCIAL INDICATORS


Blackfoot ‘opihi (*Cellana exarata*)

Human relationships with ocean environments are diverse and include social, cultural, political, economic, and environmental dimensions (Kittinger et al., 2012; Cinner et al., 2013). Humans are, therefore, an integral part of ecosystems and they can act on ecosystem functions both as stressors and caretakers of the natural environment. Correspondingly, social data can include information on a range of human activities (e.g., distribution, practices, and interactions). Ultimately, ecosystem-based management requires ecologically meaningful information that is coupled with diverse human uses and practices at operationally relevant spatial and temporal scales.

Here, we present a suite of social indicators through space and time. Our goal was to integrate dynamic and spatially explicit information on human uses, values, and governance to identify important ecosystem pressures and drivers of the system in the region. Information on human dimensions and the social indicators developed can be used as direct inputs into ecosystem models as well as shape the direction of ecosystem-based management. This work is ongoing; the ultimate outcome will be to improve our ability to assess West Hawaiʻi's ecosystem and to provide information on current and predicted states of ecosystem integrity under different scenarios. Based on outcomes from the Conceptual Ecosystem Models and additional information from social-ecological work (e.g., Kittinger et al., 2012), we have established a list of social indicators of West Hawaiʻi's marine ecosystem.!

Population Growth

Human-related pressures on ecosystem state such as coastal development, habitat degradation, and fishing pressure are based on human activities, and thus the ultimate driver behind many of these pressures is human population growth. The status and trends of individual pressures are then modified by technological advances, management practices and regulatory actions. Because historical and reliable time series information on many human-related pressures is often lacking, tracking population growth serves as an indicator (albeit broad) of human-activities that can either directly (e.g., fishing pressure) or indirectly (e.g., new development) influence marine ecosystem integrity. Population information was obtained for Hawaiʻi Island from 1959 to 2014 (Figure 5). Over the past 56 years, the population of Hawaiʻi Island has grown by 320%, from 60,658 people in 1959 to 194,190 people in 2014.

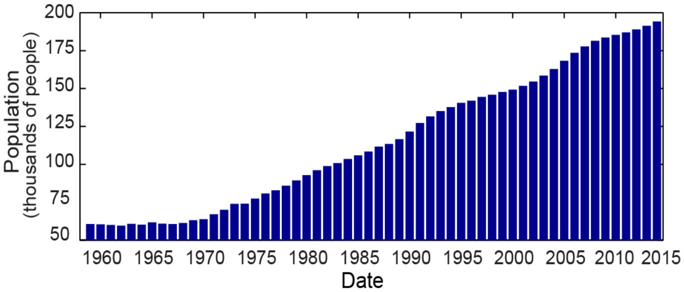

Figure 5. Population growth (thousands of people) on Hawaiʻi Island from 1959 – 2014. Data Source: State of Hawaiʻi's Department of Business, Economic Development, and Tourism.

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Tourism

Compared to other sectors, tourism is distinguished both by its size and share of Hawai i s economy and by the fact that there are few comparable opportunities for generating external sources of income. In fact, tourism expenditures represent the single largest source of economic activity in Hawai i (State of Hawaii's Department of Business, 2006). Moreover, many visitors spend the majority of their vacations within Hawai i s beach and nearshore environment. Beach and water sports, such as swimming, snorkeling, and scuba diving, are by far the most popular recreational activities among visitors (State of Hawaii's Department of Business, 2006).

The total number of visitors by air serves as an indicator of increased tourism associated with the use of the marine environment (Figure 6). Over the past 25 years, the number of visitors to Hawai i Island has shown considerable variation, from a minimum of 1.08 million in 1994 to a maximum of 1.62 million in 2007. Likely owing to the global financial crises, the number of visitors fell sharply in 2008 and 2009 but has since shown a steady increase to 1.45 million in 2014.

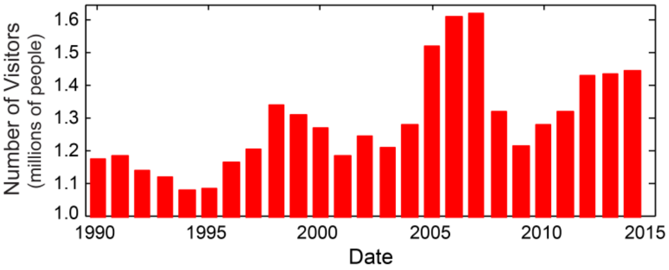

Figure 6. Total number of visitors (millions of people) by air to Hawai i Island from 1990 – 2014. Data Source: State of Hawai i s Department of Business, Economic Development, and Tourism.

Shoreline Modification

Shoreline modification in coastal areas consists of the alteration or removal of geomorphic structure as a result of human actions. Similar to land development, modification often affects sedimentation and runoff that can impact coastal water quality. Shoreline armoring also increases or accelerates erosion of beaches seaward of the structure and alter flow patterns and redirect wave energy. To map shoreline modification in West Hawai i, we integrated data on the current (2010) locations of man-made shorelines (e.g., sea walls, breakwaters, piers, fill), maintained channels and dredged areas, and offshore aquaculture (Figure 7; areas in red). Data from Wedding et al., (in review), and derived from the following: NOAA Environmental Sensitivity Index shoreline classification data, NOAA habitat maps, NOAA maintained channels, and digitized open ocean aquaculture locations.

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New Development

New development on land can affect nearshore coastal environments by exposing soil and increasing sediment runoff from construction sites. After development is completed on previously natural land, the resulting impervious surfaces increase the rate of urban runoff pollution from streets and sidewalks into the nearby ocean. To map new development, we used changes in high resolution land use/land cover data from 2005 to 2010, and extracted pixels that changed from any undeveloped (non-impervious) land use class to impervious surface (Figure 7). We then calculated the total area of new development by watershed, providing geographic context for where changes in development have the greatest potential for influence on marine ecosystem state in West Hawai i. Data from Wedding et al., (in review) and derived from the following: NOAA s Coastal Change Analysis Program (C-CAP) High Resolution Land Cover and Change datasets; U.S. Geological Survey National Hydrography Dataset Watershed Boundaries.

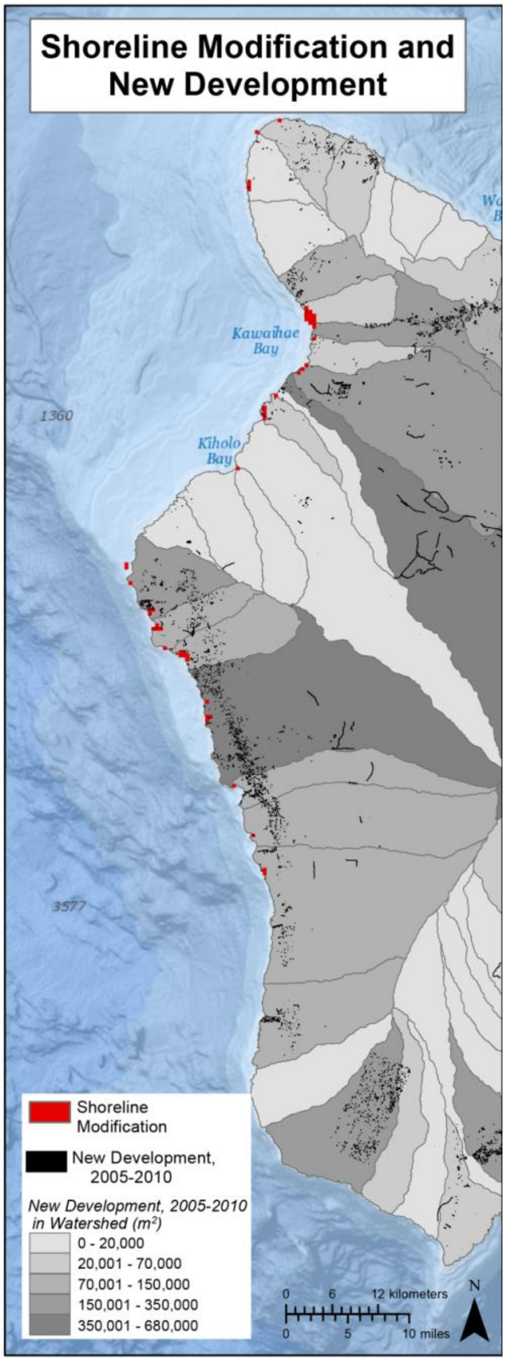

Figure 7. Map of West Hawai i indicating the spatial distribution of present-day shoreline modification (red) and new development that has occurred between 2005 and 2010 (black). The total area of new development occurring within each watershed is also shown (graduated gray colors). Data obtained from Wedding et al., (in review).

On-site Waste Disposal Systems

Much of Hawai i disposes wastewater at the location in which it is generated via on-site waste disposal systems (OSDS) (i.e., cesspools and septic tanks). In fact, nearly half of all OSDS in the state are located on the island of Hawai i and nearly 85% of those are cesspools (Whittier & El-Kadi, 2014), where the effluent receives no treatment prior to being released into the environment. With on-site disposal of wastewater come risks to both human and marine ecosystem health. OSDS can leech waste, nutrients (nitrogen and phosphorus), pharmaceuticals and pathogens into groundwater and steams that flow to the ocean. This runoff can result in algal overgrowth of corals, increase coral disease, and potential disease threats to humans (Anderson et al., 2002).

Between 1992 and 2010, the number of OSDS in West Hawai i nearly doubled (Figure 8). The associated risk to human and marine ecosystem health is directly related to the rate of effluent discharge from OSDS.

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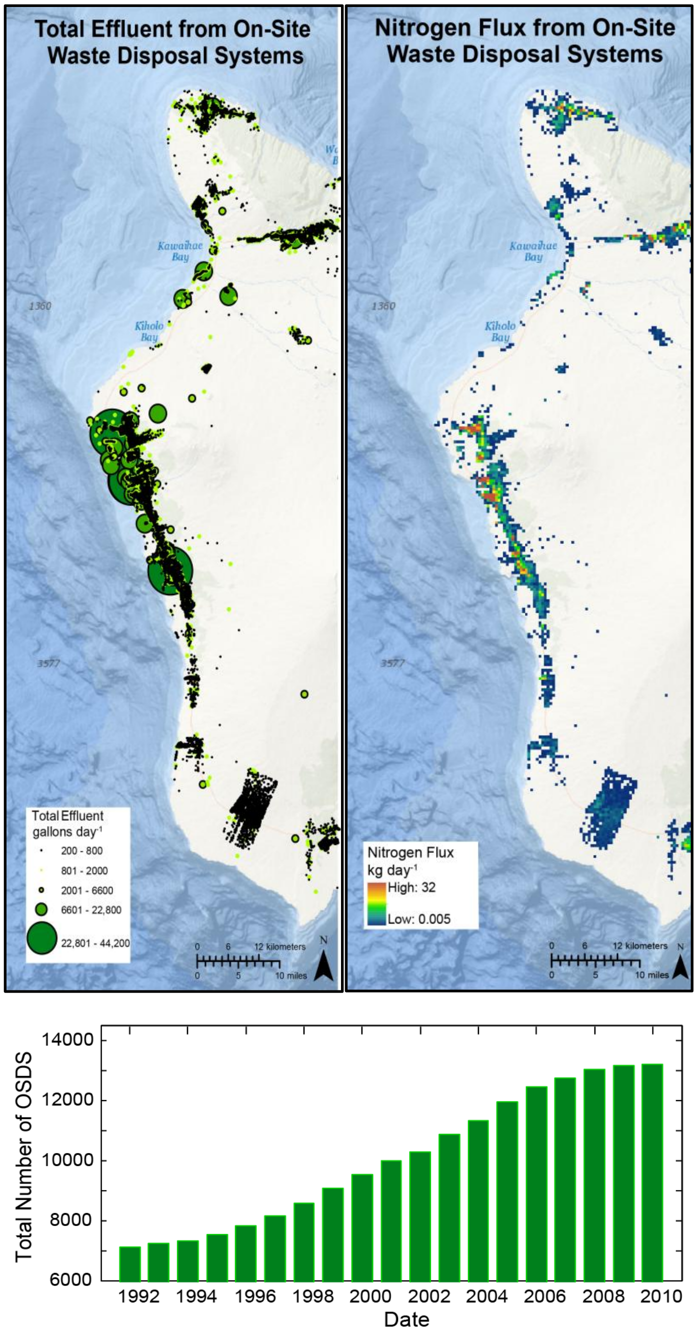

Figure 8. Maps of West Hawai i indicating the spatial distribution of on-site disposal systems (OSDS) and associated total effluent discharged into the environment (top left) and the total nitrogen flux into the environment (top right). The total number of OSDS from 1992 to 2010 in West Hawai i is also shown (bottom). Data Source: State of Hawai i Department of Health [56].

