NOAA FISHERIES

Pacific Islands Fisheries Science Center

WEST HAWAI‘I INTEGRATED ECOSYSTEM ASSESSMENT ECOSYSTEM STATUS REPORT

2019

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Executive Summary

West Hawaiʻi is home to a dynamic and productive marine ecosystem. Economic and socio-cultural value is provided to residents through numerous ecosystem services, such as commercial and non-commercial fishing, cultural and traditional practices, recreation, tourism, and coastal protection. However, ecological communities across West Hawaiʻi—particularly, coral reefs—have suffered recent and unprecedented declines. Marine ecosystem degradation can compromise underlying ecosystem functions and processes and undermine the numerous goods, services, and benefits upon which local communities depend.

This report summarizes a suite of ecosystem indicators that track the status of the region's marine ecosystem. In total, 30 indicators are presented that include climate and oceanic drivers of ecosystem change, the states of ecological communities, and the activities and relationships between people and marine resources in West Hawaiʻi. Ecosystem indicators were identified through a collaborative and participatory process led by the West Hawaiʻi Integrated Ecosystem Assessment, a NOAA program dedicated to providing robust scientific information that meets current and future marine management needs in the region.

The marine environment is a substantial contributor to economic productivity and community well-being in West Hawaiʻi. Fisheries, in particular, are socially and culturally important, with the pelagics fishery (e.g., tunas and billfishes) serving as the largest commercial fishery in the region. Since 2003, the total catch from the pelagics commercial fishery was over 6 times the combined commercial catch (by weight) of all other commercial fisheries and represented 62.3% of the total commercial fisheries revenue generated in West Hawaiʻi. Total catch of pelagics peaked in 2012 with 1.9 million pounds and $5.4 million in annual revenue. In recent years, the fishery has declined: total catch in 2017 was 1.02 million pounds, representing a 46% decline in just 5 years.

Reef-fish fishing for recreational, subsistence, and cultural purposes (i.e., non-commercial) makes up the second largest fishery (by weight) in West Hawaiʻi. The estimated annual average catch was nearly 406,000 pounds from 2003 to 2013, representing an 11.5-, 2.7-, and 24-fold increase over the annual average commercial catch of bottomfish, coastal pelagics, and reef fish, respectively. In the most heavily fished coastal areas, such as between Puakō and Kawaihae and near Kailua-Kona, approximately 29,000–33,000 pounds of reef fish were caught in an average year. As with the pelagic fishery, non-commercial reef fish catch has declined in recent years. Total catch was estimated at 265,200 pounds in 2013, approximately a 50% drop from the 525,600 pounds caught in 2008.

In terms of economic value, the commercial aquarium fishery is the most valuable inshore commercial fishery and the second most valuable commercial fishery in West Hawaiʻi. Average annual revenue from commercial aquarium fishing in West Hawaiʻi was $1.35 million over the last 14 years, comprising nearly 25% of the revenue generated from all commercial fishing activities in the region. The average total number of individuals caught was approximately 360,000 per year since 2003, with juvenile yellow tang comprising over 80% of the fishery. More recently, total revenue has increased to an average of $1.58 million per year over the last 5 years with no significant change in the number of individuals caught.

Coral reef fish indicators, such has fish abundance, size, diversity, and biomass, provide a fisheries independent assessment on the status and health of reef fish communities. Importantly, reef fish indicators provide a basis for evaluating the efficacy of the three primary management designations in West Hawaiʻi: marine protected areas (MPAs; prohibition of fishing), fish replenishment areas (FRAs; prohibition of aquarium fish collection only), and open areas (fishing allowed). Juvenile yellow tang, for example, have increased between 60 and 80% in the last 14 years across all three management designations in West Hawaiʻi, suggesting a potential spillover effect from managed to unmanaged areas.

Herbivorous fishes, which are important for reef resilience, constitute roughly 50% of total fish biomass in the region. Herbivore biomass has not changed in open areas or FRAs in the past 14 years. However, herbivore biomass in MPAs has increased by nearly a third since 2003 and is currently (2017) 1.7 times greater compared to FRAs and open areas. In fact, all reef fish indicators—total abundance and biomass, adult fish length, species richness, herbivore biomass, juvenile yellow tang—were 1.1–2 times higher in MPAs over open areas in 2017. The significant differences in key fish indicators between management designations suggest a clear and positive influence of fisheries management on the structure and function of coral reef fish communities in protected areas.

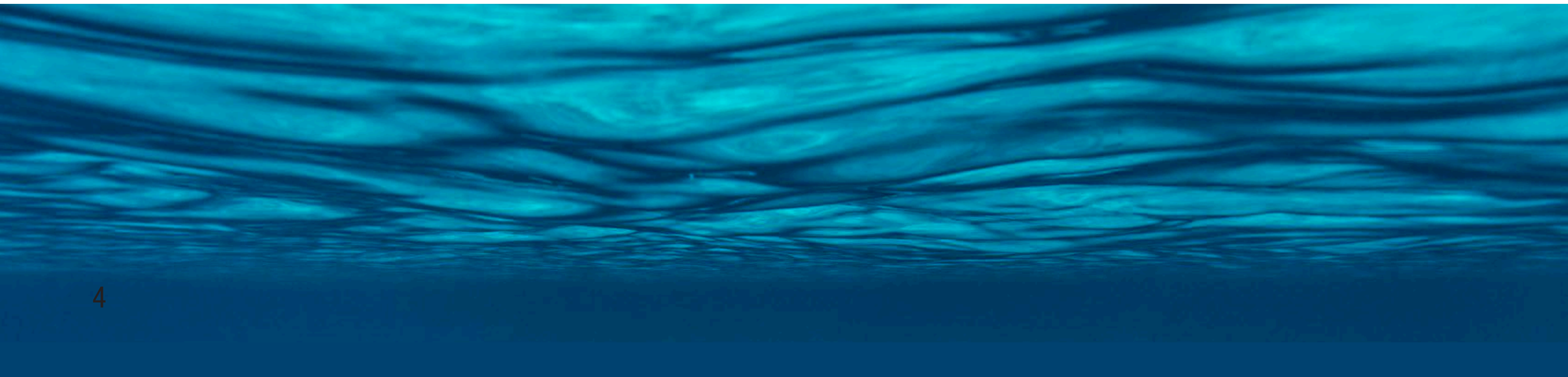
Despite the substantial contributions of commercial fishing, tourism represents the single largest source of economic activity in West Hawai‘i. Visitor arrivals and visitor spending have steadily increased over the last decade, exceeding 1.3 million arrivals and $2.1 billion in spending in 2016. December is the highest month of visitor spending each year. It has increased 75%, or from $133 million to $233 million, over the past 15 years.

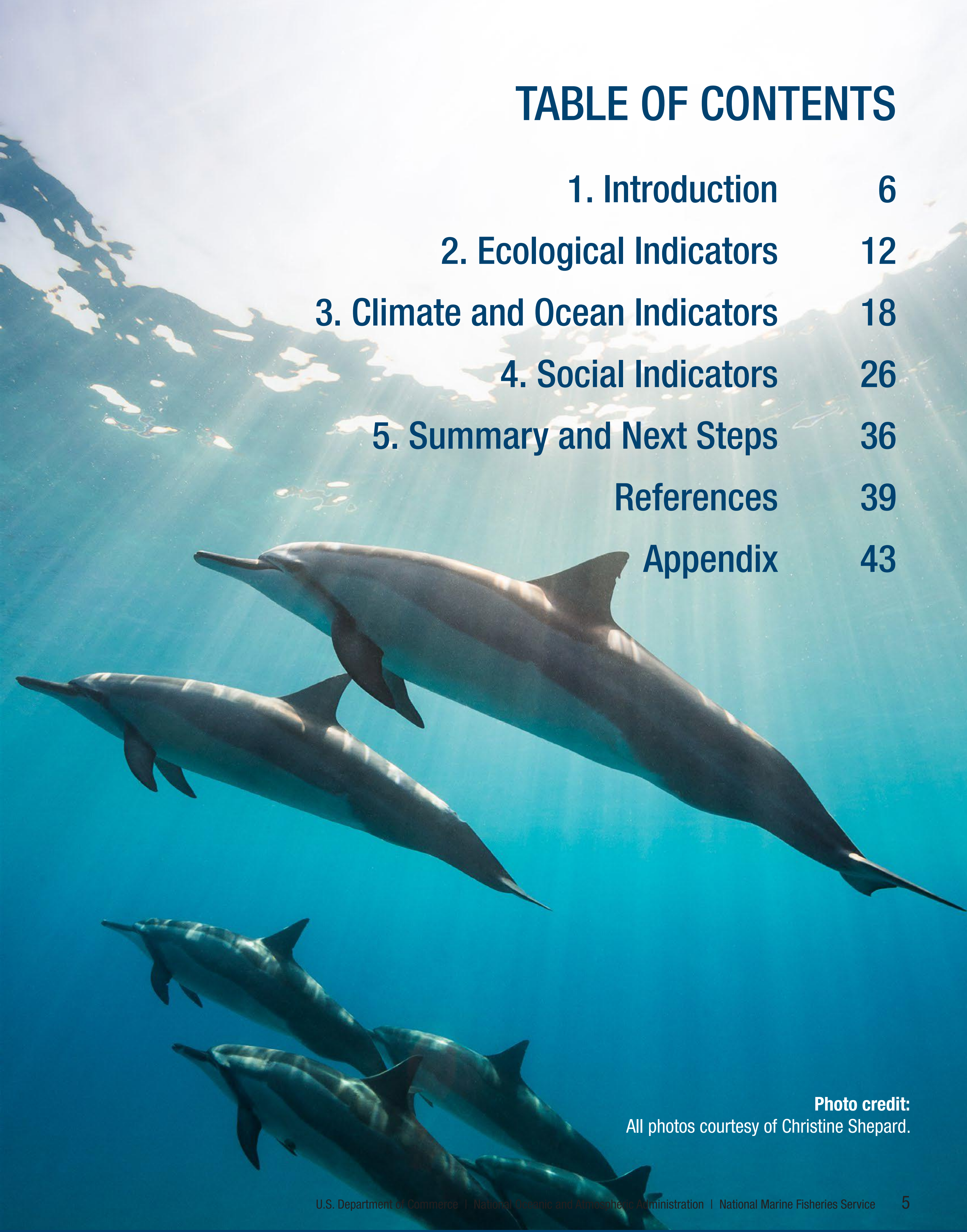
Alongside visitor growth, the resident population has steadily risen through time, increasing by over 3-fold since the 1970s. Approximately 45% of the Big Island’s population currently lives in West Hawai‘i. Over 25% of the resident population live one mile or less from the coast, and over 80% live within 5 miles.

With steadily increasing visitor arrivals and an increasing coastal resident population, the corresponding pressures of human activities, such as habitat degradation, fishing pressure, coastal development, and pollution are also increasing. Human wastewater, for example, is principally disposed via on-site sewage disposal systems (OSDS) in West Hawai‘i. OSDS leach excess pollution and nutrients into groundwater that flows to the ocean, threatening human health and degrading marine ecosystem integrity. An estimated 680 million gallons of wastewater was released into West Hawai‘i’s coastal environment in 2017. The highest concentrations of OSDS (>800 OSDS/km^2) are located in the vicinity of Kailua-Kona, where 125 million gallons of wastewater and 87,500 pounds of nitrogen enter nearshore waters each year.

In addition to pressures from local human activities, variations in the physical environment are also driving changes to marine ecosystem structure and function in West Hawai‘i. Ocean temperature, an indicator of regional and climatic forcing that is influential on numerous marine ecological processes, has been anomalously warm in recent years. The warmest year on record, 2015, resulted in widespread and severe coral bleaching in West Hawai‘i. Approximately 50% of coral cover in the region was lost due to the warm temperature anomaly. Owing to climate change, ocean temperatures are projected to substantially increase by the middle of the century resulting in a 1°C (1.8°F) warming in monthly ocean temperatures compared to present-day. Importantly, projected ocean warming will cause severe coral bleaching similar to that experienced in 2015 on an annual basis by 2040 in West Hawai‘i.

The marine ecosystem in West Hawai‘i is critically important to resident well-being and the economy vitality of the region. The ecosystem indicators presented herein provide a means for tracking ecosystem status and help evaluate the efficacy of existing marine management. This interdisciplinary report is intended to provide key insights and important context on the social-ecological system in West Hawai‘i and support ecosystem-based management of this highly productive and biologically diverse system.





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1. INTRODUCTION

West Hawaiʻi is home to a dynamic and productive marine ecosystem. Economic and socio-cultural value is provided to residents through numerous ecosystem services, such as commercial and non-commercial fishing, cultural and traditional practices, recreation, tourism, and coastal protection. However, ecological communities across West Hawaiʻi—particularly, coral reefs—have suffered recent and unprecedented declines. Marine ecosystem degradation can compromise underlying ecosystem functions and processes and undermine the numerous goods, services, and benefits upon which local communities depend.

This report summarizes a suite of ecosystem indicators that track the status of the region's marine ecosystem and help assess the efficacy of management's decision-making in West Hawaiʻi. In total, 30 indicators are presented that include climatic and oceanic drivers of ecosystem change, the states of ecological communities, and the activities and relationships of people with marine resources in West Hawaiʻi (Table 1). Ecosystem indicators were identified through a collaborative and participatory process led by the West Hawaiʻi Integrated Ecosystem Assessment (https://www.integratedecosystemassessment.noaa.gov), a NOAA program dedicated to providing robust scientific information that meets current and future marine management needs in the region.

EXISTING MARINE MANAGEMENT IN WEST HAWAIʻI

The State of Hawaiʻi Division of Aquatic Resources holds legal authority to manage West Hawaiʻi's nearshore marine environment (≤3 nautical miles from shore). In 1998, the Hawaiʻi State Legislature passed Act 306, which established the West Hawaiʻi Regional Fishery Management Area (WHRFMA). The WHRFMA was created largely in response to public concerns regarding an expanding and unregulated aquarium fishery. The overarching purposes of the WHRFMA were three-fold:

1. Effectively manage fishery activities to ensure sustainability.
2. Enhance nearshore resources.
3. Minimize conflicts of use.

In 2000, the WHRFMA designated multiple marine managed areas encompassing approximately 35% of the coastal waters in West Hawaiʻi (Rossiter and Levine 2014; Tissot et al. 2004). These managed areas were designated as fish replenishment areas (FRAs), where aquarium fish collecting was prohibited. The geographical boundaries of the restricted areas were selected using biological data and local community input (Rossiter and Levine 2014, Tissot et al. 2009). Current marine management areas encompass a range of spatial extents and various levels of fishing restrictions (Figure 1.1).

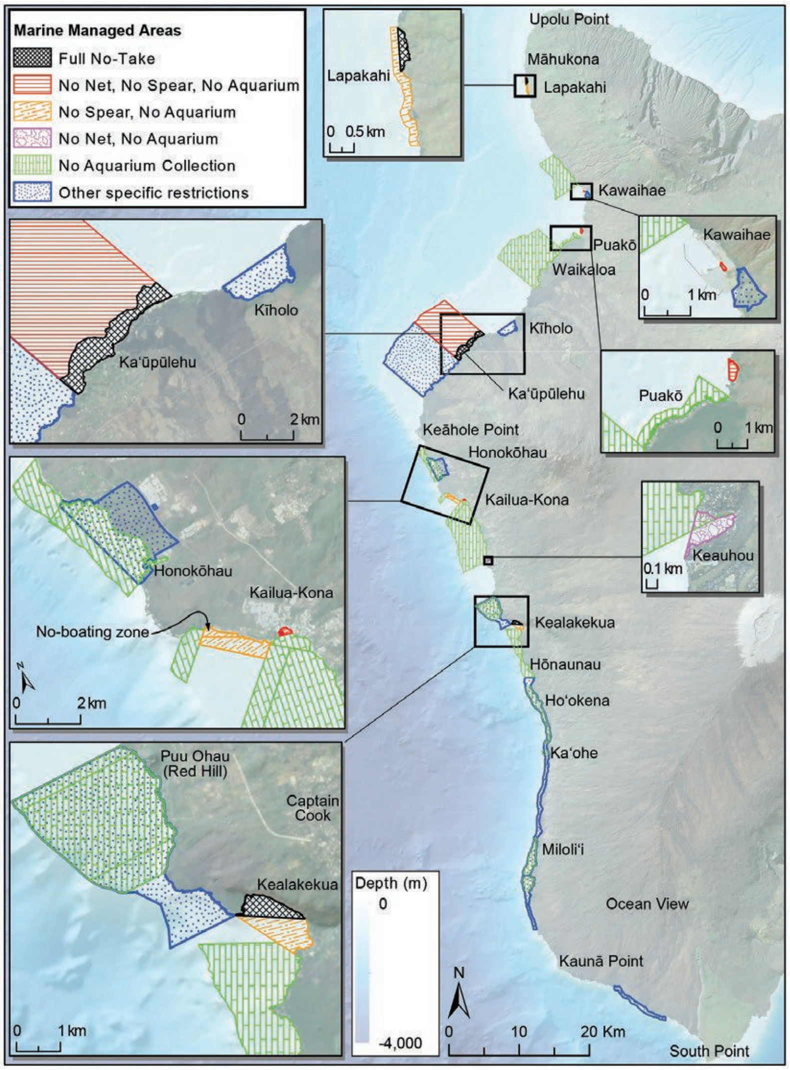


Figure 1.1. Map of West Hawaiʻi highlighting current marine managed areas (MMAs). The categories shown on the map indicate the regulations for each MMA (with respect to reef fish only) which explicitly prohibit three broad gear categories (line, net, and spear) and aquarium collection. MMAs designated as "other specific restrictions" can include species-specific take limits or gear-specific restrictions that do not prohibit an entire gear category. All other categories displayed are not necessarily all encompassing within each MMA. For example, an MMA shown as prohibiting spearfishing may also restrict take of particular species, restrict the number of lines or hooks allowed per person, or prohibit lay netting but allow throw netting. The full no-take area at Ka'ūpūlehu went into effect in July 2016, as a 10-year no-take area. See Hawaiʻi DAR (http://dlnr.hawaii.gov/dar) for more information on marine management in West Hawaiʻi.

A key stipulation in Act 306 was the requirement of *substantive involvement of the community in resource management decisions*. The West Hawaiʻi Fishery Council (WHFC; *http://westhawaiifisherycouncil.org*) was convened in 1998 to facilitate this requirement. Comprised of various stakeholders, community members, and user groups, the WHFC provided the vehicle for the community to directly participate in the development of resource management actions. In addition to the development of the network of FRAs and other measures, the WHFC has supported and facilitated the implementation of several marine management rules in the region:

- The limitation of large-scale commercial lay netting while continuing to allow subsistence netting.
- Ka'ūpūlehu Marine Reserve, a community-based initiative prohibiting the take of nearshore marine life for 10 years.

- SCUBA spear fishing prohibition.
- Prohibition on the take of *Species of Special Concern*, which includes a variety of rays and sharks.

Table 1. Summary of indicators assessing the status of West Hawai'i's marine ecosystem. Indicators are divided into three broad categories—Ecological, Climate and Ocean, Social—based on the ecosystem pressure or ecosystem attribute they represent. Indicators were selected based on local stakeholder input and information in the peer-reviewed literature, as identified under "Justification."

ECOLOGICAL				
Pressure or Attribute	Indicator	Definition and Rationale	Justification	Time Presented
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)	2003–2017
	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)	2003–2017
	Mean Adult Fish Length	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.	(Ault et al. 2014, Guillemot et al. 2014, Nadon et al. 2015, Ingram et al. 2018)	2003–2017
	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)	2003–2017

Pressure or Attribute	Indicator	Definition and Rationale	Justification	Time Presented
Reef Fish Community Integrity	Herbivore Biomass	Herbivores (i.e., species for which plant material makes up a majority of their diet) are a key component of coral reef ecosystem resilience 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.	(Green & Bellwood 2009, Kittinger et al. 2015, Williams et al. 2015b)	2003–2017
	Juvenile Yellow Tang Abundance	Approximately 70% of the aquarium fish caught in the State are from West Hawai‘i with juvenile yellow tang (*Zebrasoma flavescens*) comprising approximately 82% of the total catch.	(Walsh et al. 2003, Williams et al. 2009, Walsh et al. 2013)	2003–2017
	Mean Adult Fish Length	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.	(Ault et al. 2014, Guillemot et al. 2014, Nadon et al. 2015, Ingram et al. 2018)	2003–2017
	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)	2003–2017
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, Ingram et al. 2018)	2003–2017
	Fleshy Algal Cover	The percent cover of fleshy algae (macroalgae + turf algae) serves as an indicator for benthic community organization and health. Fleshy algae can grow rapidly and potentially inhibit coral recruitment and growth, and reduce coral survival. Tracking the abundance of fleshy algal cover can also indicate other important processes occurring within coral reef ecosystems, including nutrient enrichment and herbivory intensity.	(McClanahan et al. 2002, Hughes et al. 2007, McClanahan et al. 2011)	2003–2017
	Ratio of Calcifying: Noncalcifying	The ratio of 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, Smith et al. 2016)	2003–2017

CLIMATE AND OCEAN				
Pressure or Attribute	Indicator	Definition and Rationale	Justification	Time Presented
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.	(Fletcher 2010, Ingram et al. 2018)	1990–2018
Precipitation	Rainfall and Standardized Precipitation Index	Changes in rainfall drive changes in ground water and surface water transport to the marine environment which impacts nearshore salinity, ocean temperature, suspended sediment, and nutrient concentrations. Monthly rainfall and the Standardized Precipitation Index (SPI) are provided to track the status of rainfall in West Hawaiʻi. The SPI is a standardized index that characterizes periods of drought or abnormal wetness that correspond with the availability of different water resources (e.g., groundwater and river discharge).	(Keyantash 2018), Kevin Kodoma of NWS Honolulu	1975–2018
Large-scale Climate Forcing	North Pacific Gyre Oscillation	The North Pacific Gyre Oscillation (NPGO) index is an indicator of the variation in the rotational speed of the North Pacific Subtropical Gyre. Ocean currents in the Subtropical Gyre transport waters from the northeast Pacific to the west and south, warming as they move to the subtropical Pacific and the vicinity of Hawaiʻi. A lower NPGO, or slower Subtropical Gyre, results in warmer SST, and vice versa.	(Walsh 1984, McClanahan et al. 2011, Ingram et al. 2018)	2003–2017
	ENSO (El Niño/La Niña)	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.	(McClanahan et al. 2002, Hughes et al. 2007, McClanahan et al. 2011)	2003–2017
	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–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).	(Cinner et al. 2013, Williams et al. 2013, Smith et al. 2016)	2003–2017

Pressure or Attribute	Indicator	Definition and Rationale	Justification	Time Presented
Ocean Temperature	Sea Surface Temperature	Sea surface temperature (SST) plays an important role in a number of ecological processes in West Hawai‘i and varies on diel to decadal time scales. Anomalously warm SST can lead to high levels of thermal stress for corals and other marine organisms.	(Ingram et al. 2018, Wedding et al. 2018)	1900–2018
Climate Change	Projections of Future Sea Surface Temperature	Climate change is warming SST across the world's oceans, driving an increase in storms and thermal stress events that are causing coral damage and mass bleaching events.	van Hooidonk et al. 2016)	2006–2100

SOCIAL				
Pressure or Attribute	Indicator	Definition and Rationale	Justification	Time Presented
Human Population	Population Growth	Human population growth can put pressure on the ecosystem through overuse, habitat degradation, and fishing pressure.	(Ingram et al. 2018)	1831–2018
	Number of Visitors and Visitor Spending	The total number of visitors serves as an indicator of tourism 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.	(Ingram et al. 2018)	1990–2016
Coastal Development	Impervious Surfaces	Coastal development paves over natural land, and the resulting impervious surfaces increase the rate of pollution runoff from streets and sidewalks into the nearby ocean.	(Ingram et al. 2018, Wedding et al. 2018)	1992–2017
Human Wastewater	Total Number, Total Effluent, and Total Nitrogen Flux from On-Site Sewage Disposal Systems (OSDS)	OSDS (e.g., cesspools and septic tanks) leach excess pollution and nutrients (e.g., nitrogen) into groundwater that flows to the ocean. This runoff from land can result in harmful algal blooms, fish kills, and potential disease threats to humans. We have included the current spatial distribution and historical time series of 3 indicators of OSDS: Total Number, Total Effluent, and Total Nitrogen Flux.	(Smith et al. 1999, Anderson et al. 2002, Ingram et al. 2018, Wedding et al. 2018)	2000–2017

Pressure or Attribute	Indicator	Definition and Rationale	Justification	Time Presented
Fisheries	Total Non-Commercial Catch of Reef-Fish and Total Commercial Catch of Aquarium Fish, Reef-Fish, Coastal Pelagics, Bottom Fish, and Pelagics	West Hawai'i communities are deeply intertwined with nearshore fisheries due to their contributions to the local economy, food supply chain, and perpetuation of cultural customs and practices. In an effort to track fishing activities, we have included 6 indicators that encompass both commercial and non-commercial fisheries catch from West Hawai'i.	(Friedlander & DeMartini 2002, Friedlander et al. 2014, Kittinger et al. 2015, Ingram et al. 2018, Wedding et al. 2018)	2003–2017
Fisheries	Commercial Fisheries: Annual Revenue and Fisher Engagement	Fisheries represent an important contribution to the livelihoods of local residents and the economy in West Hawai'i. We report the annual financial revenue generated from commercial fisheries and the associated annual number of fishers engaged in the commercial fishing of pelagics, aquarium, bottomfish, coastal pelagic, and reef fish in West Hawai'i.	(Kittinger et al. 2015, Grafeld et al. 2017, Teneva et al. 2018)	2003–2016

2. ECOLOGICAL INDICATORS

Coral reefs are highly productive and biologically diverse marine ecosystems. Nearly a quarter of reef-associated fish species found in Hawai'i occur nowhere else on the planet (Randall 2007). Coral reef ecosystems provide critically important services to local communities, such as coastal protection, food-resources, tourism, cultural practices, and fisheries (Knowlton 2001). Pressures from pollution, overfishing, invasive species, and climate change are negatively impacting reefs (Knowlton & Jackson 2008, Ingram et al. 2018) and undermining the economic, social, and cultural benefits provided to the local communities in West Hawai'i (Kittinger et al. 2012, Ingram et al. 2018).

Coral reef fish and benthic indicators are presented to help track the status of West Hawai'i's reef ecosystem. These data were collected as part of a long-term monitoring effort implemented by the Division of Aquatic Resources' West Hawai'i Aquarium Project (WHAP; Walsh et al. 2013). 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. All values presented are statistically significant ($p < 0.05$) unless stated otherwise.

REEF FISH

We present a combination of indicators that relay information regarding the coral reef ecosystem and fishery status. The indicators we selected 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 – Fish density is a major factor determining the functional role and influence of reef fishes. 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).

The total abundance of nearshore fishes has shown a positive trend in all management areas— MPAs, FRAs, and open areas—across West Hawai‘i since 2003 (Figure 2.1, Total Abundance). Total abundance has increased by 28.9%, 36.0%, and 34.9% in MPAs, FRAs, and open areas, respectively (Table 2.1). Total abundance of fishes differed based on management status. For example, the total abundance of fish in 2017 was greater in MPAs compared to FRAs and open areas by 61.4% and 34.8% (Table 2.2). An anomalous recruitment pulse was observed in 2014 across a number of locations in the state (Talbot 2014) and in West Hawai‘i (Walsh 2014). The recent increase in fish abundance observed across management areas may be attributed in part to high levels of recruitment in 2014.

Total Fish Biomass – Total fish biomass conveys related but slightly different information compared to total 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 function or importance 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).

Total fish biomass, which is the body weight of the entire reef-fish assemblage per unit area, has increased in FRAs by nearly 40% since 2003 (Figure 2.1, *Total Biomass*; Table 1). Total biomass showed no significant change in MPAs or open areas over the same time period (Table 1). The most recent survey indicated that total fish biomass in MPAs was nearly 80% higher compared to FRAs and twice the biomass in open areas (Table 2).

Adult Fish Mean Length – As fishing pressure increases, the average length of targeted species decreases (Ault et al. 2014, Nadon et al. 2015). This relationship exists because fishers 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).

Adult fish length, or the mean length (cm) of mature fishes

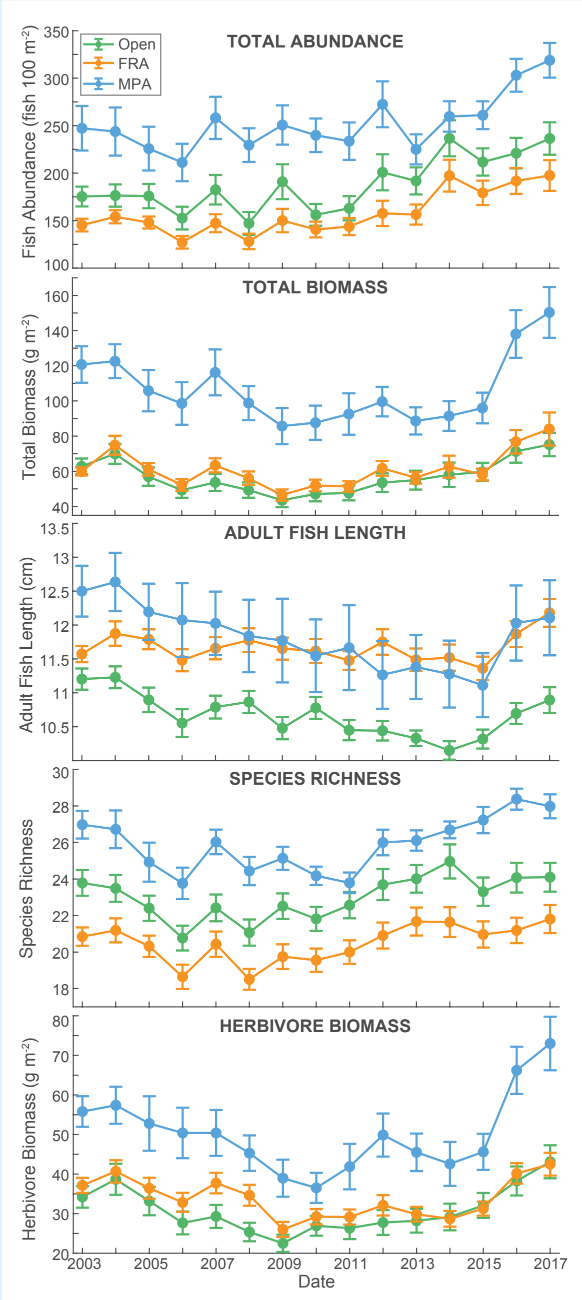


Figure 2.1. Reef fish indicators for West Hawai‘i include total fish abundance, fish biomass, adult fish length, species richness, and herbivore biomass. Indicators are grouped by management status (blue line = marine protected area (MPA); orange line = fish replenishment area (FRA); green line = open to fishing). Error bars represent ±1 standard error. Data Source: DAR’s West Hawai‘i Aquarium Project (WHAP).