Using a 2014 study conducted for the State of Hawai i s Department of Health (Whittier & El-Kadi, 2014), we provide estimates of total effluent discharge and nitrogen flux into the environment from OSDS (Figure 8). Although not all effluent and nitrogen discharged reaches the coast, there are a number of locations that have elevated risk owing to high concentration of OSDS proximate to shore, including Kawaihae to Puak! and Kailua-Kona to Kealakekua Bay (Figure 8; see Figure 2 for geographic locations).

Invasive Algae

Invasive, or alien algae, is non-native to the ecosystem and can pose a serious threat to coral reef ecosystems. Invasive algae can grow rapidly and spread quickly, smothering corals and out-competing other organisms for space and resources, and thus significantly altering ecosystem structure and function (McManus & Polsenberg, 2004). Here, we have mapped presence of invasive algal species (i.e., *Acanthophora spicifera, Gracilaria salicornia, Hypnea musciformis, Kappaphycus alvarezii*), along West Hawai i that were recorded during surveys from 2000 to 2013 (Figure 9). The occurrence of invasive algae is minimal across the region, although specific geographic areas show pockets of potential concern (e.g., Puako). Data from Wedding et al., (in review) and derived from the following: NOAA s Coral Reef Ecosystem Program (CREP), DAR, and the University of Hawai i s Coral Reef Assessment and Monitoring Program (CRAMP) surveys.

Introduced Fish

When non-native fish get introduced to coral reefs, either intentionally or unintentionally, they can negatively impact ecosystem biodiversity and fisheries. Here, we mapped areas where introduced fish species have been identified in West Hawaiʻi (Figure 9). Specifically, we show the locations where Roi (*Cephalopholis argus*, Peacock grouper), Taʻape (*Lutjanus kasmiara*, Bluestripe snapper) and Toʻau (*Lutjanus fulvus*, Blacktail snapper) were recorded during surveys from 2000 to 2013. Although introduced fish are fairly ubiquitous across West Hawaiʻi, recent research suggests that the native reef fish community appears to maintain biotic resistance to potential negative effects of introduced predatory fish (Giddins et al., in review). However, if the apparent balance between predator and prey populations were to be disturbed due to other threats, such as overfishing of native reef fish competitors or key functional groups such as herbivores, then the biotic resistance of the native fish community may be diminished. Data from Wedding et al., (in review) and derived from the following: CREP, DAR, and CRAMP.

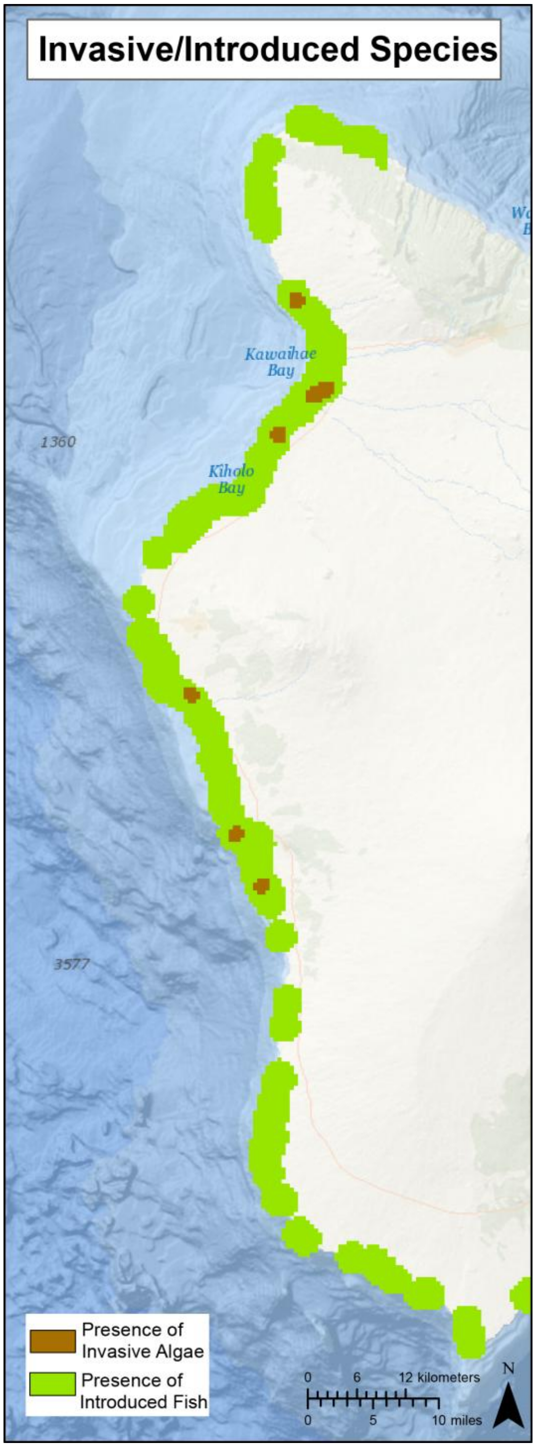

Figure 9. Map of West Hawaiʻi representing the observed presence of invasive algae (brown) and introduced fish (green). Data from Wedding et al., (in review).

Fishing Pressure

Nearshore fisheries in Hawaiʻi comprise a diverse set of species in which multiple gear types are used to harvest reef fish and invertebrates, estuarine species, and schooling coastal pelagics (Friedlander et al., 2014a). Communities in Hawaiʻi often depend on these fisheries for the economic, social, and cultural services they provide, including supporting livelihoods, providing a direct source of food, and contributing to cultural practices, customs, and traditions (Kittinger et al., 2015). Non-commercial fishing plays an important social, cultural, and subsistence role for local communities in Hawaiʻi (Kittinger et al., 2015) and is estimated to be well over two times the reported commercial catch (Everson & Friedlander, 2004; Zeller et al., 2005; Zeller et al., 2008).

In an effort to capture nearshore fishing pressure along West Hawai i, we have provided indicators that encompass both commercial and non-commercial fishing activities. Commercial catch data for the dominant gear types (i.e., Net, Line, Spear) were obtained from the State of Hawai i s Division of Aquatic Resources (DAR) for commercial reporting blocks that encompass West Hawai i (blocks 100–103). Non-commercial, shore-based catches were spatially mapped and was also divided into dominant gear types (i.e., Net, Line, Spear). Non-commercial fishing data are provided by McCoy (2015) and derived from the NOAA Fisheries Marine Recreational Information Program (MRIP; **http://www.st.nmfs.noaa.gov/recreational-fisheries/index**). Hawai i s Marine Protected Areas (MPAs) were accounted for in the analysis performed using data from NOAA s MPA Center and DAR s fishing regulations to exclude no-take zones by gear-type.

Commercial Fishing

As an indicator of nearshore fishing pressure, we present annual commercial fisheries catch from 1980 to 2012 by dominant fishing gear type for West Hawai i (Figure 10). Total commercial fisheries catch has varied considerably through time, from over 200 metric tons (mt; thousands of kilograms) in 1980, to just over 65 metric tons in 2012. The three most dominant gear types–Line, Net, and Spear–have also varied in their respective contribution to the annual catch through time. For example, Net fishing was the dominant fishing method in the 1980 s and first half of the 1990 s, comprising approximately 53% of the total commercial catch. However, from 1996 to 2012, Net fishing represents just 38% of the total catch, with Line fishing serving as the dominant method for nearshore commercial fisheries. In terms of species, the reported commercial catch consists primarily of coastal pelagics, namely ! pelu (mackerel scad, *Decapterus spp.*) and akule (big-eye scad, *Selar crumenophthalmus*) (Figure 10).

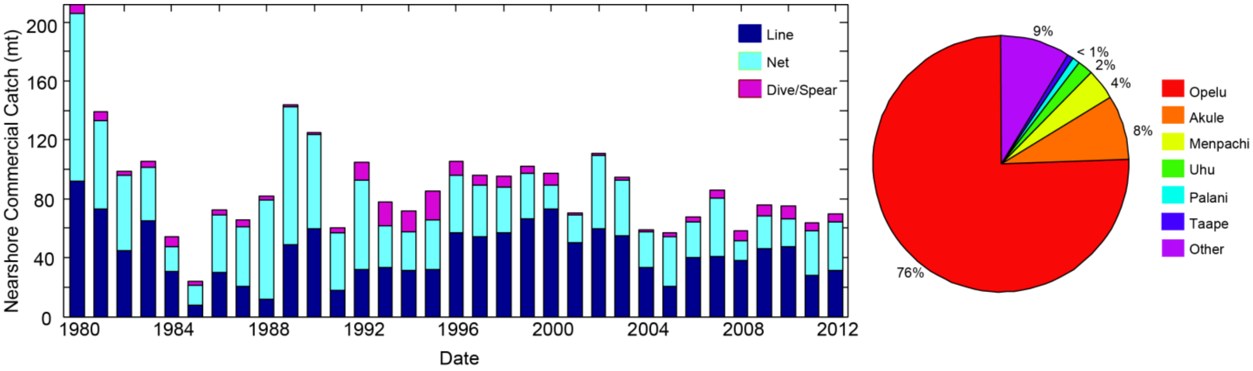

Figure 10. Time series of commercial catch from nearshore reporting blocks in West Hawai i for Line, Net, and Dive/Spear gear types from 1980 to 2012 (left). Catch data are reported in metric tons (mt; thousands of kilograms). Proportion of total commercial catch by species for the 1980 to 2012 time period (right). Only the top six species are shown. Data were obtained from the Department of Land and Natural Resources nearshore reporting blocks that encompass West Hawai i (Blocks 100–103).

Shore-based Non-commercial Fishing

Non-commercial fishing constitutes a substantial proportion of the total catch from coral reefs in Hawaiʻi, and shore-based activities are the predominate mode of non-commercial fishing (Figure 11). Shore-based fishing pressure was calculated by gear-type from island-wide average annual catch of reef fish over the 2004-2013 time-frame from McCoy (2015). Non-reef fish (e.g., akule and ʻōpelu) were excluded from this analysis. Proximity to roads and shoreline steepness were used as a proxy for access, in order to spatially distribute island-level catch estimates along the coast. Although shore-based non-commercial fishing occurs throughout West Hawaiʻi, there is considerable spatial variability in accessibility of the coastline. Line fishing is the dominant gear-type with respect to total catch, followed by Net and Spear gear-types.