(i.e., fishes reaching ≥40% of their maximum length), increased by 5.3% in FRAs with no significant change in MPAs or open areas since 2003 (Figure 2.1, *Adult Fish Length*; Table 2.1). In terms of management status, adult fish length in 2017 was approximately 11% greater in MPAs and FRAs compared to open areas (Table 2.2).

Table 2.1: Changes in mean reef fish and benthic coral reef community indicators by management status from 2003 to 2017. Indicators are grouped by management status (MPA, marine protected area; FRA, Fish Replenishment Area; Open, open to fishing). Bold values represent statistically significant differences ($p < 0.05$).

INDICATOR	MANAGEMENT STATUS	2003	2017	PERCENT CHANGE
Total Fish Abundance (number of fish/100 m²)	MPA FRA Open	247.26 145.30 175.35	318.82 197.54 236.46	+28.9% +36.0% +34.9%
Total Fish Biomass (g/m²)	MPA FRA Open	120.73 59.90 62.77	150.34 84.03 75.18	+24.5% +40.3% +19.8%
Mean Adult Fish Length (cm)	MPA FRA Open	12.50 11.57 11.20	12.11 12.18 10.89	-3.1% +5.3% -2.8%
Species Richness (number of species/survey)	MPA FRA Open	26.98 20.85 23.79	27.98 21.81 24.10	+3.7% +4.6% +1.3%
Herbivore Biomass (g/m²)	MPA FRA Open	55.81 37.15 34.22	73.01 42.50 43.11	+30.8% +14.4% +26.0%
Juvenile Yellow Tang (number of fish/100 m²)	MPA FRA Open	14.95 18.90 10.06	26.89 30.78 16.18	+79.8% +62.9% +60.8%
Coral Cover (%)	MPA FRA Open	35.29 40.96 33.76	16.77 17.30 17.31	-52.5% -57.8% -48.7%
Total Algal Cover (%)	MPA FRA Open	40.84 37.26 48.99	56.59 54.31 58.79	+36.5% +43.5% +18.6%
Calcifying:Non-Calcifying Ratio	MPA FRA Open	1.11 1.57 0.94	0.79 0.79 0.59	+36.5% +43.5% +18.6%

Table 2.2: Relative difference in reef fish and benthic coral reef community indicators by management status in 2017. Indicators are grouped by management status (MPA, marine protected area; FRA, fish replenishment area; Open, open to fishing). Bold values represent statistically significant differences ($\rho < 0.05$). See Table 2.1 for 2017 indicator values.

INDICATOR	2017 DIFFERENCE IN MANAGEMENT STATUS (%)		
	MPA – FRA	MPA – Open	FRA – Open
Total Abundance	+61.4	+34.8	-16.5
Total Biomass	+78.9	+100.0	+11.8
Adult Fish Length	-0.6	+11.1	+11.8
Species Richness	+28.3	+16.1	-1.4
Herbivore Biomass	+71.8	+69.3	-1.4
Juvenile yellow tang	-12.7	+66.2	+90.2
Coral Cover	-3.1	-3.2	0.0
Total Algal Cover	+4.4	-3.9	-7.9
Calcifying: Non-Calcifying Ratio	0.2	34.6	34.4

Species Richness – Coral reefs are renowned for being one of the most diverse and complex ecosystems on the planet, providing 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).

Species richness, or the total number of species present per survey, has not changed within each management area over the last 15 years (Figure 2.1, *Species Richness*; Table 2.1). As with other fish indicators, species richness in 2017 was greatest in MPAs compared to FRAs and open areas (Table 2.2). Note: visual surveys of reef fishes do not capture all species present in an area; therefore, the data here are considered a relative measure of species richness, which is one measure of biological diversity.

Herbivore Biomass – Herbivores (i.e., species for which plant material makes up a majority of their diet) comprise a large part of the fish community assemblage in Hawai‘i (Williams et al. 2015b). Herbivorous fishes are a key component and indicator of resilience. Resilience is defined as 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 anthropogenic drivers operating at various scales can undermine coral reef resilience, such as over-extraction of herbivores, pollution, and climate change. Of these, the diminished abundance of functionally important herbivores is one of the few drivers that is possible to ameliorate through local action.

Herbivore biomass, which represents the total weight of herbivorous fishes per unit area, increased by 30.8% in MPAs from 2003 to 2017 (Figure 2.1, *Herbivore Biomass*; Table 2.1). FRAs and open areas have shown no change in herbivore biomass over the same time period. Herbivore biomass was approximately 70% greater in MPAs over FRAs and open areas in the most recent survey (Table 2.2). Of note, herbivores in West Hawaiʻi constitute roughly half of the total biomass in each of the management areas.

Juvenile yellow tang – The yellow tang is important to the West Hawaiʻi aquarium industry as it is the primary species collected (Walsh et al. 2003). In fact, the majority of the aquarium trade sources fish from West Hawaiʻi; approximately 70–80% of the fish caught in the state are from West Hawaiʻi with juvenile yellow tang comprising ~82% of the total catch (Walsh et al. 2013). Therefore, the status of this fish around West Hawaiʻi is of high relevance for fisheries management. Observed declines in reef fishes due to the aquarium trade triggered the establishment of FRAs and associated monitoring surveys in West Hawaiʻi 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 have proven over time to be highly effective in increasing the density of these long-lived species. Collectors target young juveniles, and as such, we report juvenile yellow tang abundance here.

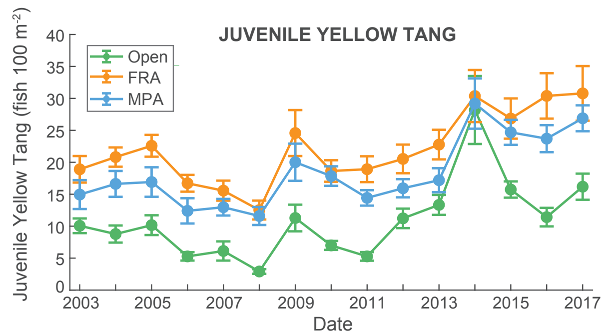


Figure 2.2 Reef fish indicator juvenile yellow tang abundance grouped by management status (blue line = marine protected area (MPA); orange line = fish replenishment area (FRA); green line = open to fishing). Error bars represent ±1 standard error. Data Source: DAR's West Hawaiʻi Aquarium Project (WHAP).

From 2003 to 2017, the abundance of juvenile yellow tang increased by 79.8%, 62.9%, and 60.8% in MPAs, FRAs, and open areas, respectively (Figure 2.2; Table 2.1). In 2017, MPAs and FRAs had 60.2% and 90.2% more juvenile yellow tang than in open areas (Table 2.1). The most recent survey indicated that MPAs and FRAs had 60.2% and 90.2% more juvenile yellow tang than in open areas (Table 2.2).

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 several reef fishes (Mumby et al. 2006). In the absence of local human pressures, calcifying organisms tend to dominate coral reef benthic 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, faster growing algal species (Pandolfi et al. 2005). Monitoring changes in benthic community organization is, therefore, critical to understanding coral reef community succession and responses to various environmental and human-related pressures. We present a few key indicators that 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). Many reef-fish species are also heavily reliant on the availability of coral-dominated, structurally-complex areas, serving as the preferred habitat for fish recruitment and fish in juvenile stages (Walsh 1984).

The total cover of hard coral across West Hawaiʻi was approximately 18% in 2017, representing a relative change of

-52.5%, -57.8%, and -48.7% in MPAs, FRAs, and open areas since 2003, respectively (Figure 2.3, *Hard Coral Cover*; Table 2.1). Much of the coral loss can be attributed to a thermal stress event in 2015, when up to 90% of corals bleached across West Hawaiʻi (Kramer et al. 2016 - see Section 3 for more detail on the thermal stress event). It is important to note that coral cover was as high as 80% in specific locations (e.g., Puakō) in the 1970s, indicating dramatic losses in coral cover in at least some locations over the past 40–50 years (Minton et al. 2012).

Total Algal Cover – Fleshy (i.e., non-calcifying) algae are part of a healthy reef community, providing food for a variety of herbivorous fishes and invertebrates. However, fleshy algae can grow rapidly and compete with hard corals for reef space, inhibit coral recruitment, and reduce coral survival (Hughes et al. 2007). Tracking the abundance of macroalgae and turf algae (i.e., total algal cover) serves as an indicator of benthic community organization, intensity of herbivory, and local pressures, such as nutrient enrichment (McClanahan et al. 2002).

Fleshy algal cover has increased across West Hawaiʻi since 2003; however, FRAs are the only management area that exhibited a significant increase (Figure 2.3, *Total Algal Cover*; Table 2.1). In the most recent survey, fleshy algal cover was approximately 55%, with no significant difference in cover between MPAs, FRAs, and open areas (Table 2.2). Changes in algal cover across West Hawaiʻi are predominantly due to changes in turf algae, as West Hawaiʻi has very low (<2%) macroalgae percent cover (Walsh 2014, Williams et al. 2015b)

Calcified to Non-calcified Ratio – Foundational benthic organisms that contribute to coral reef development and persistence are calcifying, serving a number of key ecological processes, including settlement, recruitment, and cementation of reef structure (Williams et al. 2015a). Fleshy algae directly compete with calcifying organisms for space, and in high abundance, can indicate a degraded ecological state (Hughes et al. 2010). The ratio of the combined cover of reef-building hard corals (Scleractinian) and calcifying algae (crustose coralline algae and Halimeda) to the combined cover of fleshy algae indicates benthic community dynamics and the extent to which a given system is dominated by reef-accreting benthic organisms.

In 2017, the ratio of calcified to non-calcified cover across West Hawaiʻi was ≤1 (Figure 2.3, *Calcified to Non-calcified Ratio*). This threshold represents a relative dominance of non-calcifying benthic organisms. The relative dominance of reef builders to maintain net accretion is likely reef specific 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).

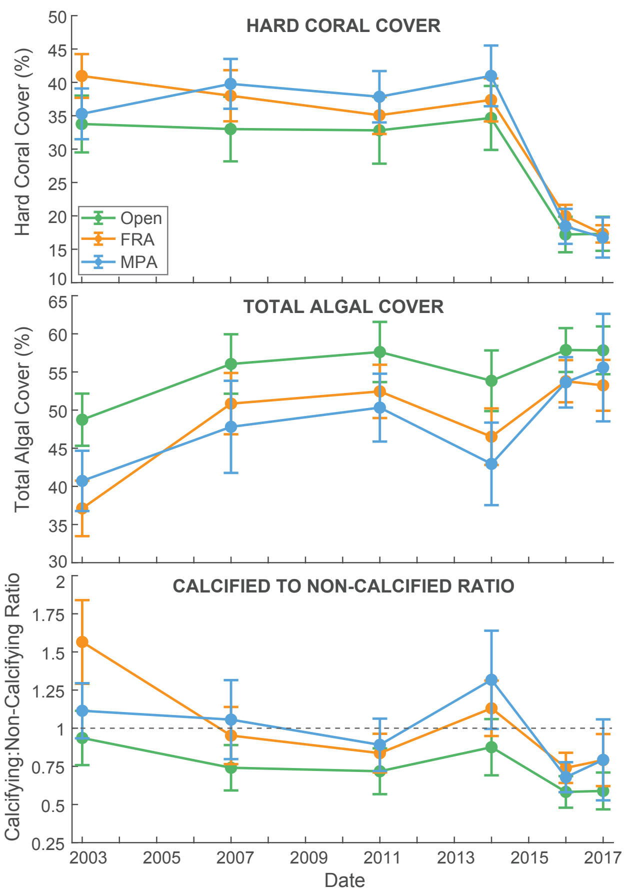


Figure 2.3. Coral reef benthic community indicators for West Hawaiʻi include hard coral cover, total algal cover, calcified to non-calcified ratio. Indicators are grouped by management status (blue line = marine protected area (MPA); orange line = fish replenishment area (FRA); green line = open to fishing). Error bars represent ±1 standard error. Data Source: DAR's West Hawaiʻi Aquarium Project (WHAP).

3. CLIMATE AND OCEAN INDICATORS

Large-scale climate patterns shape the physical environment of marine organisms, influencing feeding, migration, and reproductive success. Significant climatological changes, including increased sea surface temperature, sea level rise, decreased ocean pH, and shifting storm patterns are 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. Climate and oceanographic indicators are presented here to help track and predict changes in the natural environment of West Hawaiʻi's marine ecosystem.

Sea Level – Long-term sea level rise can lead to chronic coastal erosion, coastal flooding, and drainage problems. Long-term sea level rise also exacerbates short-term fluctuations in coastal sea level driven by waves, storms, and extreme tides. Tracking the status and trends in sea level is critically important for coastal planning and management of nearshore marine ecosystems.

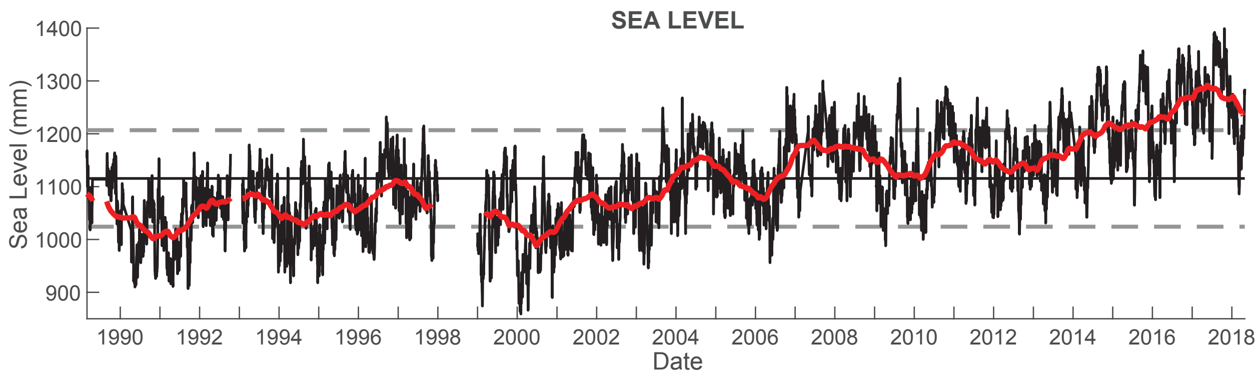


Figure 3.1. Daily sea level data from Kawaihae Harbor from 1990 to 2018 (black line). Red line represents a 12-month moving average. Horizontal lines represent the long-term mean (1990-2018; solid line) and ±1 standard deviation (dashed line). Data source: University of Hawaiʻi Sea Level Center.

Long-term sea level measurements (1990–2018) from Kawaihae indicate a clear positive trend (Figure 3.1), increasing by 0.27 m (0.89 ft) in the past 28 years. Over the next 30 to 70 years, properties, infrastructure, and critical habitat located on or near the West Hawaiʻi's shorelines will increasingly be flooded, eroded, or completely lost to the sea. Example areas that will be exposed to chronic flooding include Kaʻūpūlehu, Kawaihae, and South Point. Portions of the Hualālai Resort in Kaʻūpūlehu, an economically important tourist destination in North Kona, would be permanently flooded with 1 m (3.3 ft) of sea level rise, which is expected by the end of this century (Hawaiʻi Climate Change Mitigation and Adaptations Commission, 2017). As sea level continues to rise, low-lying, populated coastal communities, such as Puakō would experience increased frequency and extent of flooding. Beaches, such as those between Kailua-Kona and Kawaihae, will increasingly be eroded and permanently lost. Native Hawaiian cultural and historical resources, many of which are located near the shoreline, will also be severely threatened and potentially lost with continued sea level rise. For more detailed information on the potential impacts of sea level rise in Hawaiʻi, please see the Hawaiʻi Climate Change Mitigation and Adaptations Commission's Report 2017 (*https://climateadaptation.hawaii.gov/wp-content/uploads/2017/12/SLR-Report_Dec2017.pdf*).

Rainfall – The Hawaiian Islands have one of the most diverse rainfall patterns on Earth. 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).

Rainfall patterns in West Hawaiʻi are somewhat unique for the Hawaiian Islands. Rainfall is principally driven by well-developed and reliable land and sea breezes 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.

Changes in rainfall will influence groundwater and surface water transport to the marine environment, which can impact nearshore salinity and temperature, as well as suspended sediment and nutrient concentrations.

Monthly rainfall and the monthly Standardized Precipitation Index (SPI) are shown from 1975 to 2018 from three locations in West Hawaiʻi: Waikoloa, Opihihale (Captain Cook), and Hōnaunau (Figure 3.2). The monthly SPI was developed by the National Center for Atmospheric Research (NCAR) and represents a standardized approach to calculate monthly rainfall, facilitating the comparison of rainfall anomalies from separate regions with differing climates (Keyantash 2018). In short, SPI standardizes rainfall at a given location and can be interpreted as the number of standard deviations by which the observed anomaly deviates from the long-term mean. SPI values of 1, 1.5, and 2

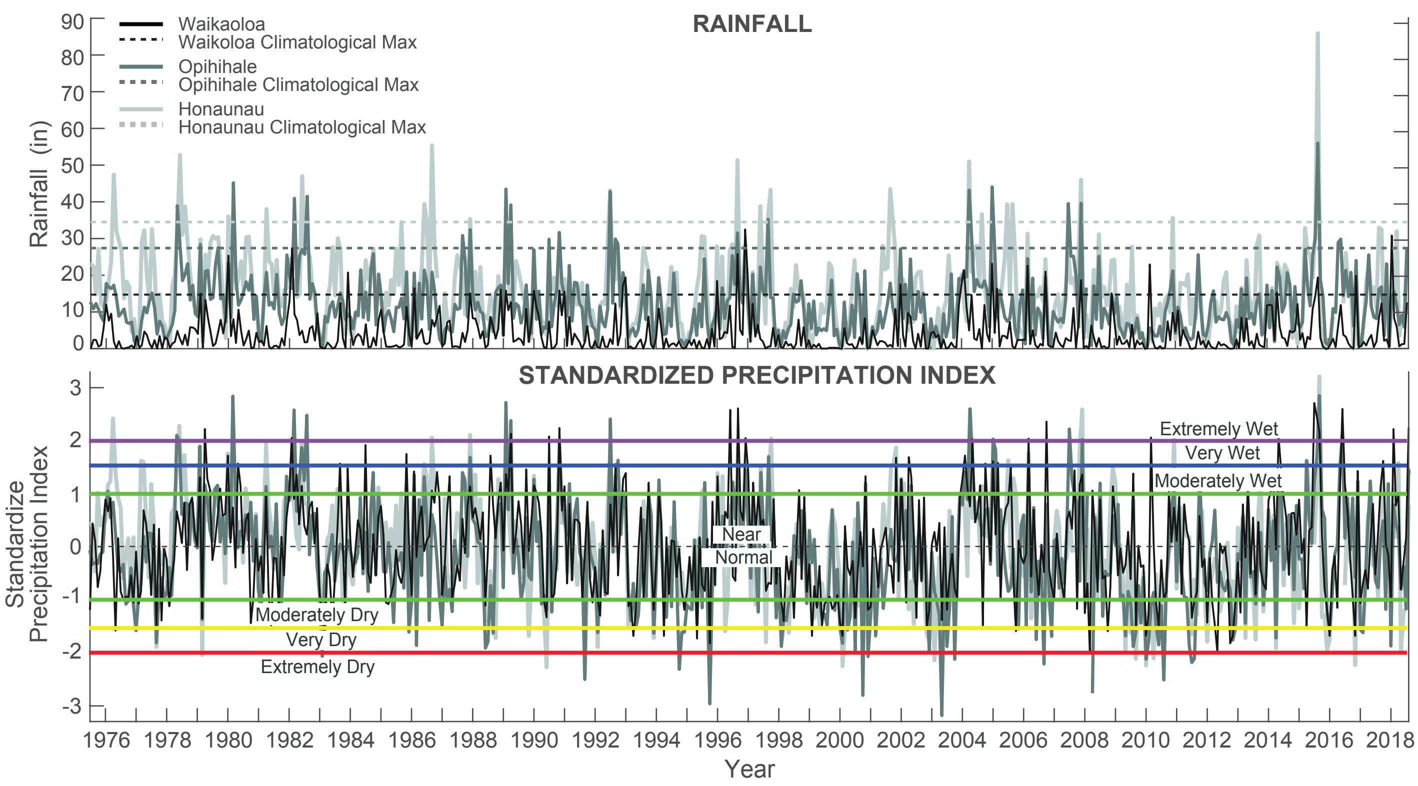


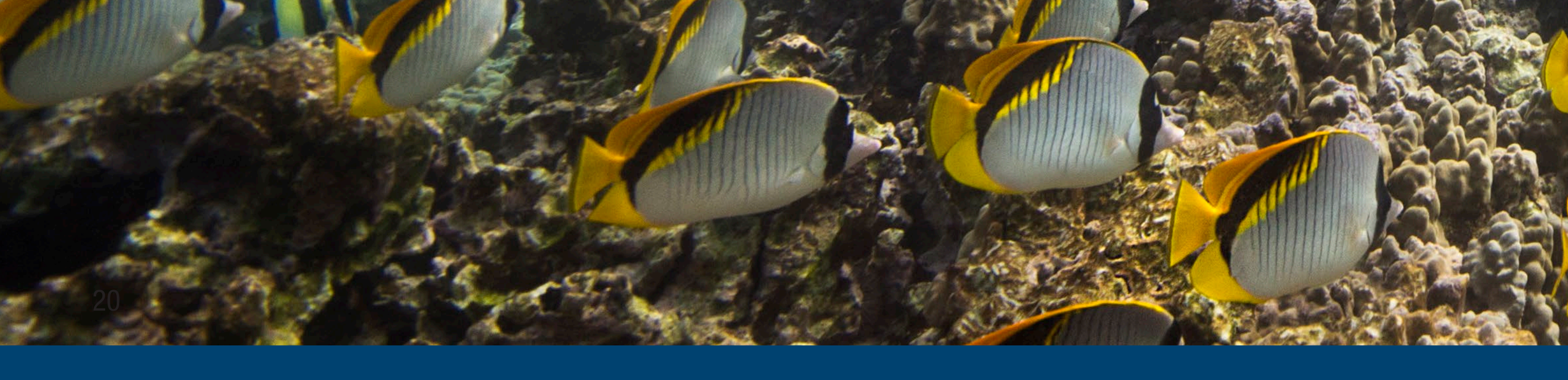
Figure 3.2. Monthly rainfall (inches solid line) and climatological monthly maximum (dashed line) from 1975 to 2018 at three locations in West Hawaiʻi: Waikoloa (black line), Opihihale (dark gray line), and Honaunau (light gray line) (top). Monthly Standardized Precipitation Index (SPI) for the same locations (in the same colors) as shown in *Rainfall* (bottom). The monthly SPI represents a standardized approach to calculate monthly rainfall, facilitating the comparison of rainfall anomalies from separate regions with differing climates (Keyantash 2018). In short, SPI standardizes rainfall at a given location, interpreted as the number of standard deviations by which the observed anomaly deviates from the long-term mean. The SPI provides the ability to assess rainfall patters as near normal (0, dashed line), extremely wet (2 standard deviations above the mean, purple line), very wet (1.5 standard deviations above the mean, blue line), moderately wet (1 standard deviation above the mean, green line), moderately dry (1 standard deviation below the mean green line), very dry (1.5 standard deviations below the mean, yellow line) and extremely dry (2 standard deviations below the mean, red line). For more information visit: *https://climatedataguide.ucar.edu/climate-data/standardized-precipitation-index-spi*. Data Source: Kevin Kodama, NOAA National Weather Service, Honolulu Forecast Office.

above/below zero represent rainfall conditions categorized as moderately wet/moderately dry, very wet/very dry, and extremely wet/extremely dry. More information on SPI is provided by NCAR (*https://climatedataguide.ucar.edu/climate-data/standardized-precipitation-index-spi*) and by NOAA's National Weather Service, Honolulu Forecast Office (*http://www.prh.noaa.gov/hnl/hydro/pages/spi_web_page.php*).

Waikoloa, Opihihale, and Hōnaunau have experienced progressively increased rainfall, with climatological monthly maximum rainfall values of 14.7 in (374 mm), 27.4 in (696 mm), and 34.5 in (876 mm), respectively (Figure 3.2, *Rainfall*). The highest rainfall event over the 42-year time series was at Hōnaunau in September 2015, when 86 in (2,183 mm) of rain was recorded in a single month. SPI values from each of the three locations show periods of *very wet* (e.g., 1980, 1989, 1997) and *very dry* (e.g., 1995, 2003 2010) conditions (Figure 3.2, *SPI*). The overarching trend over the 42 years has been a shift towards dryer conditions. The total number of months that exceeded the *very dry* threshold (-1.5) at Waikoloa, Opihihale, and Hōnaunau was 2.6, 2.3, and 1.9 times higher during the most recent 20-year time period (1997–2016) compared to the previous 20 years (1976–1996). Conversely, the two time periods were nearly similar (between 80 and 100%) with respect to the number of months that exceeded the *very wet* threshold (1.5).

Sea Surface Temperature –Surface ocean temperatures in Hawai‘i can vary over a broad range of temporal scales owing to the oceanic setting and geographic location in the central-northern Pacific. Diel, intra-seasonal (e.g., mesoscale eddies), seasonal, interannual (e.g., ENSO), and decadal (e.g., PDO) forcing, as well as fluctuations in the rotational speed of the subtropical gyre all influence ocean temperatures in the main Hawaiian Islands.

Seasonal and interannual variability are readily discernible in ocean temperatures dating back to 1900 (Figure 3.3). Seasonally, ocean temperatures are coolest in March (24.8°C; 76.6°F) and warmest in September (27°C; 80.6°F). This seasonal cycle can be shifted, accentuated, or dampened over longer time scales owing to large-scale ocean-atmosphere climate phenomena. Ocean temperature in 2015 clearly stands out as the warmest on record in Hawai‘i due to the confluence of local conditions and large-scale processes. We provide a generalized description of this anomalously warm year in the following section.



WHY WAS 2015 SO HOT IN HAWAI‘I?

Sea surface temperature (SST) in the main Hawaiian Islands reached the highest recorded monthly temperature in well over a century (Figure 3.3). Temperatures in West Hawai‘i were even warmer, reaching 30.3°C (86.5°F) in September of 2015 (Gove et al. 2016). These anomalously warm and prolonged ocean conditions wreaked havoc on coral reefs in West Hawai‘i, causing upwards of 90% of coral bleaching and an overall relative loss of approximately 50% of coral cover across West Hawai‘i (Kramer et al. 2016).

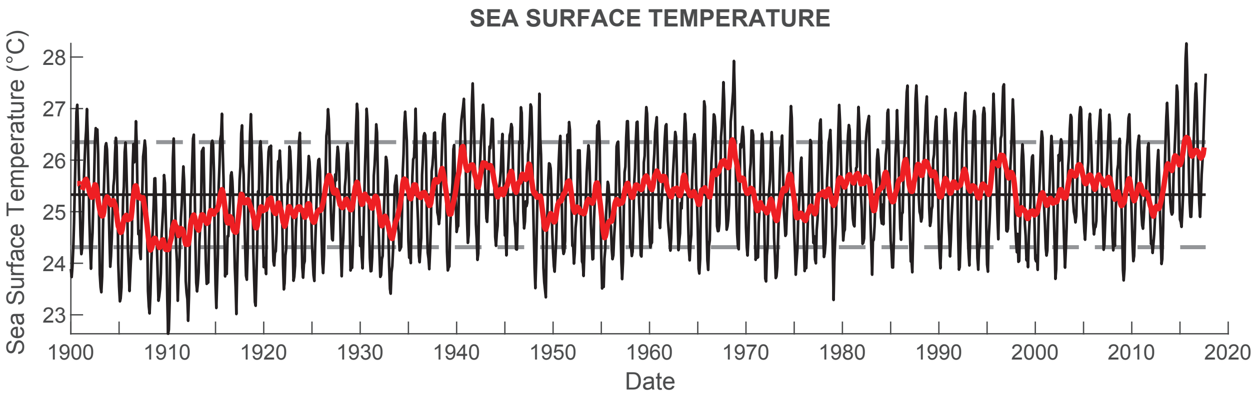


Figure 3.3. Weekly sea surface temperature for the main Hawaiian Islands from 1900–2018 (black line). Red line represents a 12-month moving average. Horizontal lines represent the long-term mean (1900–2018; solid line) and ±1 standard deviation (dashed line). Data Sources: Sea surface temperature, NOAA's Extended Reconstructed Sea Surface Temperature, version 4 (*https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v4*).

Although the dynamics governing ocean temperatures can be complex, it appears that the combination of local conditions and large-scale climate processes superimposed to produce the extremely warm temperatures observed in Hawai‘i in the summer of 2015. Here, we provide a descriptive and generalized explanation of this anomaly.

One source of variation in ocean temperatures is driven by the speed of the Subtropical Gyre, a ring-link system of ocean currents rotating clockwise across the North Pacific (Figure 3.4). Ocean currents in the Subtropical Gyre transport cooler waters from the northeast Pacific to the west and south, warming as it moves to the subtropical Pacific and the vicinity of Hawai'i. Similarly, warm water from the western subtropical Pacific is transported towards Japan, cooling as it moves northward. When the rotational speed of ocean currents in the Subtropical Gyre is accelerated, cool waters from the northeast take less time to reach Hawai'i, arriving cooler than normal, while the warm water in the western Pacific arrives warmer when it reaches Japan (Figure 3.4, *Fast Gyre*). Conversely, when the rotational speed of ocean currents in the Subtropical Gyre are slowed, cool waters from the northeast take more time to reach Hawai'i and, therefore, arrive warmer than normal (Figure 3.4, *Slow Gyre*).

The North Pacific Gyre Oscillation (NPGO) is an indicator of the variation in the rotational speed of ocean currents in the Subtropical Gyre (Di Lorenzo et al. 2008). When comparing the NPGO and sea surface temperature in Hawai'i, there is clearly a negative correlation—warmer SST is coincident with a lower NPGO, or slower Subtropical Gyre, and vice versa (Figure 3.4, *Sea Surface Temperature vs. North Pacific Gyre Oscillation*). The NPGO captures much of the decadal variation in SST around Hawai'i, including the warm temperatures observed in 2015. However, while September 2015 represented a decadal peak in SST, the NPGO alone was not sufficient to result in such anomalously warm ocean temperatures.