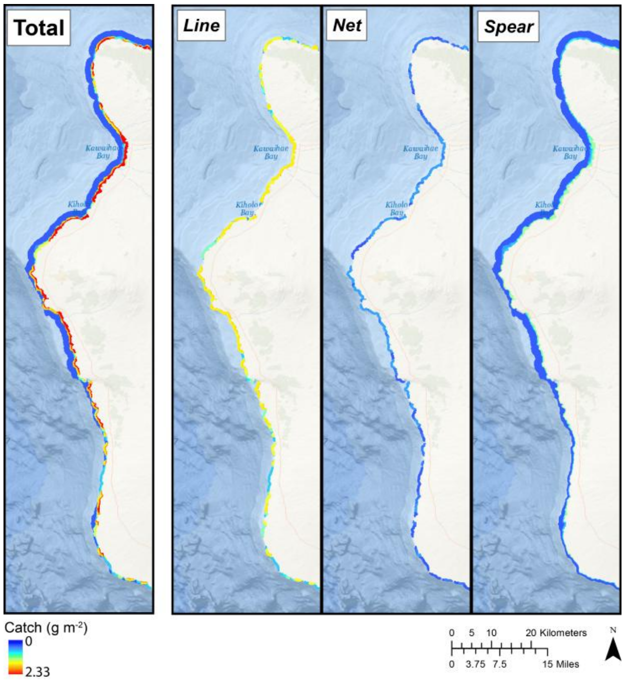

Figure 11. Map of estimated shore-based non-commercial catch along West Hawaiʻi. Total fishing pressure (left) is split into the three dominant gear-types; Line, Net and Spear. Data Source: McCoy, 2015.

Non-commercial fishermen are not required to report their catch in Hawaiʻi. As such, information presented herein serves as the best available proxy for such activities. Recent work by Kittinger et al., (2015) employed participatory surveys to gather community-based information in Kiholo, West Hawaiʻi, providing additional insight into non-commercial catch in the region. In terms of species, herbivorous fishes were the dominant group extracted, accounting for 36% of the total non-commercial catch, with planktivores, secondary consumers, and apex predators accounting for 33%, 20%, and 11%, respectively (Kittinger et al., 2015). Given the only fisheries data reported in the region is commercial-based, which is unrepresentative of both total catch (Everson & Friedlander, 2004; Zeller et al., 2005) and species composition (Kittinger et al., 2015), we lack a comprehensive understanding of the dominant fisheries-related pressure to West Hawaiʻi's reef ecosystem.

BIOLOGICAL INDICATORS

CORAL REEF ECOSYSTEMS

Coral reefs are one of the most productive and biologically diverse marine ecosystems on the planet, serving key ecological functions across tropical marine environments. Moreover, coral reef ecosystems provide important ecosystem services, including coastal protection, food-resources, tourism, and fisheries, that are critical for coastal communities and local economies (Knowlton, 2001). However, coral reefs across the globe continue to decline due to the combined impacts from pollution, overfishing, invasive species, climate change, and other pressures (Knowlton & Jackson, 2008). These threats undermine the economic, social, and cultural benefits provided by coral reefs, including important food security functions, cultural practices, and livelihoods (Kittinger et al., 2012).

Here, we present a suite of indicators to track the status and trends of West Hawaiʻi's coral reef fish and benthic communities. These data were collected as part of a long-term monitoring effort implemented by DAR's West Hawaiʻi Aquarium Project (WHAP; Walsh et al., 2013). As such, indicators are based on a combination of ecological relevance, sensitivity to local pressures (e.g., fishing pressure), and being applicable to the *in situ* survey data collected by the WHAP monitoring program.

Fourspot butterflyfish (*Chaetodon quadrimaculatus*)

Reef Fish

Reef fisheries have substantial social, cultural and economic value in Hawaiʻi, yet knowledge on their sustainability is relatively limited (Pauly & Zeller, 2014). This is in part because coral reef fisheries are characteristically multi-species, multi-gear and have significant non-commercial components (Kittinger et al., 2015). Indeed, non-commercial fishing plays an important social, cultural, and subsistence/consumptive role for local communities in Hawaiʻi and is estimated to be well over two times the reported commercial catch (Zeller et al., 2005; Zeller et al., 2008). Here we present a combination of indicators that relay information on the coral reef ecosystem and fishery status. We have used a selection of indicators that track the status and trends at the individual species, functional group, and community levels. As described in more detail below, these indicators convey information specific to detecting fishing effects, ecosystem structure and function and coral reef ecosystem resilience.

Total abundance

This is a community level indicator of fish density, the total number of reef fish standardized by the unit area of reef (Figure 12A). Fish density is a major factor determining the functional role and influence reef fishes have in a coral reef ecosystem. Spatial and temporal variability in fish density is a product of numerous factors. For instance, fish abundance varies by habitat quality (Feary et al., 2007), environmental variability and its influence on population demography (i.e., recruitment and natural mortality) (Sale 2004), and fishing pressure (Friedlander & DeMartini, 2002; Guillemot et al., 2014). Since 2003, total abundance in West Hawai i has been greater in the South compared to the North (Figure 12A). In both regions, total abundance was relatively unchanged from 2003 to 2011. However, an apparent increasing trend was evident from 2011 to 2014. An anomalous recruitment pulse was observed in 2014 across a number of locations in the state (Talbot, 2014) and also West Hawai i (Walsh, 2014). The recent increase in fish abundance observed in both regions is likely attributable to this anomalous year for fish recruitment.

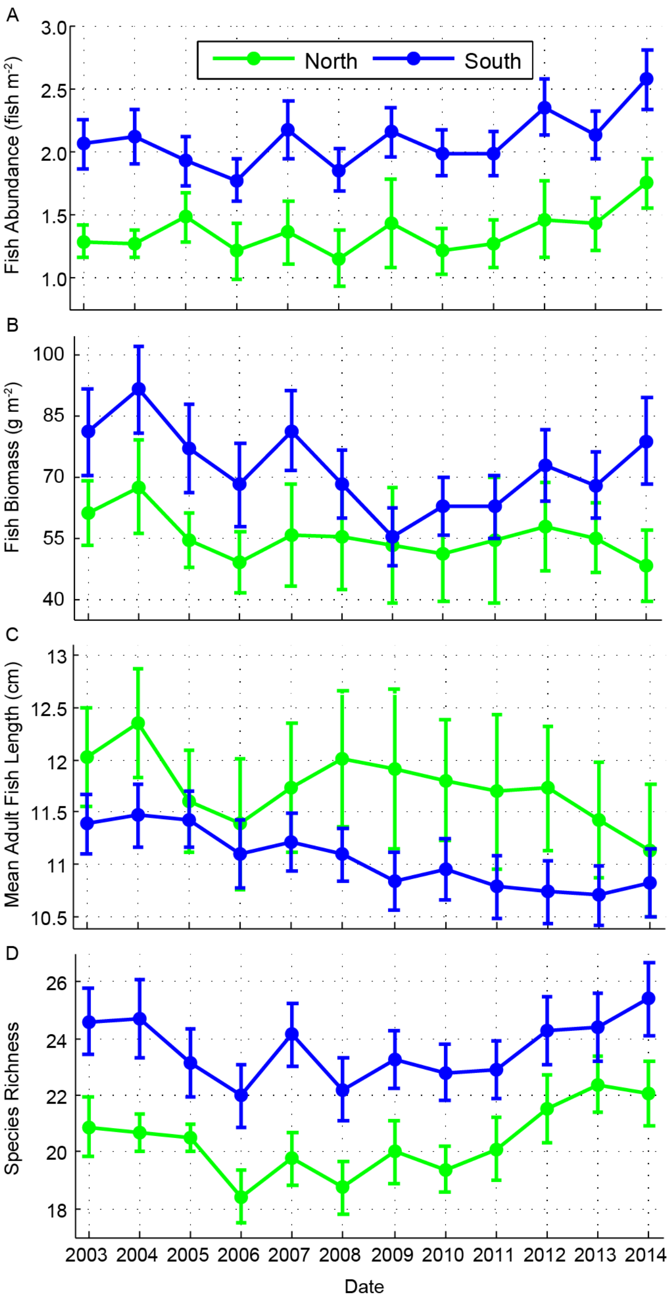

Figure 12. Reef fish indicators (A) Total Fish Abundance, (B) Fish Biomass, (C) Mean Fish Length, and (D) Species Richness. Indicators are split by North (green) and South (blue) regions of West Hawai i. Error bars represent ± 1 standard error. Data Source: DAR s West Hawai i Aquarium Project.

Total Biomass

The body weight of individual fish per survey is calculated based on their body length and then aggregated to the body weight of the fish assemblage per unit area. Fish biomass conveys related, but slightly different information compared to fish abundance. Specifically, two reefs might have the same abundance, but very different biomass estimates based on the size distribution of fishes in the assemblage. It is useful to consider biomass in addition to abundance because the ecological impact of fishes on a reef is often related to the size of fishes (see herbivore biomass description below). In addition, the status of the fishery is more directly related to fish population biomass rather than solely on the number of fish (Guillemot et al., 2014). In West Hawai i, total biomass has historically been greater in the South than the North, but has changed markedly through time in both regions (Figure 12B). In the North, biomass showed an overall decline of ~ 20% since 2003, while in the South, total biomass dropped by 40% from 2003 to 2009, and then increased by a similar amount from 2009 to 2014.

Mean Adult Fish Length

Mean adult fish Length is the mean length (cm) of mature fishes and is calculated by averaging all fishes larger than 40% of their maximum length. As fishing pressure increases, the average length of targeted species decreases (Ault et al., 2014; Nadon et al., 2015). This is because fisheries tend to target large fishes, and because fishing mortality reduces the number of fishes that reach older and larger life stages. Previous work has found that reductions in mean length of the whole assemblage are indicative of a shift towards smaller species and/or smaller individuals of the same species, and that this can be driven by moderate levels of fishing pressure (Guillemot et al., 2014). Since 2003, mean fish length has showed a decreasing trend in both regions of West Hawai i (Figure 12C). In addition, the North has observed greater declines in mean fish length and was nearly equal to the South in the most recent survey year.

Species Richness

Species richness is the total number of species present per survey. Coral reefs are renowned for being one of the most diverse ecosystems on the planet and these complex ecosystems provide important ecosystem services. The majority of tourists that visit Hawai i engage in marine-based activities, including diving and snorkeling (Beukering & Cesar, 2004), and fish diversity is one amongst a variety of factors that drives visitor destination choice (Uyarra et al., 2005). In addition to the aesthetic value, biodiversity is intrinsically linked to ecosystem function and greater species diversity supports more productive fisheries (Moberg & Folke, 1999; McClanahan et al., 2011). Furthermore, species diversity is linked to diversity in responses to environmental change amongst species that perform similar ecosystem functions on a reef, and as such is considered a critical aspect of ecosystem resilience (Elmqvist et al., 2003). Species richness has historically been greater in the South than in the North (Figure 12D) but overall has not shown the same dramatic changes as some of the other reef fish indicators presented herein (e.g., Total Biomass). Note: visual surveys of reef fishes do not capture all species present in an area, and so the data here are best considered as a relative measure of species richness, which is one measure of biological diversity.