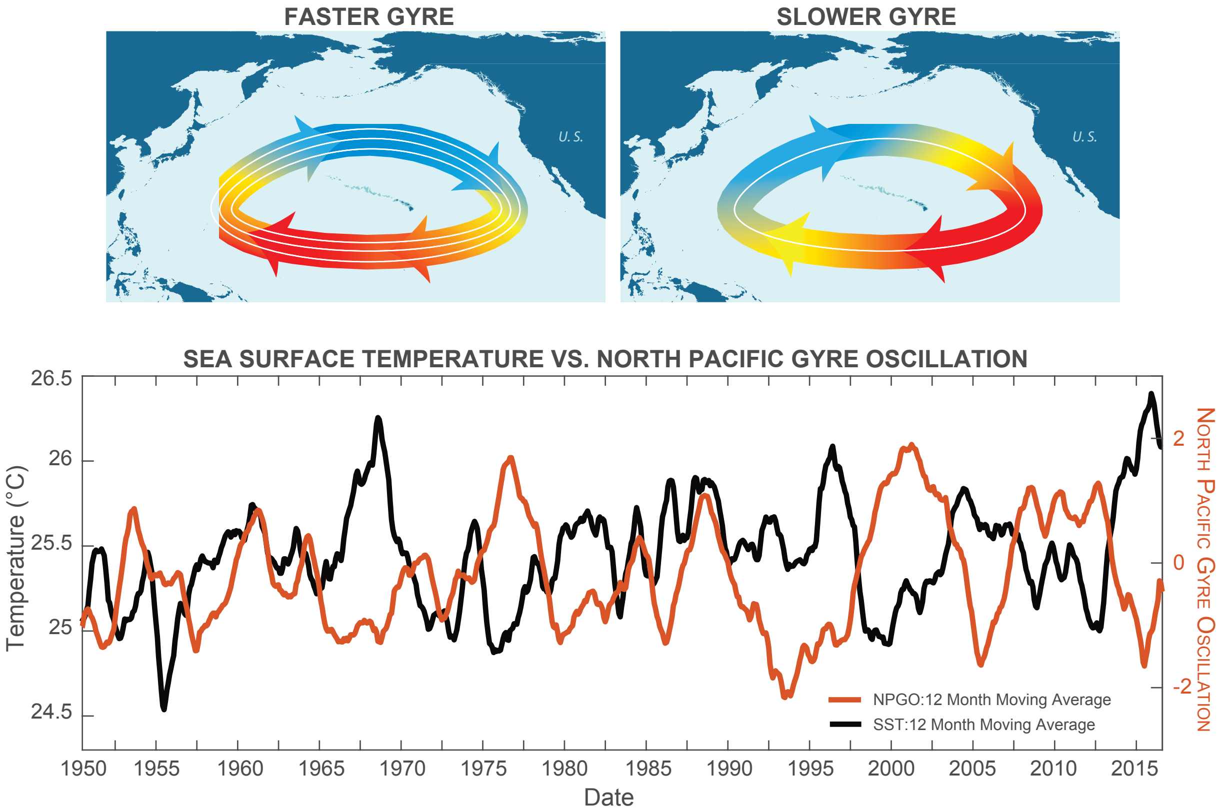


Figure 3.4. Graphical representation of the North Pacific Subtropical Gyre, with faster (top left) and slower (top right) gyre rotations and corresponding differences in Pacific-wide sea surface temperature (top) with color gradient from blue (cold) to red (hot) (top). Twelve-month moving average of sea surface temperature for the main Hawaiian Islands (black line) and the North Pacific Gyre Oscillation (NPGO; orange line) from 1950 to 2016 (bottom). Negative NPGO values indicate a slower rotation of the Subtropical Gyre, resulting in warmer ocean temperatures. Data Sources: Sea surface temperature, NOAA's Extended Reconstructed Sea Surface Temperature, version 4 (*https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v4*); NPGO index, Di Lorenzo et al. (2008). Link: *http://www.oces.us/npgo*.

In addition to the rotational speed of the Subtropical Gyre, two other broad-scale climate processes can drive variation in ocean temperatures around Hawai‘i. The first is the El Niño Southern Oscillation (ENSO). ENSO is an irregular (3–7 years), 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 (Figure 3.5). 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 second major climatic driver of changes in ocean temperatures in Hawai‘i is the Pacific Decadal Oscillation (PDO). The PDO is often described as a long-lived ENSO-like pattern of Pacific climate variability. As seen with the better-known 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 either warm or cool, defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean (Figure 3.5).

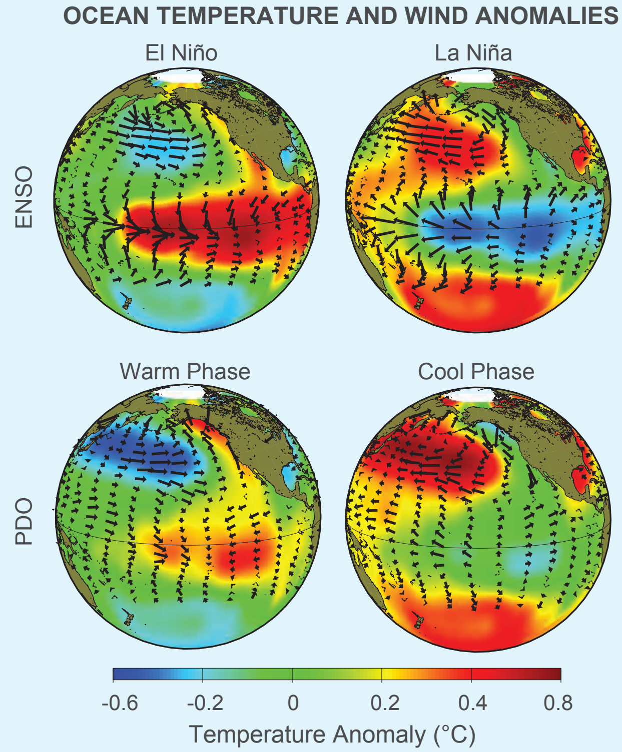


Figure 3.5. Typical sea surface temperature anomalies (color) and wind anomalies (black arrows) experienced during El Niño and La Niña (top left) and Warm and Cool Phases of the Pacific Decadal Oscillation (PDO, bottom left) across the Pacific Ocean. Graphic obtained from *http://research.jisao.washington.edu/pdo/graphics.html* and presented here with permission.

In 2015, there was both a powerful El Niño and a warm phase of the PDO (Figure 3.6, *ENSO & PDO Time Series*), resulting in higher local ocean temperatures than either alone would typically produce. In 2014 and 2015, the equatorial and mid-latitude connection between the El Niño and warm phase of the PDO is thought to have been especially strong, resulting in the largest marine heat wave (i.e., "The Blob") ever recorded in the Northeast Pacific that caused enhanced ocean warming across the Hawaiian Islands (Di Lorenzo & Mantua 2016).

On a local scale, variations in wind conditions likely exacerbated the warming induced by the large-scale climate processes previously described. When winds are weaker than normal, they decrease the intensity of ocean mixing, which reduces the amount of deeper, cooler waters reaching the surface ocean, and results in increased warming. Throughout August and early September of 2015, wind speeds were weaker than average over 80% of the time (Figure 3.7). During this same period, reef-level (10 m; 33 ft) temperatures from Lapakahi, located 16 km (~10 miles) north of Kawaihae, increased by over 2.5°C (4.6°F) (Figure 3.7). At the peak of the warming event, local wind speeds were equal to or stronger than the long-term average for more than two weeks, helping to mix the upper surface and drive down ocean temperatures, ultimately contributing to the end of the 2015 thermal stress event.

Thus, the typical seasonal cycle, reduced wind conditions, and the combination of three major large-scale climate phenomena—NPGO, ENSO, PDO—all contributed to producing the highly anomalous warm ocean temperature around Hawaiʻi in September 2015.

Looking toward the future, ocean temperature in West Hawaiʻi is projected to steadily increase as a result of climate change (Figure 3.8). By the middle of the century, average monthly SST will be about 1°C (1.8°F) warmer than present-day, and for about 6 months of the year will be warmer than the present-day average September SST (27°C;

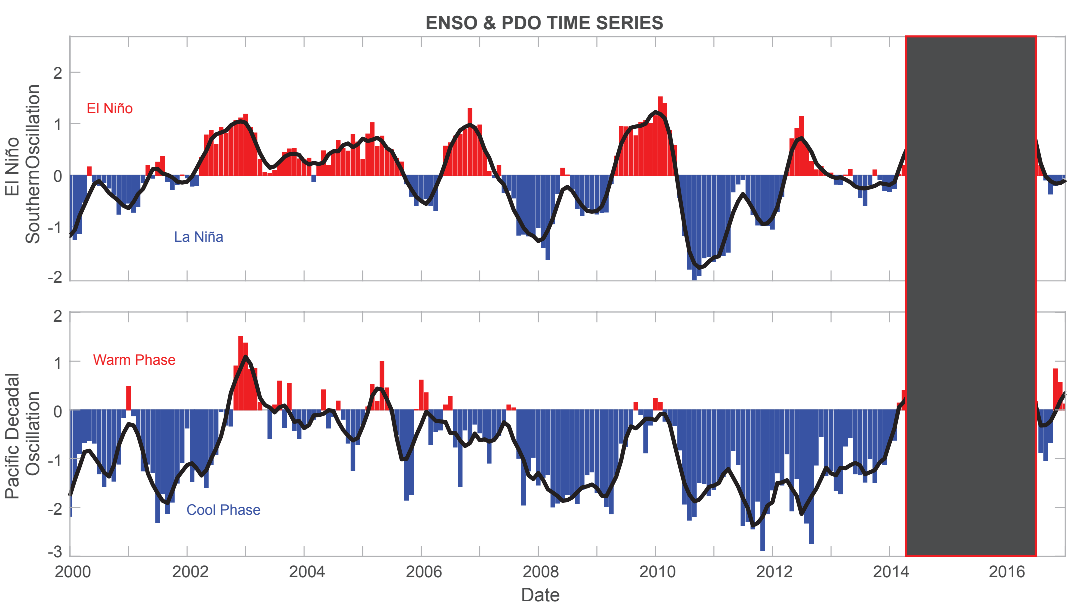


Figure 3.6: Indices representing the El Niño Southern Oscillation (ENSO), with El Niño and La Niña represented as red (positive) and blue (negative) values (top) and the Pacific Decadal Oscillation (PDO), with the warm phase and cool phase represented as red (positive) and blue (negative) values (bottom). The black line represents a 6-month moving average. The gray box is shown to highlight the relatively strong El Niño and warm phase in the PDO co-occurring in 2015. Data sources: Multivariate ENSO Index was obtained from NOAA's Earth System Research Laboratory (*https://www.esrl.noaa.gov/psd/enso/mei*). The PDO index was obtained from NOAA's Centers for Environmental Information (*https://www.ncdc.noaa.gov/teleconnections/pdo*).

80.6°F) (van Hooidonk et al. 2016). Further, it is likely the climate models used in these projections do not fully capture the large-scale climate variability—NGPO, ENSO, PDO—that influence SST and, therefore, may underestimate future ocean temperatures in West Hawai'i.

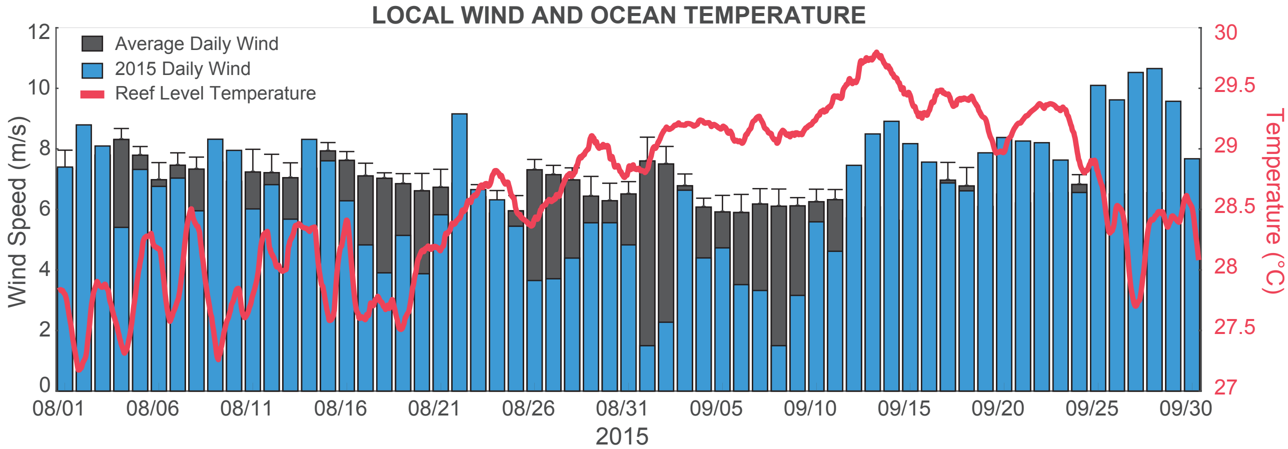


Figure 3.7. Local wind and ocean temperature observed during the 2015 thermal stress event (August–September, 2015) in West Hawai'i. Long-term (2009–2014) averaged daily wind speed (gray bars, error bars represent ±1 standard deviation), daily wind speed (blue bars), and reef-level temperature (10 m; 33 ft) at Lapakahi, located approximately 16 km (10 miles) north of Kawaihae (red line), are shown. Data Sources: Daily wind is from NOAA's ASCAT wind product, obtained from NOAA's Environmental Research Division Data Access Portal (*https://coastwatch.pfeg.noaa.gov/erddap/griddap/erdQAwind1day.html*); reef-level temperature is from NOAA's West Hawai'i IEA.

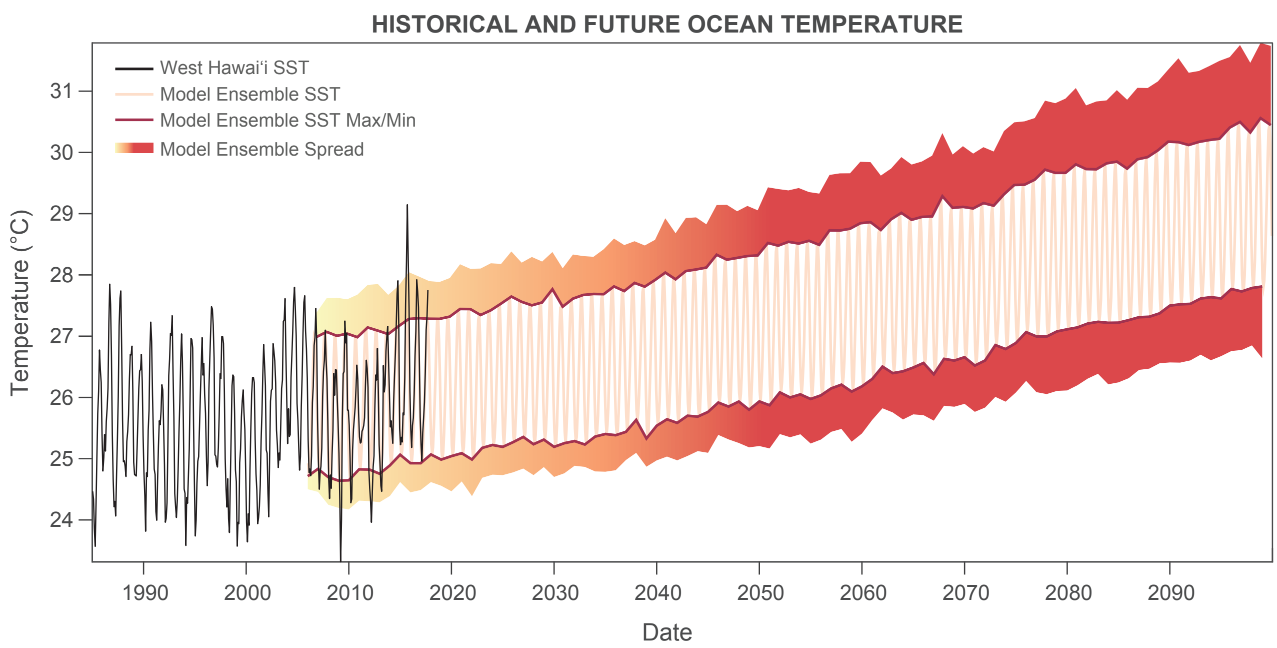


Figure 3.7. Historical and future projections of sea surface temperature for West Hawai'i. Sea surface temperature (black line) projected change in sea surface temperature (orange line) in West Hawai'i this century (from an ensemble of IPCC-approved climate models and based on business-as-usual emissions scenario RCP8.5). Data Sources: Sea surface temperature, NOAA's Ocean Watch (*http://oceanwatch.pifsc.noaa.gov*). Sea surface temperature projections are from van Hooidonk et al. (2016).

4. SOCIAL INDICATORS

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

Based on outcomes from stakeholder engagement (Ingram et al. 2018) and information from social-ecological work (e.g., Kittinger et al. 2012), we have identified a suite of social indicators for West Hawaiʻi's marine ecosystem. Our goal was to integrate dynamic and spatially explicit data on human uses, values, and governance. Information on human dimensions and social indicators can be 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 better assess West Hawaiʻi's ecosystem and to provide information on current and predicted states of ecosystem integrity under different scenarios.

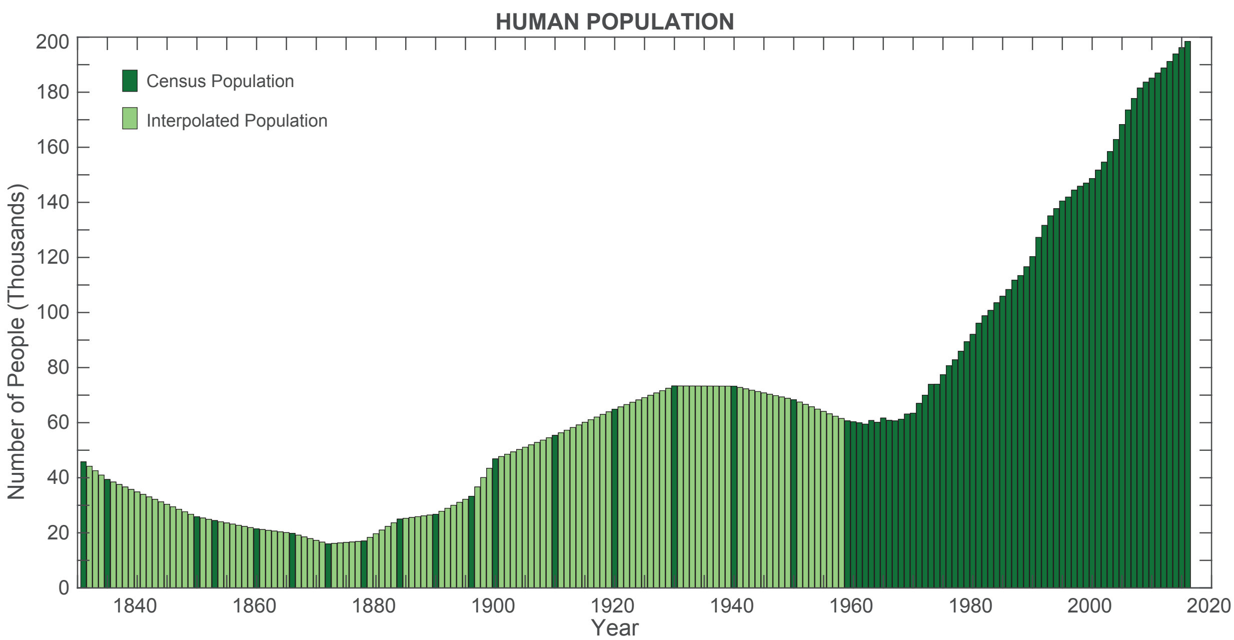


Figure 4.1. Resident human population (thousands of people) on Hawaiʻi Island from 1831 to 2016. Note that dark green values represent actual census population values while light green are linearly interpolated population values. Data Source: State of Hawaiʻi's Department of Business, Economic Development, and Tourism (*http://dbedt.hawaii.gov/economic/databook/*).

Population Growth – Human population growth can result in a range of pressures on marine ecosystems. As resident populations increase, so can impacts such as overuse and habitat degradation. Technological advances, management practices, engagement in stewardship, and regulatory actions can modify the status and trends of individual activities. Because historical and reliable time-series information on specific activities is often lacking, tracking resident population growth serves as a broad indicator of human activities that can either directly (e.g., fishing) or indirectly (e.g., new development) influence the integrity and function of marine ecosystems.

Resident population of Hawaiʻi Island from 1831 to 2016 (185 years; Figure 4.1) was obtained from the State of

Hawai‘i’s Department of Business, Economic Development, and Tourism (DBEDT; *http://dbedt.hawaii.gov/economic/databook/*). In 1831, approximately 45,800 people lived on the island. That number steadily decreased over the next 40 years, reaching a minimum of 16,000 in 1872. Resident population subsequently increased until the 1940s, when it began declining to a low of approximately 60,000 residents from 1959–1968. Since the beginning of the 1970s, the population of Hawai‘i Island has rapidly increased by over three-fold to nearly 200,000 residents in 2016 (Figure 4.1). The spatial distribution of the present-day resident population in West Hawai‘i is highly concentrated along the coastline: over 25% live 1 mile or less from the coast and over 80% live within 5 miles (Figure 4.2). Areas with the highest density of residents include Kailua-Kona, Kalaoa, Waikoloa Village, and Waimea.

Visitor Arrivals and Spending – Compared to other sectors, tourism is distinguished by both its size and share of Hawai‘i’s economy. In fact, tourism expenditures represent the single largest source of economic activity in Hawai‘i (State of Hawai‘i DBEDT 2006). Moreover, many visitors spend the majority of their vacations at Hawai‘i’s beaches 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 Hawai‘i DBEDT 2006).

Visitor arrivals and visitor spending for West Hawai‘i was obtained from State of Hawai‘i DBEDT (Figures 4.3 and 4.4) and serve as indicators of tourism use of the marine environment and the importance of tourism to the local economy. From 1990 to 2016, visitor arrivals to Kona increased by over 30%, with approximately 992,000 arrivals in 1990 and over 1.3 million in 2016 (Figure 4.3, *Visitor Arrivals*). Between 70 and 80% of total arrivals are domestic visitors. The total number of days spent by all visitors in West Hawai‘i has increased nearly twofold, from approximately 4.93 to 9.35 million days (Figure 4.3, *Visitor Days*). Further, the average length of stay has increased 42% over the last 27 years, from an average of 4.97 to 7.05 days.

Annual visitor spending in West Hawai‘i increased by 62% since 2004, to nearly 2.1 billion dollars in 2016 (Figure

HUMAN POPULATION

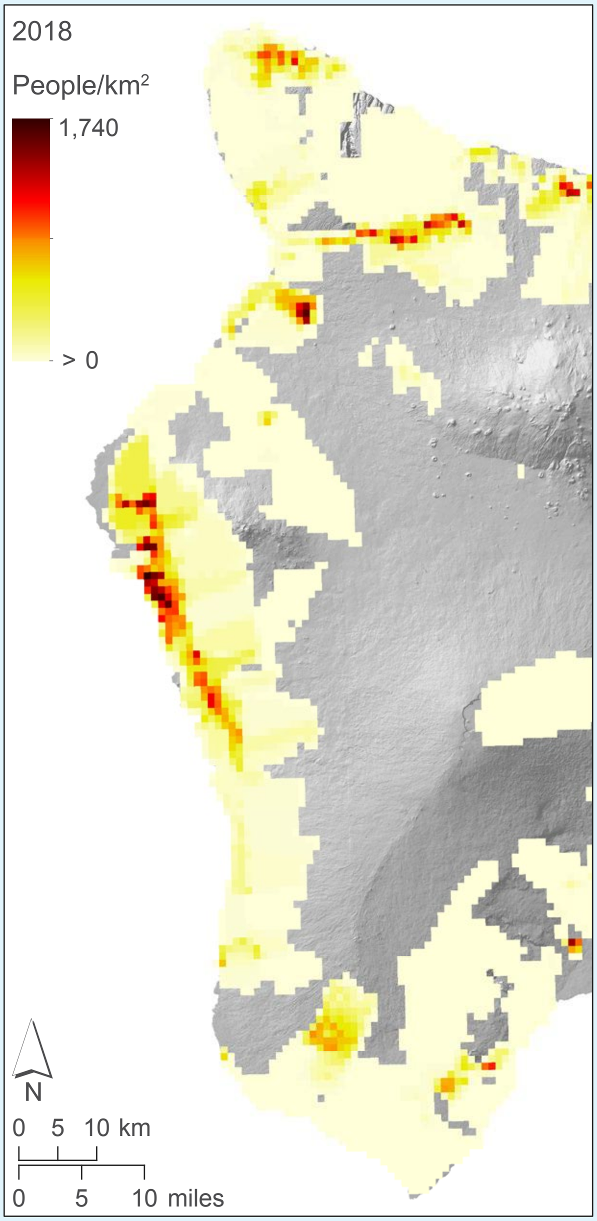


Figure 4.2. Map of West Hawai‘i indicating the spatial distribution of present day (2018) resident human population. Darker colors indicate a higher density of individuals per square kilometer. Human population is distributed over the land surface based on NASA’s Gridded Population of the World (v4) dataset interpolated for year 2018. The dataset combines US Census data by census block and land use land cover data to allocate human population to land use types where humans live. Data source: NASA Socioeconomic Data and Applications Center (*http://sedac.ciesin.columbia.edu/data/collection/gpw-v4*).

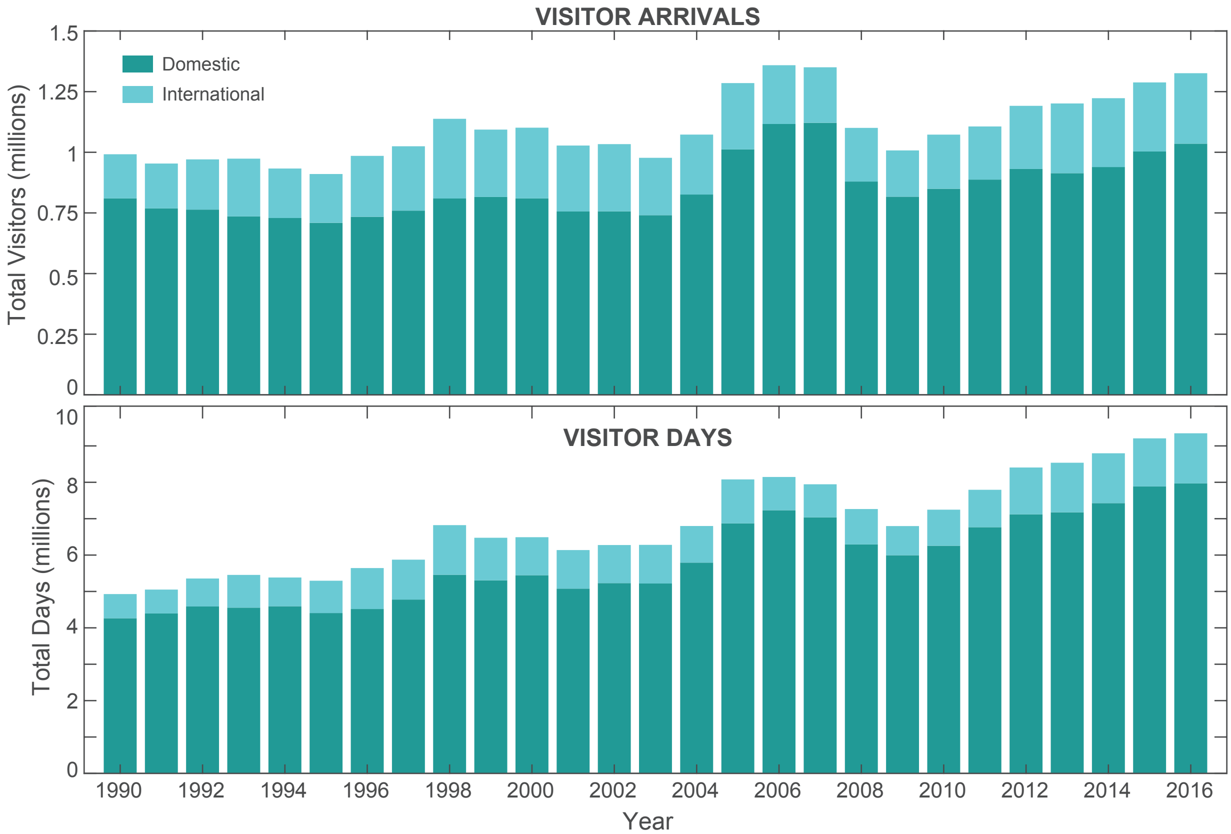


Figure 4.3. The total number of annual visitors arriving to Kona (top; millions of people), and the total number of days spent each year by visitors (bottom; millions of days) in Kona from 1990 to 2016. Visitor arrivals and days spent in Kona are by air and are split by domestic (dark green) and international (light green). Data Source: State of Hawai'i's Department of Business, Economic Development, and Tourism (*http://dbedt.hawaii.gov/*).

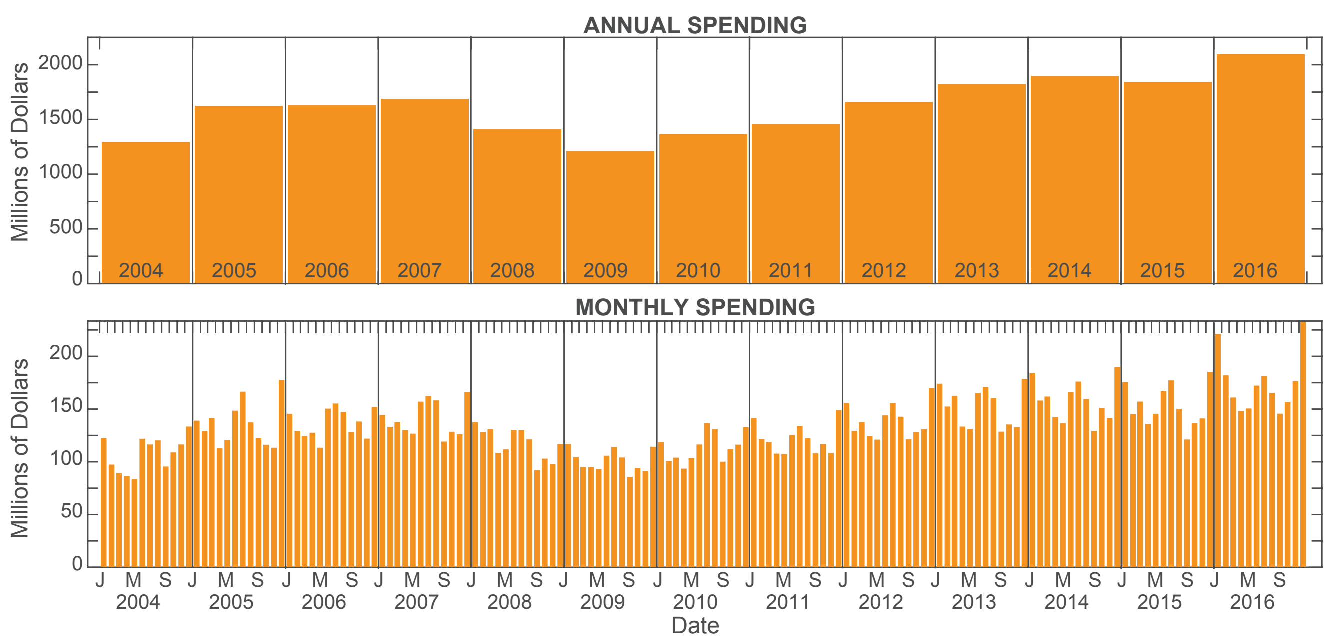


Figure 4.4. The total spending by visitors in Kona by year (top) and by month (bottom) from 2004 to 2016. Visitor spending is in millions of dollars. Data Source: State of Hawai'i's Department of Business, Economic Development, and Tourism (*http://dbedt.hawaii.gov/*).