Herbivore Biomass

Herbivore biomass represents the total weight of herbivorous fishes per unit area. Herbivores (i.e., species for which plant material makes up a majority of their diet) compromise a large part of the fish community assemblage in Hawai i (Williams et al., 2015b). Herbivorous fishes also make up ~ 1/3 of species landed by nearshore fishing in certain areas of West Hawai i, with the majority being kept for home consumption, although they also dominate the reef fish species sold to commercial markets (Kittinger et al., 2015). In addition to being important commercial and non-commercial reef fisheries targets, herbivorous fishes are a key component and indicator of resilience, that is, the ability of a reef to maintain or recover to a coral dominated state following disturbance, and avoiding a phase-shift into algal dominance (Green & Bellwood, 2009). Multiple drivers, operating at various scales can undermine coral reef resilience, such as over-extraction, pollution and climate change. Of these, the diminished abundance of functionally important herbivores is one of the few that is possible to manage through local management action. Overall, herbivore biomass has declined in both regions in West Hawaiʻi since 2003 (Figure 13A). Herbivore biomass in the North has showed a rather steady decline over the twelve year time period while in the South, herbivore biomass declined dramatically from 2003 to 2009, increased from 2009 to 2012, and remained unchanged from 2012 to 2014.

Target Fish Biomass

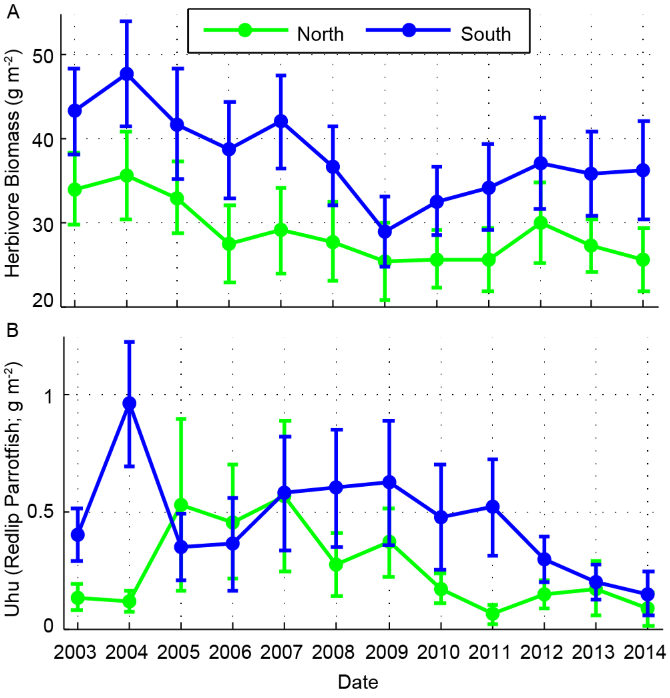

Figure 13. Reef fish indicators (A) Herbivore Biomass and (B) Uhu (Redlip Parrotfish). Indicators are split by North (green) and South (blue) regions of West Hawaiʻi. Error bars represent ± 1 standard error. Data Source: DAR's West Hawaiʻi Aquarium Project.

Large parrotfishes, like Uhu (e.g., Redlip Parrotfish, *Scarus rubroviolaceus*), are a preferred fisheries target throughout the Pacific, and the Redlip Parrotfish is one of the main target species within the parrotfish complex in Hawaiʻi (Sabater & Carroll, 2009; Houk et al., 2011; Bejarano Chavarro et al., 2013; DeMartini & Howard 2016). The deep gouging bites of large herbivores, like Uhu, can prevent macroalgae from becoming established, as well as open up new settlement sites for coral recruitment (Bonaldo et al., 2014). The fact that functional impact (the area grazed) increases non-linearly with parrotfish size (Lokrantz et al., 2008), combined with this species' life history rendering it vulnerable to fishing pressure, means that the Uhu can be considered a disproportionately important yet susceptible component of the fishing community. Based on the duality of this species in terms of fisheries and functional importance, its biomass can be indicative of two things: fishing pressure and reef resilience. Uhu biomass in both regions has shown considerable variation over the data record (Figure 13B). However, current (2014) Uhu biomass is lower than the maximum biomass observed in 2007 and 2004 for the North and South, respectively.

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Juvenile Yellow Tang Abundance

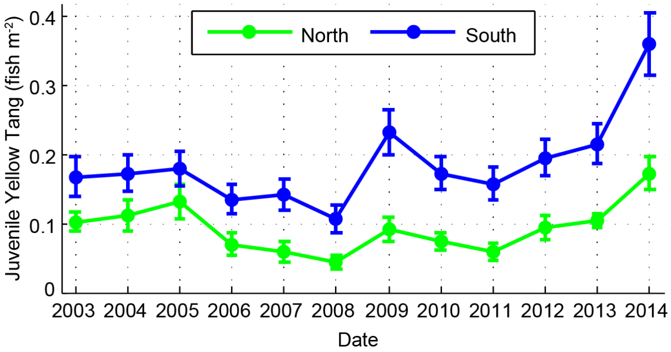

Figure 14. Reef fish indicator Juvenile Yellow Tang abundance from the North (green) and South (blue) regions of West Hawai i. Error bars represent ± 1 standard error. Data Source: DAR s West Hawai i Aquarium Project.

The yellow tang is of significant importance to the Hawaiian aquarium industry, as it is the primary species collected in Hawai i (Walsh et al., 2003). The bulk of the aquarium trade sources fish from West Hawai i; approximately 70% of the fish caught in the State are from West Hawai i with juvenile yellow tang comprising ~ 85% of the total catch (Walsh et al., 2013). As such, the status of this fish around West Hawai i is of high fisheries management relevance. Observed declines in reef fishes due to the aquarium trade are what triggered the establishment of the Fish Replenishment Areas (FRAs) in West Hawai i in 1999. The data presented here are collected as part of the long-term monitoring conducted to assess the efficacy of this network of closed areas, which over time have proved to be highly effective in increasing the density of these long-lived species. Over an 8 year period of closure, the density of juvenile yellow tang was five times greater inside the closed areas compared to the open areas (Williams et al., 2009). Collectors target young juveniles, and as such, we report juvenile yellow tang abundance here. Historical trends in juvenile yellow tang indicate a decline in both North and South regions between 2003 and 2008. However, from 2008 to 2014, juvenile yellow tang have increased approximately three-to four-fold in the North and South of West Hawai i, respectively (Figure 14).

BENTHIC CORAL REEF COMMUNITIES

Coral reef development and persistence are reliant on benthic, sessile organisms that deposit calcium carbonate, namely hard (Scleractinian) corals and crustose coralline algae (CCA). Fleshy algae, such as turf and various forms of erect macroalgae, also serve important ecological functions such as providing food resources for a number of reef fishes (Mumby et al., 2006). In the absence of local human pressures, calcifying organisms tend to dominate coral reef ecosystems (Williams et al., 2015a). Although variations in environmental forcing can tip the competitive balance in favor of fleshy algae on remote, undisturbed reefs (Gove et al., 2015), human-related pressures are more often responsible for shifting reef communities towards a dominance of weedy, fast growing algal species (Pandolfi et al., 2005). Monitoring changes in benthic community organization is therefore critical if we hope to understand coral reef community succession and responses to various environmental and human-related

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pressures. Here we present a few key indicators that help track the status and trends in ecological function and integrity of benthic coral reef communities.

Hard Coral Cover

The total cover of hard coral (Scleractinian) in a given area generally corresponds with the amount of reef topographic complexity, habitat structure, reef accretion, and diversity and abundance of coral-dependent species (McClanahan et al., 2011). A number of recent studies have shown hard coral cover to be somewhat robust to underlying changes in key ecological process (e.g., McClanahan et al., 2011). As such, hard coral cover is a lagging indicator and may not be the most effective for tracking overall coral reef ecosystem health. However, the reproductive life cycle of the Yellow Tang and a number of other species is heavily reliant on the availability of coral dominated, structurally complex areas, serving as the preferred habitat for recruitment and juvenile stages (Walsh, 1984). The data presented here are collected as part of the long-term monitoring program targeted at assessing the status and trends in aquarium fishes in the region. Therefore, we include hard coral cover as an indicator of habitat availability for juvenile fishes targeted by this important and management relevant industry.

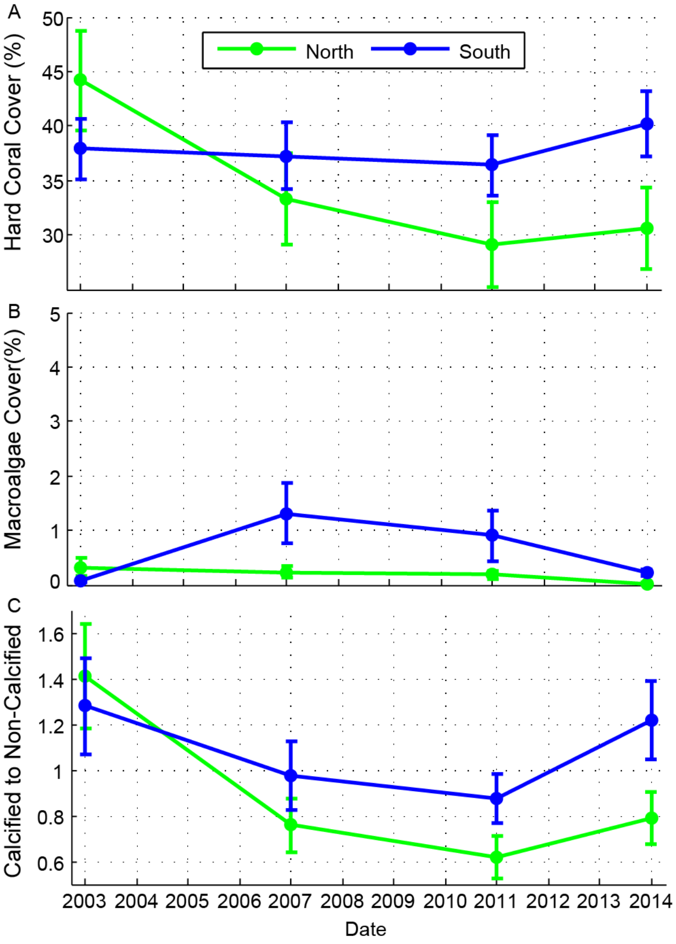

Figure 15. Coral reef benthic community indicators (A) Hard Coral Cover, (B) Fleshy Macroalgae Cover, and (C) Calcified to Non-Calcified Ratio for the North (green) and South (blue) regions of West Hawai i. Error bars represent ± 1 standard error. Data Source: DAR s West Hawai i Aquarium Project.

Since 2003, hard coral cover has declined by ~30% in the North and has remained relatively constant over the same time period in the South (Figure 15A). Coral cover declines are particularly accentuated at specific locations within the North region. For example, coral cover at Puak! decreased from 47.8% to 34.2% from 2007 to 2011 (Walsh et al., 2013). Historical data from Puak! indicate coral cover was as high as 80% in the 1970s, indicating far more dramatic losses in coral cover have occurred over the past 40 years (Minton et al., 2012).

Macroalgae Cover

Fleshy (i.e., non-calcifying) macroalgae are part of a healthy reef community, providing food for a variety of herbivorous fishes and invertebrates. However, macroalgae can grow rapidly and if left unchecked can compete with hard corals for reef space, inhibit coral recruitment, and reduce coral survival (Hughes et al., 2007). In addition to serving as an indicator for benthic communities organization and health, tracking the abundance of macroalgae can also indicate other important processes occurring within coral reef ecosystems, including nutrient enrichment and the intensity of herbivory (McClanahan et al., 2002). Macroalgae percent cover has remained low in West Hawai i; less than 2% across all years in both regions (Figure 15B). Similarly low macroalgae percent cover has also been reported for Hawai i Island in other studies (Bruno et al., 2014; Williams et al., 2015a), indicating West Hawai i has generally avoided the excessive fleshy macroalgae overgrowth that has been observed in other some reef ecosystems (e.g., Hughes, 1994).

Calcified to Non-Calcified Ratio

The ratio of calcified to non-calcified benthic organisms represents the combined cover of reef building hard corals (Scleractinian) and calcifying algae (crustose coralline algae and *Halimeda*) to the combined cover of turf and fleshy macroalgae. Foundational benthic organisms that contribute to coral reef development and persistence are those that are calcifying, serving a number of key ecological processes including settlement, recruitment, and cementation of reef structure (Williams et al., 2015a). Fleshy and turf algae directly compete for space and in high abundance indicate a degraded ecological state (Hughes et al., 2010). Therefore, calcified to non-calcified ratio of benthic organisms serves as an important indicator of coral reef community dynamics and the extent to which a given system is dominated by reef accreting benthic organisms.

From 2003 to 2011, calcified to non-calcified ratio declined in both the North and South regions (Figure 15C). Over that time, the North showed the biggest change, with the calcified to non-calcified ratio decreasing by half. A potentially important threshold for this indicator is 1, as it represents a shift in the relative dominance between calcifying and non-calcifying benthic organisms. The most recent survey in 2014 shows that the benthic communities in the North region fell below this threshold, indicating the benthic community is now dominated by algae. It is uncertain what proportion of the benthos needs to be dominated by reef builders to maintain a reef in a state of net accretion as oceanographic conditions, community structure, and local human impacts each play a role in overall reef growth. However, it seems logical that coral reef ecosystems with a greater abundance of reef builders will have higher rates of net reef growth and accretion compared to reefs dominated by non-calcifying organisms (Smith et al., 2016).

Coral Disease

Tracking patterns in coral health and disease dynamics is important for understanding underlying causes of changing coral reef ecosystem health. During the last four decades, coral disease has steadily increased both spatially and temporally across the globe, affecting coral health from the physiological to the ecosystem-level. Originally restricted to the Caribbean, coral disease is now a major threat to Indo-Pacific and Hawaiian reefs (Aeby et al., 2011; Ruiz-Moreno et al., 2012). While the causes of increasing coral disease are poorly understood, coral disease risk has been linked to the compounding effects of climate change, local anthropogenic inputs, and distribution of susceptible host populations (Harvell et al., 2007; Williams et al., 2014). For this reason, coral disease is a useful early indicator of changing reef health and changing environmental conditions.

Along West Hawai i, coral health and disease assessments conducted in 2010 and 2011 indicated that overall disease prevalence was higher in shallow (3-6 m) zones (average of 15.2%) than deep (10-15 m) zones (10.6%), but varied considerably across the coastline (Figure 16). Spatial patterns were primarily driven by the most prevalent disease *Porites* growth anomalies, which occurred at 100% of the sites at an average prevalence of 13.7% (Couch et al., 2014a). Based on high prevalence of certain coral health conditions, Couch et al., (2014a) identified four regions of concern (Puak! , Mauna Lani, Kaupulehu, and H! naunau; see Figure 2 for geographic locations). Other studies along West Hawai i indicate that *Porites* growth anomalies dynamics may be driven by exposure to elevated nutrients in submarine groundwater discharge (Couch et al., 2014b), colony size, and water motion (Couch, 2014). The high spatial variation in coral health not only advances our understanding of coral disease ecology, but also supports reef resilience planning by identifying vulnerable areas that would benefit most from targeted conservation and management efforts.

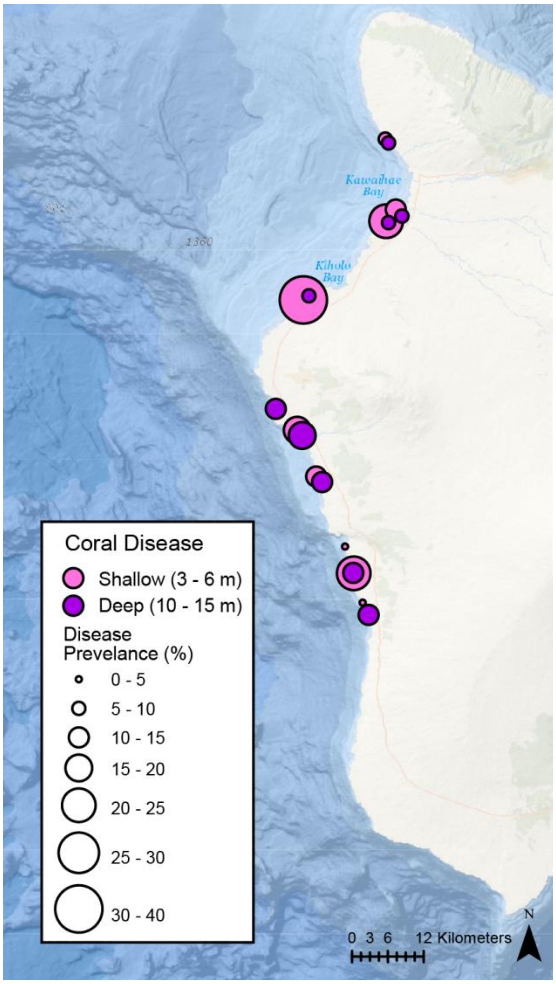

Figure 16. Map of coral disease prevalence for shallow (3 – 6 m; pink circles) and moderate (10 – 15 m; purple circles) depths at specific sampling sites along West Hawai i. The relative size of the circle is proportional to disease prevalence. Data Source: Couch, 2014.

CLIMATE AND OCEAN INDICATORS

Variations in large-scale climate patterns are influential in shaping the physical environment of marine organisms, and affect many aspects of their physiology such as feeding, migration, and reproductive success. With significant climatological changes predicted to occur in coming decades, it is increasingly important to understand the major physical forces impacting West Hawaiʻi and the effects these forces may have on the biology and management of the ecosystem. Here we present a number of climate and oceanographic indicators which are useful for tracking and predicting changes in the natural environment of West Hawaiʻi's marine ecosystem.

Pacific Decadal Oscillation

The Pacific Decadal Oscillation (PDO) is often described as a long-lived El Niño-like pattern of Pacific climate variability. As seen with the better-known El Niño Southern Oscillation (ENSO), extremes in the PDO pattern are marked by widespread variations in temperature, wind patterns, ocean mixing, and biological productivity (Polovina et al., 1994). The extreme phases of the PDO have been classified as being either warm or cool, as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean. When SSTs are anomalously warm in the northeastern and tropical Pacific and when sea level pressures are below average over the north Pacific, the PDO has a positive value (i.e., warm phase) (Mantua & Hare, 2002).

Warm and cool phases of the PDO tend to prevail for multiple decades with punctuated and short-lived, intermittent reversals (Figure 17). For example, a warm phase dominated over the late 1970s to late 1990s; however, a short-lived cool phase was observed from 1989 to 1992. The PDO was in a cool phase much of the past two decades. More recently, the PDO has switched to a warm phase, which may lead to an increase in the storminess of the North Pacific (Bond & Harrison, 2000) and when coincident with a positive phase of ENSO (i.e., El Niño), can result in an increase in hurricane activity in Hawaiʻi during the summer months (Rooney et al., 2008).

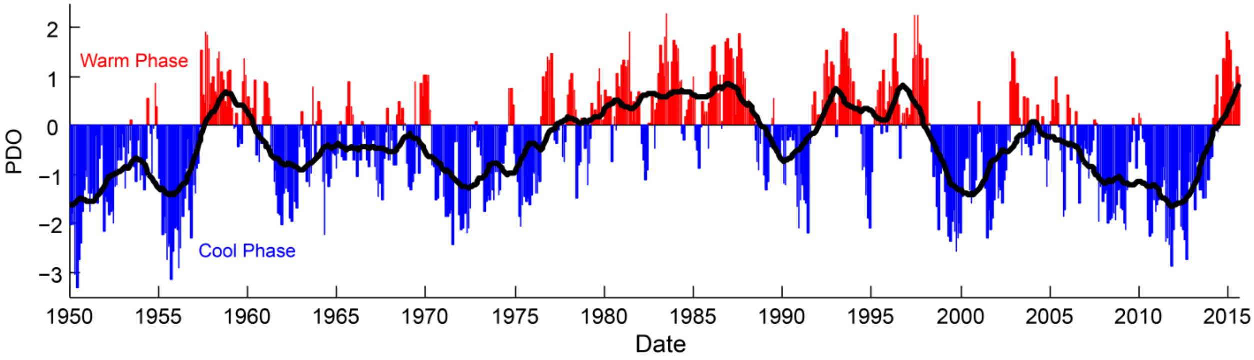

Figure 17. Pacific Decadal Oscillation Index from 1950 to present. Positive (red) values represent Warm Phase conditions and negative (blue) represent Cool Phase conditions. Black line is a 3-year moving average. Data source: NOAA's National Centers for Environmental Information.

El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) is an irregular, large-scale ocean-atmosphere climate phenomenon. El Niño represents the warm phase of the ENSO cycle, characterized by weakening of the trade winds across much of the Pacific and warming of ocean temperatures in the Equatorial Pacific. El Niño events typically last 9-15 months, with peak forcing occurring in the northern hemisphere winter. La Niña represents the cool phase and is associated with stronger than normal trade winds and the anomalously cool ocean temperatures (Philander, 1990). On average, La Niña is a less extreme anomaly than El Niño but tends to last longer, approximately 1-3 years.

The Multivariate ENSO Index (MEI) is an indicator of ENSO strength: positive values represent El Niño conditions while negative values represent La Niña conditions (Figure 18). Throughout the past half-century, ENSO has oscillated between El Niño and La Niña numerous times. However, since 1976, there has been a shift towards increased frequency and strength in El Niño conditions. Most notable were the strong El Niños observed in 1982-1983 and 1997- 1998, and recently in 2015. Although no two El Niños are the same, changes in local climate and oceanographic conditions, such as lower than average precipitation (see *Rainfall*) and larger-than-average wave events (see *Wave Forcing*), are often observed in the in Hawaiʻi during a strong El Niño.

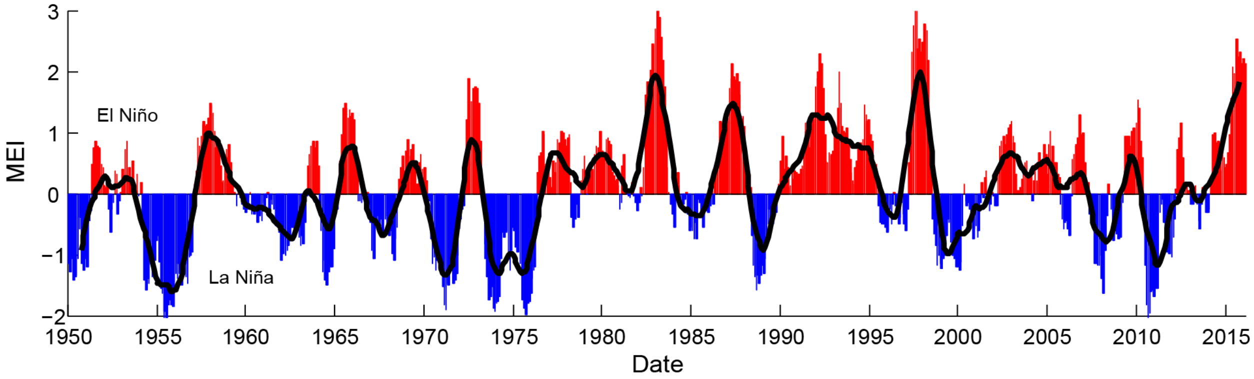

Figure 18. Multivariate ENSO Index from January 1950 to December 2015. Positive (red) values represent El Niño conditions and negative (blue) represent La Niña conditions. Black line represents an 18-month moving average. Data source: NOAA's Earth System Research Laboratory.