4.4, *Annual Spending*). Visitor spending is highly seasonal, with peaks in both wintertime (December/January) and summertime (June/July) (Figure 4.4, *Monthly Spending*). December spending, which is the highest single month of visitor spending each year, increased by 75% over the 13-year time period, from 133 to 233 million dollars.

Impervious Surfaces – Land-based development can affect nearshore coastal environments by creating impervious surfaces, such as pavement, roads, buildings, and roof tops. These man-made surfaces prevent rainwater from being absorbed into the land. The modification of natural land into impervious surfaces increases the amount of runoff from streets and sidewalks and influences nearshore ocean salinity and temperature.

We mapped the percent cover of impervious surfaces and estimated the potential runoff to the nearshore marine environment in 2017 (Figure 4.5, *Impervious Surface*) using land use and land cover data from NOAA's Coastal Change Analysis Program (*https://coast.noaa.gov/ccapftp*). The highest density of impervious surfaces and associated runoff is near Keāhole Point, Kailua-Kona, and between Puakō and Kawaihae. Overall, the total area of impervious surfaces increased by nearly 35% during 1992–2017, from approximately 81 km^2 to 109 km^2 (Figure 4.5, *Total Impervious Surface Area*).

On-Site Sewage Disposal Systems (OSDS) – On-site sewage disposal systems (e.g., cesspools and septic tanks) and injection wells are common in much of West Hawai'i, where municipal sewer systems have not been constructed across a majority of the region. Nearly half of all OSDS in the state are located on Hawai'i Island, and nearly 85% of those are cesspools (Whittier & El-Kadi 2014), where the effluent receives no treatment prior to being released into the environment. OSDS can leach nutrients (nitrogen and phosphorus), pharmaceuticals, and pathogens into groundwater and streams that flow to the ocean. Abaya et al. (2018) performed a dye-tracer study in Puakō, a community with homes located within a few hundred meters of the coast, and found that the travel time of wastewater to the nearshore waters ranged from 9 hours to 3 days. This runoff can result in algal overgrowth of corals, increased coral disease, and potential disease threats to humans (Anderson et al. 2002).

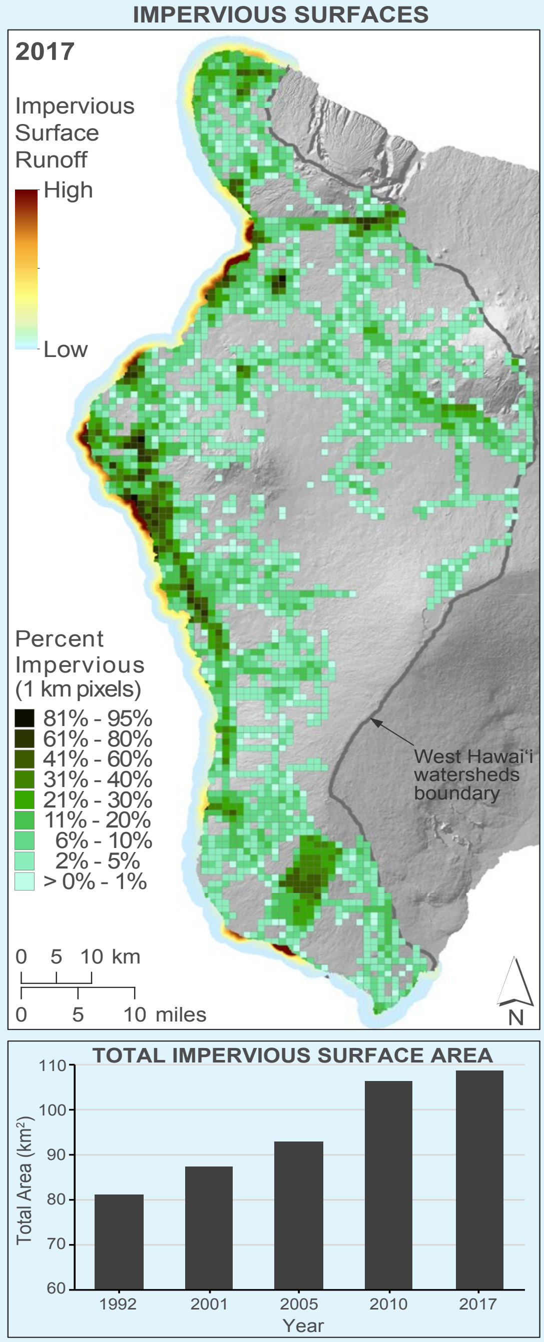


Figure 4.5 Map of West Hawai'i indicating the 2017 spatial distribution of impervious surfaces and potential run-off associated with the density of impervious surfaces (top). Below the map is a time series of total impervious surface area in West Hawai'i from 1992 to 2017 (bottom). Note the gray line in the map indicates the boundary of watersheds in West Hawai'i, which was used to enumerate the total area of impervious surfaces in the bar graph. Data Sources: NOAA Coastal Change Analysis Program (C-CAP; *https://coast.noaa.gov/ccapftp*) and LANDSAT satellite imagery (*https://landsat.usgs.gov*).

We have included the following indicators based on Hawaiʻi's Department of Health (*http://health.hawaii.gov/sdwb*) information to capture the influence of OSDS and injection wells (henceforth referred to simply as OSDS) on the marine environment: total number of OSDS, total effluent released, and total nitrogen flux (Figure 4.6). All indicators were compiled taking into account the time wastewater takes to reach the coastline. Specifically, we only included OSDS located from the shoreline to the one-year time of travel line of ground water (TOT; Figure 4.6, black line). The one-year TOT demarcation was chosen to indicate the likely intrusion of pathogens and nutrients to the nearshore, thereby capturing the potential impact of wastewater on human and ecological health (Whittier & El-Kadi 2014). It should be noted that the amount of nitrogen from wastewater that enters the groundwater is considered highly conservative and will likely reach the coast even when the source OSDS lies well beyond the one-year travel line. The values presented here are therefore a conservative estimate of the total effluent and nitrogen flux actually reaching the coastline.

The spatial distributions of all three indicators are shown from the most recent data available (2017), as well as a time series extending from 2000 to 2017 (Figure 4.6). The maximum concentration of OSDS (818 OSDS/km^2) within the one-year TOT is near Kailua-Kona. High concentrations of OSDS (400 OSDS/km^2) also occur in Miloliʻi and between Puakō and Kawaihae. The total amount of effluent in nearshore waters is as high as 63 million gallons/yr/km^2 with a total nitrogen flux of 43.6 thousand lb/yr/km^2. In 2017, the total number of OSDS across West Hawaiʻi (within the one-year TOT) was just under 7,200 (Figure 4.6, *Annual Number of OSDS*). This number of OSDS released a total of 680 million gallons of effluent per year (Figure 4.6, *Annual OSDS Effluent*) and a total of 400,000 pounds of nitrogen per year (Figure 4.6, *Annual OSDS Nitrogen Flux*).

ENGAGEMENT IN FISHING

Human communities in Hawaiʻi are deeply intertwined with fisheries due to their contributions to the local economy, food supply chain, and perpetuation of cultural customs and practices (Kittinger et al. 2015, Grafeld et al. 2017, Pascua et al. 2017, Teneva et al. 2018). Nearshore fisheries, for example, provide 7 million meals to local communities annually (Grafeld et al. 2017). Multiple gear types are used to harvest reef fish and invertebrates, estuarine species, and schooling coastal pelagics (Friedlander et al. 2014). Fisheries contribute to many aspects of ecosystem services and human well-being.

In an effort to describe fishing activities, we have included total catch, annual revenue, and fisher engagement indicators that encompass both commercial and non-commercial fishing in West Hawaiʻi. For fisher confidentiality, catch records are excluded if fewer than 3 fishers reported per DAR reporting block, year, gear, and species. Therefore, the total catch presented is likely a conservative estimate of actual catch.

Reef Fish Fishing: Non-Commercial Catch – Reef fisheries have substantial social, cultural, and economic value in Hawaiʻi, yet knowledge regarding their sustainability is 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). Non-commercial fishing plays an important social, cultural, and subsistence/consumptive role for local communities in Hawaiʻi and is estimated to be over 10 times the reported commercial catch (by weight) on Hawaiʻi Island (McCoy et al. 2018)

Total non-commercial catch was calculated by gear type from 2004 to 2013 from island-wide average annual catch estimates of Hawaiʻi Island reef fish (McCoy et al. 2018). Here, we estimated catch for West Hawaiʻi using proximity to roads and shoreline accessibility, distance to nearest harbor or launch ramp, gear-specific spatial footprints, and gear prohibitions within MPA boundaries to spatially distribute island-level catch estimates from Upolu Point to South Point (Wedding et al. 2018). Data were filtered by species to include nearshore reef-associated finfish only.

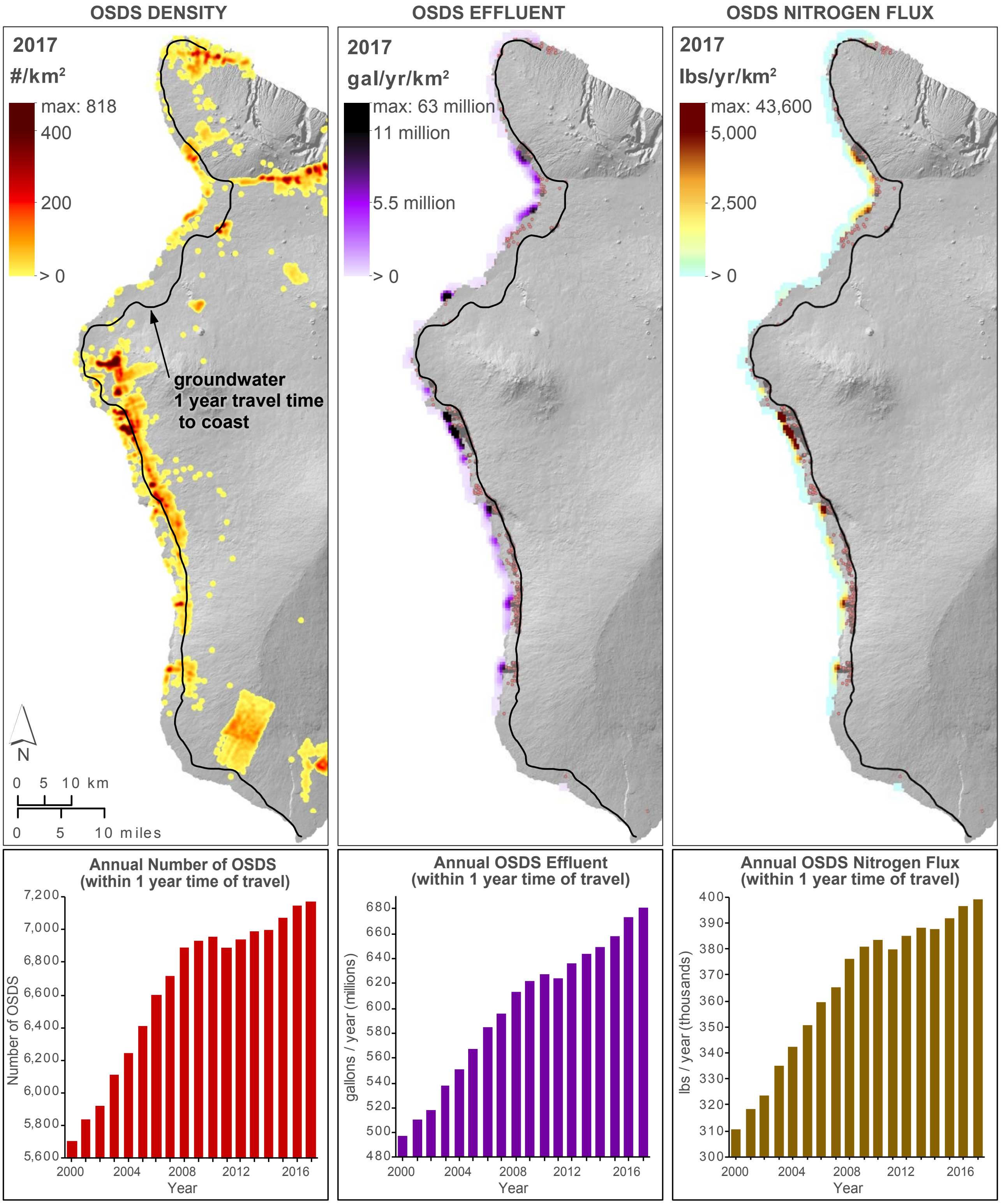


Figure 4.6 Maps of West Hawaiʻi indicating the spatial distribution of on-site sewage disposal systems (OSDS; top left), total effluent from OSDS into the coastal environment (top middle) and total nitrogen flux from OSDS into the coastal environment (top right). Note the black line indicates the one-year time of travel for effluent from OSDS reaching the coast. Below each map are annual values for the total number of OSDS (bottom left), total effluent from OSDS (millions of gallons/year) (bottom middle), and total nitrogen flux (thousands of lb/year) (bottom right) from OSDS within the 1-year time of travel contour from 2000 to 2017. Note these values represent a conservative estimate of OSDS numbers and associated effluent influencing marine ecosystem health. Data Source: State of Hawaiʻi Department of Health (*http://health.hawaii.gov/sdwb*).

The estimated annual average catch was nearly 406,000 lb during the 2004–2013 time period (Figure 4.7 Non-Commercial Catch). A five-fold difference in the annual average catch was observed, indicating spatial differences in catch among different regions of West Hawaiʻi. Approximately 29–33 thousand pounds of reef fish were caught per year in some of the most heavily fished areas, such as between Puakō and Kawaihae and near Kailua-Kona, while 5–8 thousand pounds of reef fish were caught in areas with less fishing, such as in the vicinity of South Point. Overall, the non-commercial reef fish fishery has declined in recent years: total catch in 2013 was estimated at 265,200 lb, a roughly 50% drop from the 525,600 lb caught in 2008. Line fishing was the dominant gear type, constituting between 55 and 70% of the total catch.

Reef Fish Fishing: Commercial Catch – Commercial reef-fish catch is reported to Hawaiʻi DAR by the reporting blocks as shown in Figure 4.7. *Commercial Catch* data were filtered by species to include nearshore reef-associated finfish only.