Rainfall

Tracking the status and trends in rainfall patterns is important for a variety of resource management issues in West Hawaiʻi. Changes in rainfall dictate the amount and intensity of ground water and surface water transport to the marine environment, which can influence nearshore salinity and temperature, as well as suspended sediment and nutrient concentrations.

The Hawaiian Islands have one of the most diverse rainfall patterns on earth. The persistent trade winds, mountainous terrain, and diel heating and cooling of the land interact to produce areas of uplift in distinct spatial patterns associated with the islands' topography. The resulting clouds and rainfall produced by this uplift lead to dramatic differences in mean rainfall over short distances (Giambelluca et al., 2012).

West Hawai i s rainfall patterns are somewhat unique for the Hawaiian Islands. Rainfall is principally driven by well-developed and reliable land and sea breezes that predominate in the region owing to a combination of diel land heating and a blocking of the trade winds by Mauna Loa and Mauna Kea. This diurnal pattern is particularly strong during the summer months.

Using data compiled for the Rainfall Atlas of Hawai i (Giambelluca et al., 2012), we combined monthly data from 15 rainfall data sets obtained from locations spread along West Hawai i from 1950 to 2012 (Figure 19). Over this historical record, rainfall in the region exhibited somewhat consistent seasonal and inter annual patterns. However, since the mid-90s, rainfall patterns have been at or below the long-term average while the intensity of short-term events has increased over the same time period. Similar changes in rainfall patterns have been observed state wide (Fletcher, 2010).

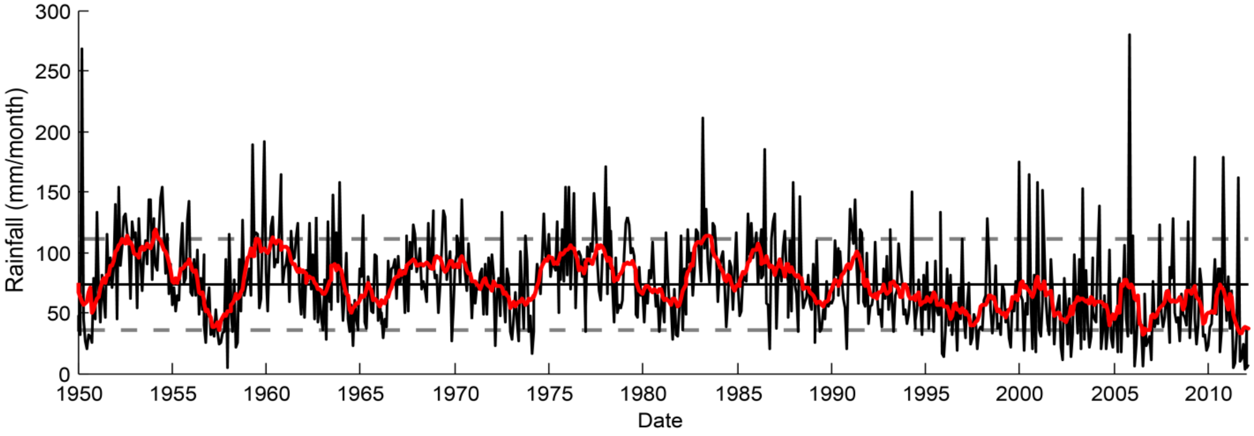

Figure 19. Monthly rainfall (mm) from West Hawai i. Red line represents a 12-month moving average. Horizontal lines represent the long-term mean (1950-2012; solid line) and ± 1 standard deviation (dashed line). Rainfall data represent an average of 15 separate rain gauges located throughout West Hawai i. Data source: University of Hawai i M#noa Rainfall Atlas of Hawai i (Giambelluca et al., 2012).

Sea Level

Tracking the status and trends in sea level is important for coastal communities and nearshore marine ecosystems. Over long time periods, sea level rise can lead to chronic coastal erosion, coastal flooding, and drainage problems. Moreover, long-term increases in sea level exacerbate short-term fluctuations in coastal sea level driven by waves, storms, and extreme tides. Continued sea-level rise will increase inundation of coastal roads and communities and result in salt intrusion into coastal wetlands, groundwater systems, taro fields, and anchialine pools (Fletcher, 2010).

Long-term sea-level measurements (1990-2015) from Kawaihae indicate an increasing trend (Figure 20), with a sea-level rise rate estimated at 3.79 mm per year (Vitousek et al., 2009). Based on sea-level rise rates and taking into account the global acceleration in sea level rise reported in the literature, it s estimated that mean sea level will increase in West Hawai i by 0.19 m and 0.48 m by 2050 and 2100, respectively (estimates are relative to 2008 mean sea level) (Vitousek et al., 2009).

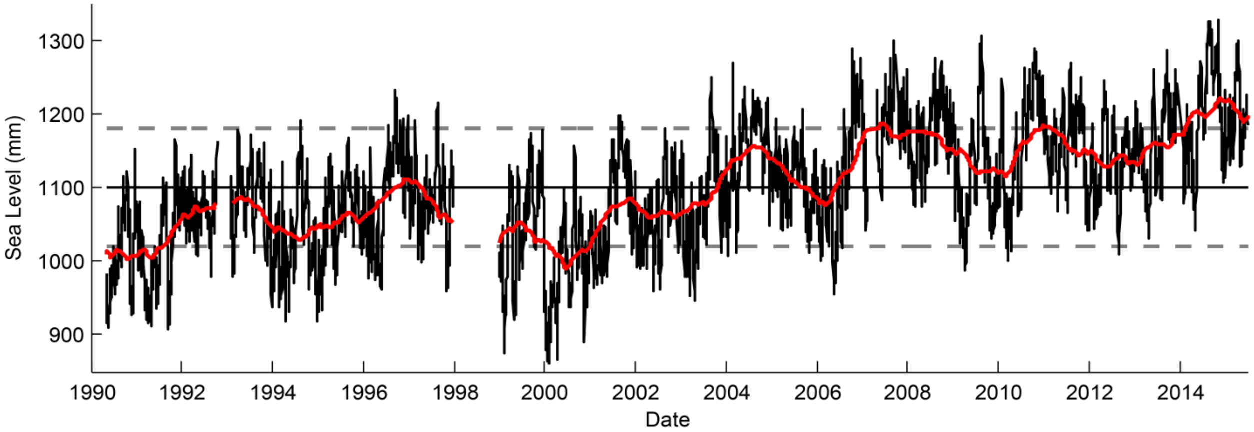

Figure 20. Daily sea level data from Kawaihae Harbor (black line). Red line represents a 12-month moving average. Horizontal lines represent the long-term mean (1990-2015; solid line) and ± 1 standard deviation (dashed line). Data source: University of Hawai i Sea Level Center.

Eddy Activity

The combination of prevailing northeasterly trade winds and island topography results in the formation of vigorous mesoscale (~ 100 km) eddies in the lee of Hawai i Island (Lumpkin, 1998). Eddy formation is attributed to a funneling of the northeast trade winds through the Alenuih#h# Channel, between Hawai i Island and Maui, as well as around the southern flank of Mauna Loa at South Point. As a result, cyclonic (counterclockwise) ocean eddies are commonly formed in the North region and anticyclonic (clockwise) eddies are commonly formed in the South region of West Hawai i. The strength and location of these eddies depends heavily on the strength of the trade winds and the stage of eddy development (Bathen, 1975).

Eddies have important biological implications for West Hawai i. Cyclonic eddies, for example, can drive upwelling of cooler, nutrient rich water that influences ocean temperatures and fuels a localized increase in phytoplankton production (Seki et al., 2002), an essential source of energy for higher trophic groups. The presence and strength of eddies may also have a negative effect on certain organisms. For example, Fox et al., (2012) found significant negative correlations between annual patterns of cold-core cyclonic mesoscale eddies and young-of-the-year totals of several fish species on the west coast of the island of Hawai i.

Eddy Kinetic Energy (EKE) is a measure of eddy activity. Higher EKE values are an indicator of increased eddy activity and, therefore, a potentially greater influence on marine ecosystem processes. We split EKE into North and South in order to capture the strength of the cyclonic

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and anticyclonic eddies in the respective regions (Figure 21). EKE has a prominent North-South split, with the South region characterized by more active eddy activity. EKE in both regions indicates historical time periods of increased activity, such as 1999, 2005-2007, and recently in 2013.

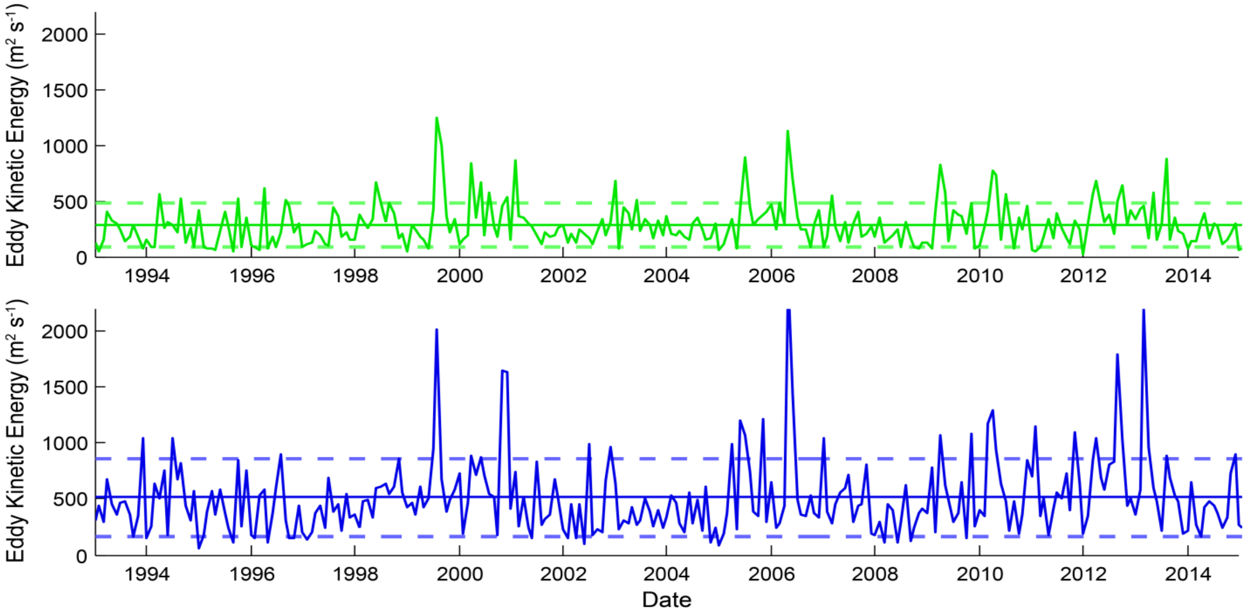

Figure 21. Monthly Eddy Kinetic Energy from 1992-2015 for the North (green; upper panel) and South (blue; lower panel) sections of West Hawai i. Horizontal lines represent the long-term mean (1992-2015; solid line) and ± 1 standard deviation (dashed line). Data Source: Aviso Geostrophic Currents.

Sea Surface Temperature

Sea surface temperature (SST) plays an important role in a number of ecological processes and varies over a broad range of temporal scales. SST can vary in response to diel, intra-seasonal (e.g., mesoscale eddies), seasonal, interannual (e.g., ENSO) and decadal (e.g., PDO) forcing. Ecosystem responses can include changes in primary productivity, species migration patterns, and if anomalous enough, coral mortality (Hoegh-Guldberg, 1999). In West Hawai i, regional satellite-derived SST shows both strong seasonal and interannual variability (Figure 22). Seasonally, ocean temperatures are coolest in March (24.8 C) and warmest in September (26.9 C). However, this seasonal cycle can vary from year-to-year owing to large-scale ocean-atmosphere climate phenomena such as ENSO and PDO. Although the dynamics between local temperature changes and large-scale climate forcing is complex, generalizations can be made based on historical information. In general, ocean temperatures tend to be warmer than average during El Ni o conditions and warm phases of the PDO and cooler than average during La Ni a conditions and cold phases of the PDO. The recent increase in SST observed in West Hawai i is likely indicative of these large-scale processes influencing regional scale conditions.

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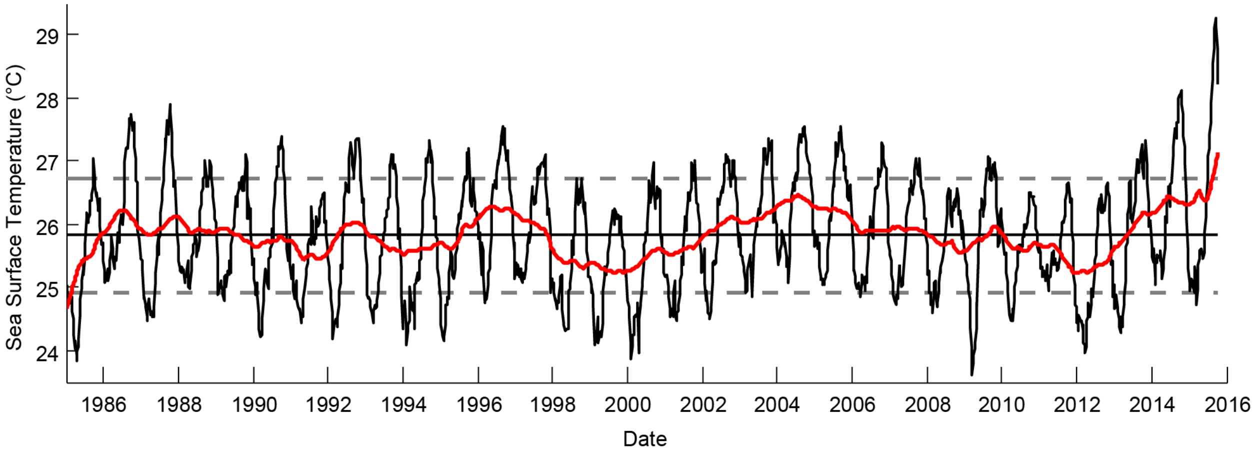

Figure 22. Weekly sea surface temperature for the entire region of West Hawai i from January 1985 – October 2015 (black line). Red line represents a 12 month moving average. Horizontal lines represent the long-term mean (1985-2015; solid solid) and ± 1 standard deviation (dashed line). Values Data source: NOAA s Coral Reef Watch.

Thermal Stress

Thermal stress is an indicator of increased SST that exceeds typical maximum summertime temperatures, resulting in stress-inducing conditions for coral reef ecosystems. Coral bleaching–the loss of corals photosynthetic symbionts–can result if thermal stress is > 1 C above the maximum summertime temperatures and sustained for extended periods of time.

Over the last three decades, West Hawai i s coral reefs have experienced multiple years with thermal stress (Figure 23), although rarely have ocean temperatures exceeded the coral reef bleaching threshold (> 1 C thermal stress) until 2015. The 2015 thermal stress event resulted in satellite-derived temperatures reaching a maximum of ~ 2.5 C above typical summertime temperatures. Rising ocean temperatures and the associated increase in thermal stress are expected to increase the frequency and severity of coral bleaching events in the future (Pandolfi et al., 2011).

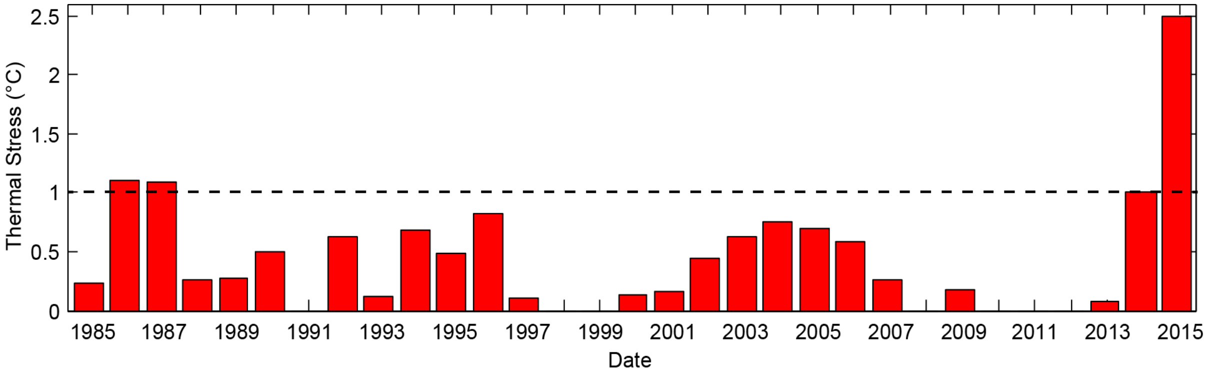

Figure 23. Annual maximum Thermal Stress HotSpot for West Hawai i from January 1985 – October 2015. Values represent temperatures that exceeded the maximum climatological monthly mean. No data represents years that experienced no thermal stress anomalies. Data Source: NOAA s Coral Reef Watch.

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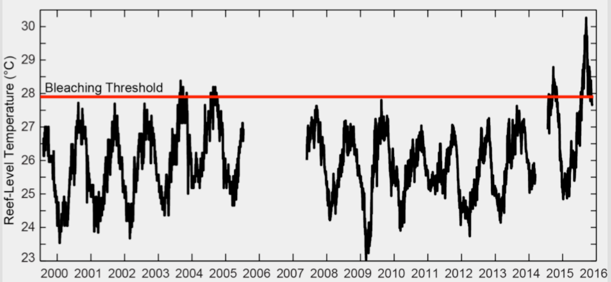
CORAL BLEACHING EVENT OF 2015

The 2015 warming event resulted in widespread and severe coral bleaching across West Hawai i. Reef-level temperatures were anomalously warm throughout the summer, reaching as high as 30.3 C (86.5 F) in September, far exceeding the coral reef bleaching threshold for the region (see figure below). The overall severity of bleaching, or the percentage of corals bleached at a given site, was estimated at 30-80%, with some geographic areas exhibiting upwards of 90% coral bleaching (DAR and The Nature Conservancy, unpublished data). Coral bleaching was widespread across coral species, although some (e.g., *Pavona duerdina* and *Pocillopora damicornis;* 100% bleached) were hit harder than others (e.g., *Montipora incrassate* and *Leptastrea purpure;* 40-47% bleached). The two most dominant reef-building coral species in West Hawai i, *Porites lobata* and *Porites compressa*, exhibited > 50% coral bleaching.



Reef-level temperature (15 m) information obtained from a DAR long-term monitoring site located in the North region shows the anomalously warm temperatures observed in 2015. Temperatures peaked at 30.3 C (86.5 F) in late September, surpassing the coral bleaching threshold by 2.4 C (Data source: DAR).

Coral bleaching was widespread in West Hawai i in 2015. Here, a photograph of a bleached *pocillopora damicornis* coral is shown. An estimated 40-80% of corals bleached in the region.

Coral bleaching does not necessarily result in coral mortality; corals can survive temporarily in the absence of their photosynthetic symbionts and completely recover from a bleaching event. However, local human stressors such as sedimentation, excess nutrient input, and removal of herbivorous fishes can impede their ability to recover. Projected future increases in ocean temperatures are expected to increase the frequency and severity of coral bleaching in Hawai i. Effective management strategies that mitigate local human stressors and thereby bolster coral reef resiliency to future bleaching events are critical in this era of rapid climate change.

Photograph courtesy of The Nature Conservancy.

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Wave Forcing

Wave forcing is a major environmental forcing mechanism in marine ecosystems. Variations in wave forcing can influence important ecological processes such as coral reef development (Dollar & Tribble, 1993), spatiotemporal patterning in benthic and reef fish communities (Friedlander et al., 2003), sediment transport and resuspension (Storlazzi et al., 2004), and shoreline and beach morphology (Rooney & Fletcher, 2005). Wave forcing can drive mixing of the upper water column that can reduce ocean temperatures during warming events (McClanahan et al., 2005) and potentially enhance surface nutrient availability (Wolanski & Delesalle, 1995).

Hawaiʻi receives large ocean swell from extra-tropical storms in the northwest Pacific. During winter months, the Aleutian low intensifies and the strong winds associated with these storms produce large swell events that travel for thousands of miles until reaching Hawaiʻi (Rooney et al., 2008). However, because seven of the main eight Hawaiian Islands lie to the northwest of Hawaiʻi Island, significant wave shadowing (i.e., blocking) occurs, dramatically reducing nearshore wave forcing along West Hawaiʻi (Vitousek et al., 2009). This blocking effect is particularly accentuated north of Keahole Point. As such, we have split waves into North and South West Hawaiʻi (Figure 24).

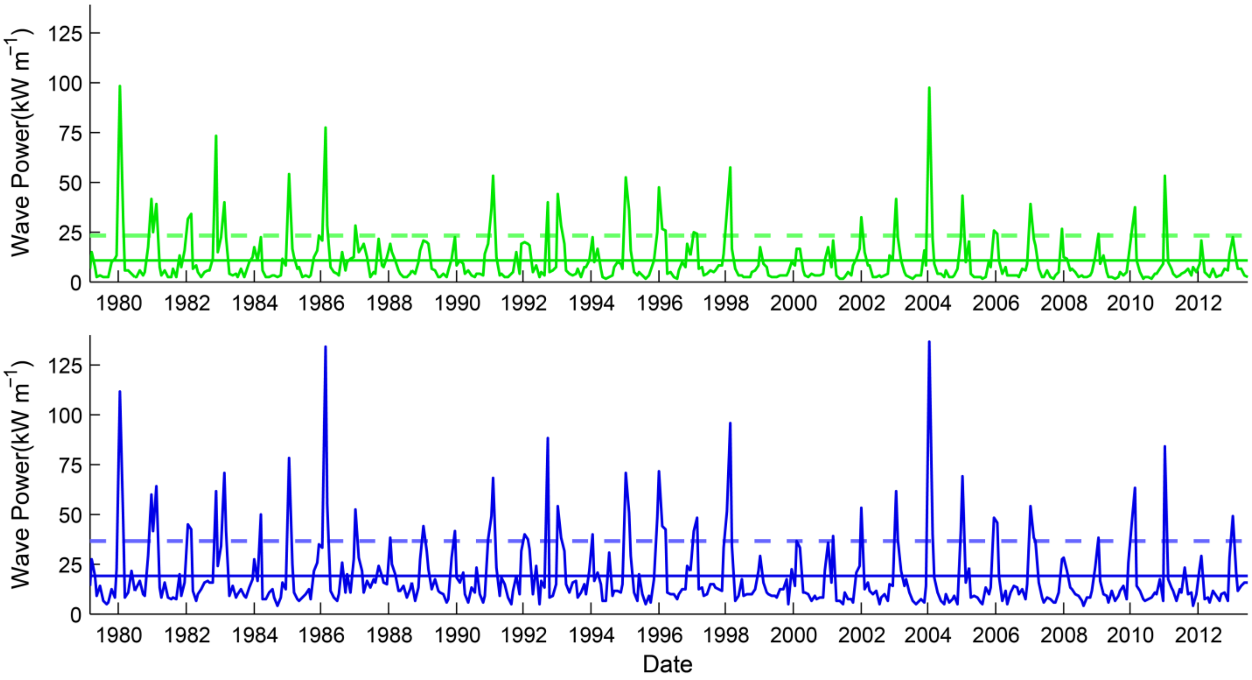


Figure 24. Monthly peak wave power (kW m^{-1}) calculated for the North (green; upper panel) and South (blue; lower panel) regions in West Hawaiʻi. Data represent maximum daily values in each month, from 1979-2013. Horizontal lines represent the long-term mean (1979-2013; solid line) and + 1 standard deviation (dashed line). Data Source: Li et al., (2016); International Pacific Research Center (IPRC) at the University of Hawaiʻi.

Although wave height is frequently used in ecological research and is often easier to contextualize, it underrepresents wave conditions owing to the importance of wave period in determining the overall impact of wave forcing (Gove et al., 2013). *Wave power* (kW m^{-1}), a calculation that includes both wave period and wave height, is a more realistic estimate of wave forcing, and therefore, a more ecologically relevant indicator with which to assess wave forcing on marine ecosystems (Gove et al., 2013).

Wave power in West Hawai i is highly seasonal with wintertime months typically experiencing significantly greater wave forcing that summertime months (Figure 24). Wave forcing is, on average, greater in the South compared to the North. Peak swell events are also typically greater to the South. From 1979 to 2013, wave events in 1980, 1986, and 2004 stand out in both records as the largest events of the 35-year record.

Phytoplankton Biomass

Phytoplankton production is an essential source of energy in the marine environment. The extent and availability of phytoplankton biomass drives the trophic-structure of entire marine ecosystems (Iverson, 1990), dictating the distribution and production of the world s fisheries (Chassot et al., 2010). The ecological impacts of increased phytoplankton biomass are especially acute near coral reef ecosystems as they predominantly reside in nutrient impoverished waters that lack new production (Hamner & Hauri, 1981).

Changes in phytoplankton biomass are predominantly driven by changes in nutrient concentrations. Nutrients can increase through a variety of natural processes that bring deeper waters to the upper surface of the ocean. For example, bathymetric influences on ocean currents can drive turbulent mixing, lee eddy, and wake affects that increase nutrients on the lee side of an island. Internal waves, generated from tidal currents interacting with underlying bathymetry, can also drive vertical changes in the background stratification that deliver cooler, nutrient-rich waters to the near surface (Leichter et al., 1998).

However, human activities can also increase nearshore nutrient levels that artificially elevate planktonic production in coastal marine ecosystems (Vitousek et al., 1997). Sources of nutrients include urban development and agricultural land use as well as wastewater effluent (e.g., on-site waste disposal systems) and storm outfalls (Smith et al., 1999; Anderson et al., 2002). Precipitation events and outflow from rivers can mobilize and carry land-based pollutants and other terrigenous input that can also stimulate phytoplankton production (Anderson et al., 2002).

We use chlorophyll-*a*, a widely used proxy for phytoplankton biomass, as an indicator for changes in phytoplankton production. Owing to existence of cyclonic and anticyclonic eddies off West Hawai i and other geographically variable factors that can influence phytoplankton production (e.g., wave forcing), we split the region into North and South in order to more effectively track changes in phytoplankton biomass in the region (Figure 25). Phytoplankton biomass is generally greater in the North compared with the South, and shows a seasonal pattern, with peaks occurring in October to December. However, there is clear intra-seasonal and interannual variability observed in both regions. More recently, phytoplankton biomass was considerably and anomalously low in 2014, but has since increased above long-term averages in both regions.

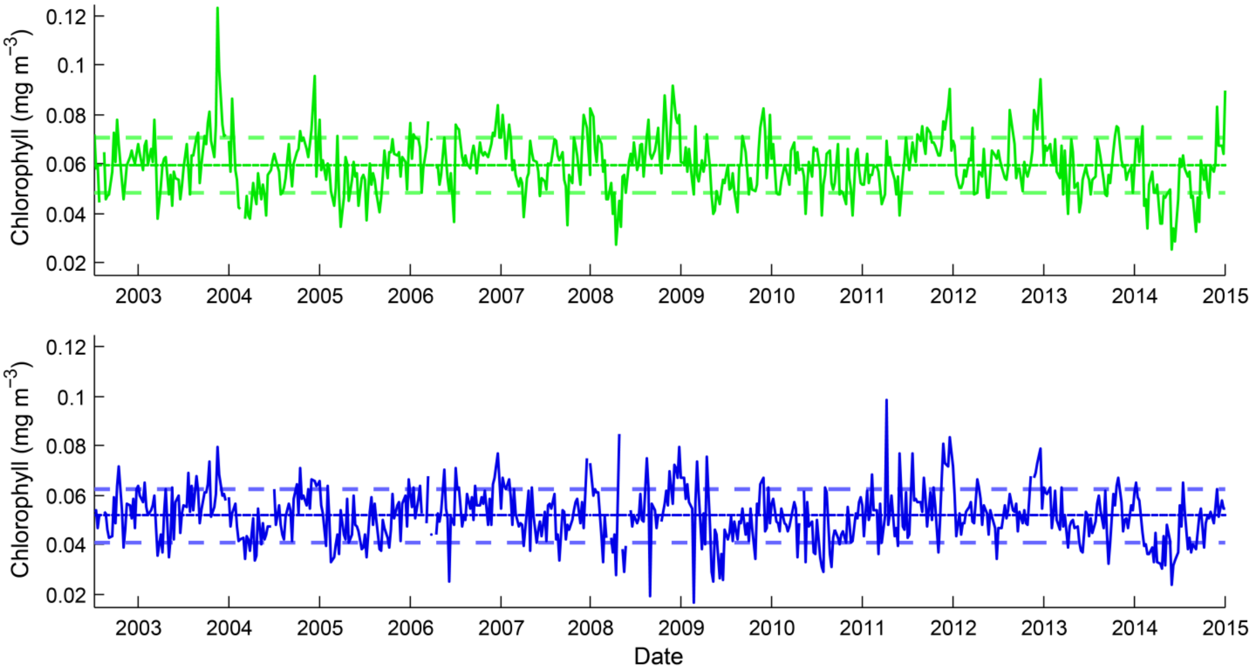
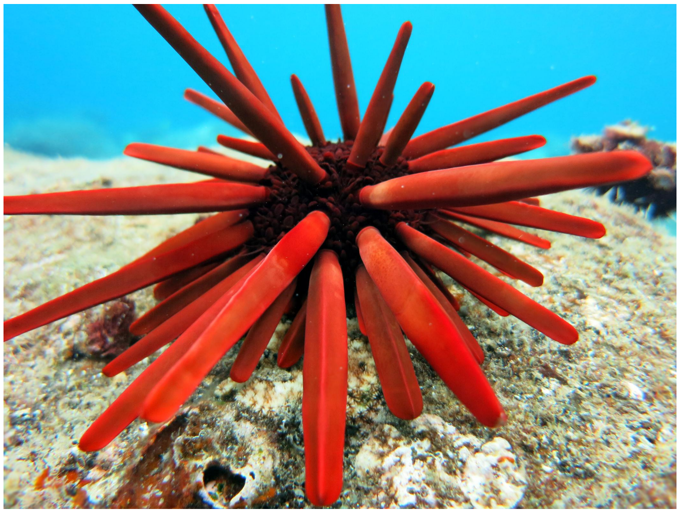


Figure 25. Eight-day chlorophyll-*a* (proxy for phytoplankton biomass) information from 2002 – 2015 for the North (green, upper panel) and South (blue; lower panel) regions in West Hawaiʻi. Horizontal lines represent the long-term mean (solid) and ± 1 standard deviation (dashed). Data Source: NASA's Moderate Resolution Imaging Spectroradiometer.

SUMMARY AND CONCLUSION



Red slate pencil urchin *(Heterocentrotus mamillatus)*

Ecosystem indicators provide the ability to track the trends and status of West Hawaiʻi's marine ecosystem. Here, we compiled 29 individual indicators identified via a combination of community and expert opinion, region-specific research results, and our current scientific understanding of sub-tropical marine ecosystems. Ecosystem indicators presented herein span a wide range of ecosystem components that include social, ecological, climatic, and oceanographic drivers of ecosystem change. From this synthesis of information, a number of key findings have emerged, including (but not limited to):

Social Indicators

- The current population of Hawaiʻi Island is approximately 194,000, an increase of 320% in 56 years.
- Cesspools—where effluent receives no treatment prior to being released into the environment—comprise 85% of all on-site waste disposal systems.
- Total nearshore commercial fisheries catch has decreased from over 200,000 kg in 1980 to just over 65,000 kg in 2012.
- Net fishing was historically the dominant commercial fishing method, comprising approximately 53% of the total commercial catch. However, during the mid-1990s, gear preferences shifted, with Net fishing representing just 38% of the total catch and Line fishing replacing it as the dominant method for nearshore commercial fisheries.

Ecological Indicators

- Hard coral cover decreased by 30% from 2003 to 2014 in the North while showing no change in the South.
- Macroalgae cover is extremely low across the region.
- The ratio between the cover of calcifying and non-calcifying benthic organisms has declined across West Hawaiʻi, with the benthic coral reef community presently (2014) dominated by non-calcifying benthic organisms in the North.
- Mean fish length has tended to decline since 2003.

- Total fish biomass has declined by ~ 20% in the North while in the South, biomass varied considerably with no overall net change observed over the data record.
- Herbivorous fishes, including Uhu (e.g., Redlip Parrotfish, *Scarus rubroviolaceus*), a targeted herbivorous fish, have shown declining trends since 2003.
- Total fish abundance and species richness have increased since 2003.
- Juvenile yellow tang increased approximately three- to four-fold and is presently at the highest density levels since monitoring began in 1999.

Climate And Ocean Indicators

- ENSO has shifted over the last four decades towards increased frequency and severity in El Niño conditions, with the recent 2015 El Niño as one of the strongest on record.
- Rainfall has been at or below the long-term average over the past 15 years while the intensity of short-term events has increased.
- Sea level is rising at a rate of 3.79 mm/year and is expected to reach 0.48 m higher than present day levels by 2100.
- Sea surface temperature was anomalously warm in recent years and reached a record level of Thermal Stress HotSpot (a proxy for coral bleaching) in September 2015. Widespread and severe coral reef bleaching was observed in West Hawaiʻi as a consequence of the warming event.

Although we have assembled a suite of relevant ecosystem indicators to help track changes in key ecological processes in West Hawaiʻi, many gaps remain. Moreover, our understanding of ecosystem dynamics and the myriad social-ecological interactions occurring in the region continues to evolve. As such, the evaluation and synthesis of information and development of ecosystem indicators is an adaptive and continual process that will continue beyond this publication. Nevertheless, this interdisciplinary report elucidates key linkages across different components of West Hawaiʻi's marine ecosystem, providing important context as we move toward ecosystem-based management in the region.

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