A majority of the reported commercially caught reef fish over the 2003–2017 time period was from the reporting block that spans from Keāhole Point to Miloliʻi, with an average annual catch of 8,400 lb (Figure 4.7, *Commercial Catch*). Total catch for all of West Hawaiʻi varied over six-fold across the 15-year time period, ranging from a low of 5,500 lb in 2004, to a high of 34,400 lb in 2010 (Figure 4.7, *Annual Commercial Catch*). As with non-commercial catch, line fishing was by far the dominant gear type, ranging from 60 to 100% of the commercial reef fish catch. The dominant reef fish species caught in the commercial fishery, by weight, are ʼūʼū, or menpachi (soldierfish, *Myripristis spp.*) and uku (gray jobfish, *Aprion virescens*), which combined account for 70% of the catch. When compared to non-commercial catch, commercial reef fish fishing is a very small fraction (1/24) of the total catch from coral reef ecosystems in West Hawaiʻi.

Reef Fish Fishing: Commercial Aquarium Collection - Aquarium collection is the live capture of ornamental aquatic organisms for sale in the aquarium industry. Commercial

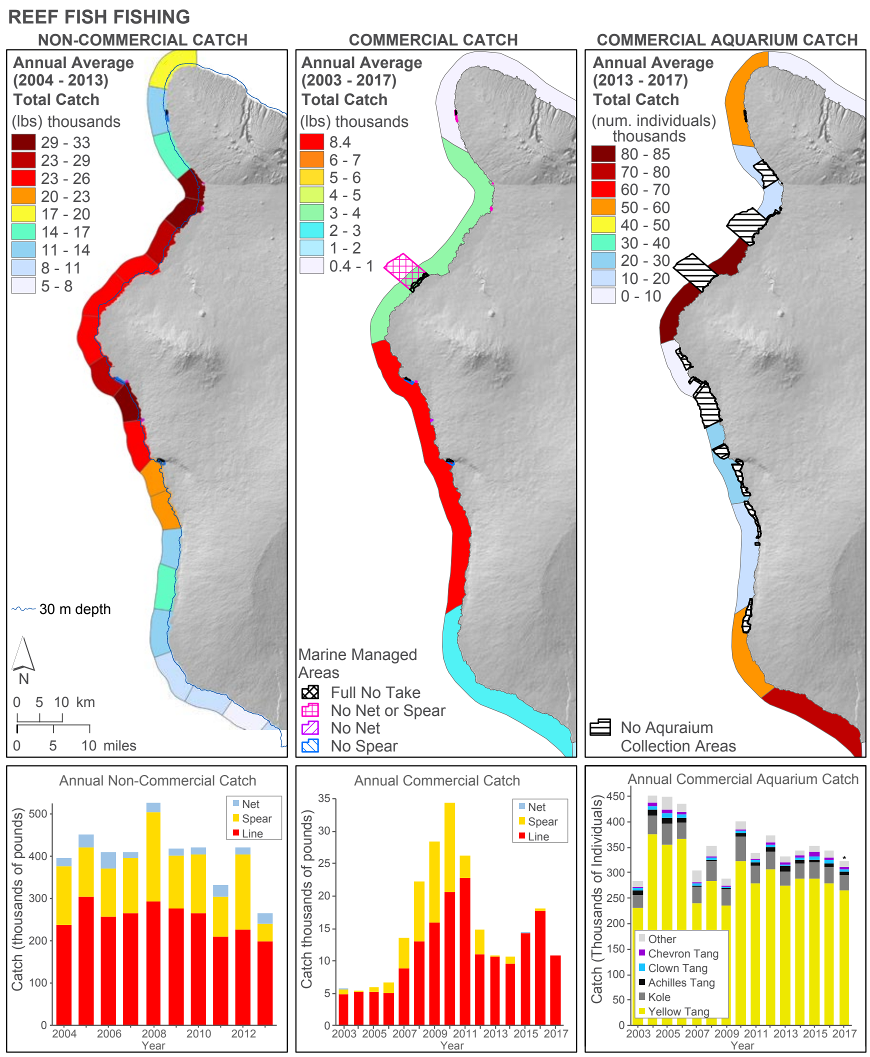


Figure 4.7. Maps of West Hawaiʻi indicating the spatial distribution of average annual reef fish fishing catch, including non-commercial catch (top left), commercial catch (top middle), and commercial aquarium catch (top right). Note for non-commercial catch (top left), the 30-m contour is provided for context of areas containing reef fish. Coastal segments are shown for the purposes of visualization only, and do not represent the outward spatial extent over which catch was enumerated. Below each map are annual values for the total catch of reef fish, including non-commercial catch from 2004 to 2013 (bottom left), commercial catch from 2003 to 2017 (bottom middle), and commercial aquarium catch from 2003 to 2017 (bottom right). Data Sources: Non-commercial catch estimates from McCoy et al. (2018) and mapping methods from Wedding & Lecky et al. (2018). Commercial catch and aquarium catch from Hawaii DAR (*http://dlnr.hawaii.gov/dar*) and from NOAA Fisheries.

aquarium collection is the most economically valuable commercial inshore fishery in the state (Walsh et al. 2013). Aquarium collectors typically target juvenile fish, and catch is reported in number of individuals taken rather than by weight. As with other commercial fisheries, total catch is recorded by reporting block (e.g., Figure 4.7, *Commercial Catch*). However, in 2013, smaller reporting blocks, or subzones, were implemented specifically for aquarium collection in West Hawai'i. Here, we report annual average aquarium catch by subzone from 2013 to 2017 to provide greater spatial resolution on the take of aquarium fishes (Figure 4.8, *Commercial Aquarium Catch*); however, total commercial aquarium catch is provided, by species, from 2003 to 2017 (Figure 4.8, *Annual Commercial Aquarium Catch*).

The average annual commercial aquarium catch differs greatly along West Hawai'i. For example, 80–85 thousand individual fish are caught per year in the reporting block that spans north from Keāhole Point to Waikoloa (Figure 4.7, *Commercial Aquarium Catch*), which comprises 25% of the total catch in an average year. In contrast, fewer than 10,000 individuals were caught from the reporting block that spans south from Keāhole Point to Kailua-Kona. The total catch across the region from 2003 to 2017 was, on average, approximately 360,000 individual fish per year (Figure 4.7, *Annual Commercial Aquarium Total*). However, large year-to-year differences were observed, ranging from an industry maximum of over 452,000 individuals in 2004, to a minimum 288,072 individuals in 2009, a difference of more than 160,000 individuals. Laui'pala (yellow tang, *Zebrasoma flavescens*) is the most popular aquarium fish caught in West Hawai'i, accounting for 82% of average annual catch over the 15-year time period. Kole (goldring surgeonfish, *Ctenochaetus strigosus*) and pāku'iku'i (Achilles tang, *Acanthurus achilles*) account for 12% and 2.5% of average total catch, respectively, while all other species comprise less than 3% in an average year.

In July 2017, the Hawai'i Circuit Court ruled that, based upon a Hawai'i Supreme Court opinion issued on September 6, 2017, existing 'aquarium' permits for use of fine mesh nets/traps to catch aquatic life for aquarium purposes were illegal and invalid pending a full review of the fishery under the Hawai'i Environmental Policy Act. Although collecting was still allowed as long as fine mesh nets/traps were not used, total catch in 2017 would presumably have been higher if not for the ruling.

In January 2018, DLNR announced that after applying a Hawai'i Supreme Court ruling from 2017 to the existing West Hawai'i Regional Fishery Management Area administrative rule (HAR §13-60.4), no aquatic life may be taken for commercial aquarium purposes in West Hawai'i waters until an environmental review is completed. In July 2018, after review of two Final Environment Assessments (EAs) prepared by the Pet Industry Joint Advisory Council (PIJAC), Suzanne Case, the Chair of the Board of Land and Natural Resources, determined that the preparation of an Environmental Impact Statement (EIS) was required. As of the writing of this report (Nov 2018), the West Hawai'i aquarium fishery is still closed.

Commercial Fishing: Coastal Pelagics – We define coastal pelagic fishes as two species: akule (bigeye scad, *Selar crumenophthalmus*) and 'ōpelu (mackerel scad, *Decapterus macarellus*). Though they can be found seasonally in large schools proximate to shore, they are distinguished from reef fish because they principally reside in nearshore pelagic waters.

On average, nearly 80%, or 113,000 lb of coastal pelagic catch comes from one reporting block (101), which extends from Keāhole Point to Miloli'i (Figure 4.8, *Coastal Pelagics*). 'Ōpelu dominate the coastal pelagic catch, comprising greater than 95% of the average annual catch (Figure 4.8, *Annual Coastal Pelagics Catch*). During the last 15 years, the total catch has shown an overall decline, with present day total catch (77,000 lb) approximately 1/3 of the total catch in 2003 (218,700 lb).

Commercial Fishing: Bottom Fish – The most commonly caught bottomfish species, comprised of six deep water snapper species and one grouper, are referred to as the "Deep 7." The Deep 7 are more actively managed than other fisheries, including annual catch limits, vessel registration, and reporting requirements. Bottomfish are primarily caught with deep-sea hand line in depths of approximately 300–1300 ft (~100–400 m).

On average, nearly 1/3 of the total commercial bottomfish catch near West Hawaiʻi was reported in the block that includes North Kona and South Kohala (Figure 4.8, *Bottomfish*). However, the total catch across the region has varied considerably over the last 15 years, with a six-fold difference between the lowest catch (12,350 lb; 2004) and the highest catch (73,600 lb; 2009) (Figure 4.8, *Annual Bottomfish Catch*). The dominant species caught in West Hawaiʻi was ʻōpakapaka (pink snapper, *Pristipomoides filamentosus*), comprising approximately 52% of the annual catch by weight.

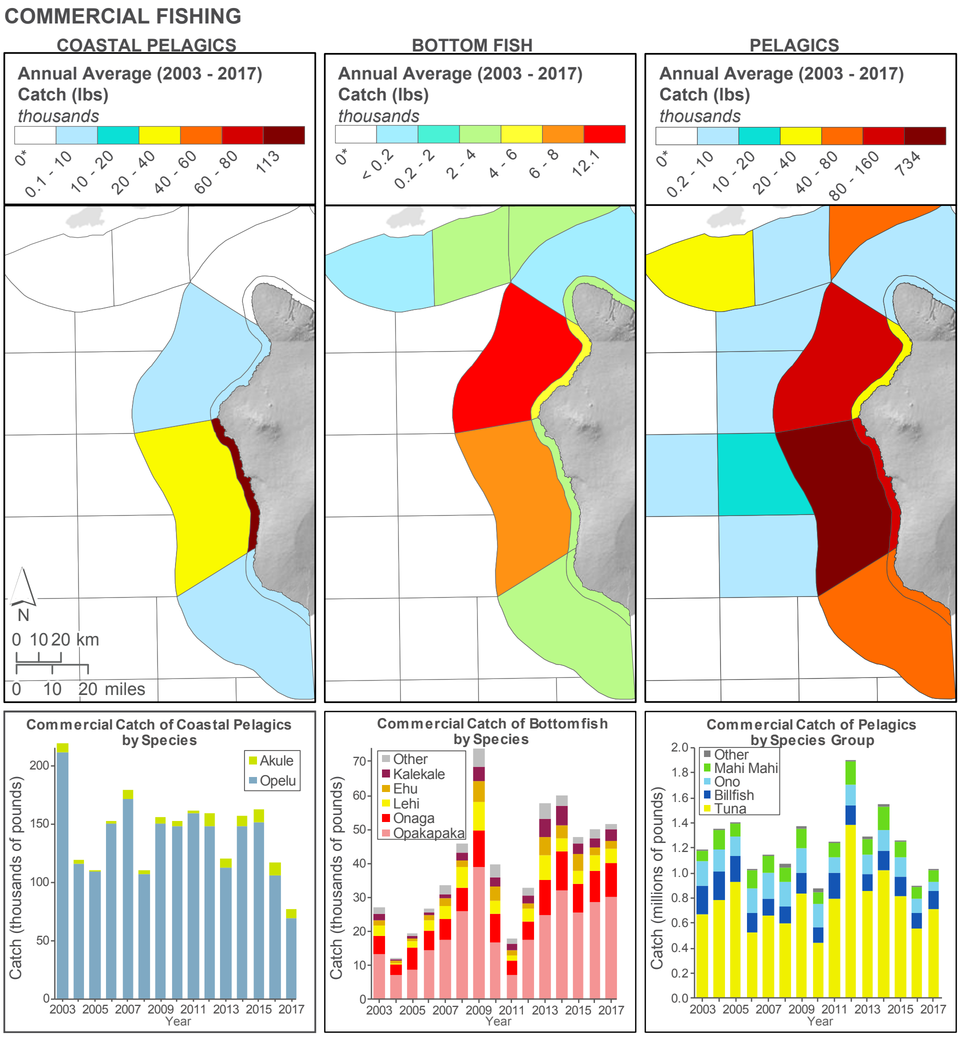


Figure 4.8. Maps of West Hawaiʻi indicating the spatial distribution of average annual commercial fishing catch for non-reef fishes by Hawaiʻi DAR reporting block, including coastal pelagics (top left), bottomfish (top middle), and pelagics (top right). Below each map are annual values for the total commercial catch of non-reef fishes from 2003 to 2017 by species, including coastal pelagics (bottom left), bottomfish (bottom middle), and pelagics (bottom right). Data Sources: Hawaii DAR (http://dlnr.hawaii.gov/dar) and NOAA Fisheries.

Commercial Fishing: Pelagics – Pelagic species include some of the most highly recognizable food fish, such as tunas and mahimahi, as well as popular sport fishing species, like marlins and swordfish. Pelagics are typically large-bodied, fast-swimming fishes that live in pelagic waters with geographic ranges spanning much of the Pacific. Pelagics are the largest fishery in West Hawaiʻi in terms of both weight caught and estimated dollar value.

In the vicinity of West Hawaiʻi, over 70% of the average annual commercial catch of pelagic fishes was from the two reporting blocks off South Kona (i.e., from Keāhole Point to Miloliʻi) (Figure 4.8, *Pelagics*). Tunas, namely ahi (bigeye and yellowfin tunas, *Thunnus obesus* and *Thunnus albacares*) and aku (skipjack tuna, *Katsuwonus pelamis*), comprise the largest proportion of catch, with an average of 62.5% over the 15-year time period (Figure 4.8, *Annual Pelagics Catch*). Aʻu (striped marlin, *Kajikia audax*), ono (wahoo, *Acanthocybium solandri*), and mahimahi (*Coryphaena hippurus*) each account for a similar share of average annual catch (13%, 13%, and 10%, respectively). Across all of West Hawaiʻi, the pelagic fishery averaged 1.24 million pounds of total catch per year, with a peak of 1.9 million pounds in 2012. In more recent years, the total catch has declined: the 2017 total catch was 1.023 million pounds, representing a 46% decline in just 5 years.

Commercial Fishing Annual Revenue and Fisher Engagement – The annual revenue generated and the total fishers engaged in commercial fishing activities in West Hawaiʻi are shown from 2003 to 2016 in Figure 4.9. All data were obtained from the State of Hawaiʻi DAR dealer reports (Walsh et al. 2013, PIFSC 2018), specifically for fishers that live in West Hawaiʻi (based on fisher zip code). Revenue values were corrected for inflation to 2016 dollar amounts using the Bureau of Labor Statistics' Honolulu Consumer Price Index for all urban consumers (*www.bls.gov*). The pelagics

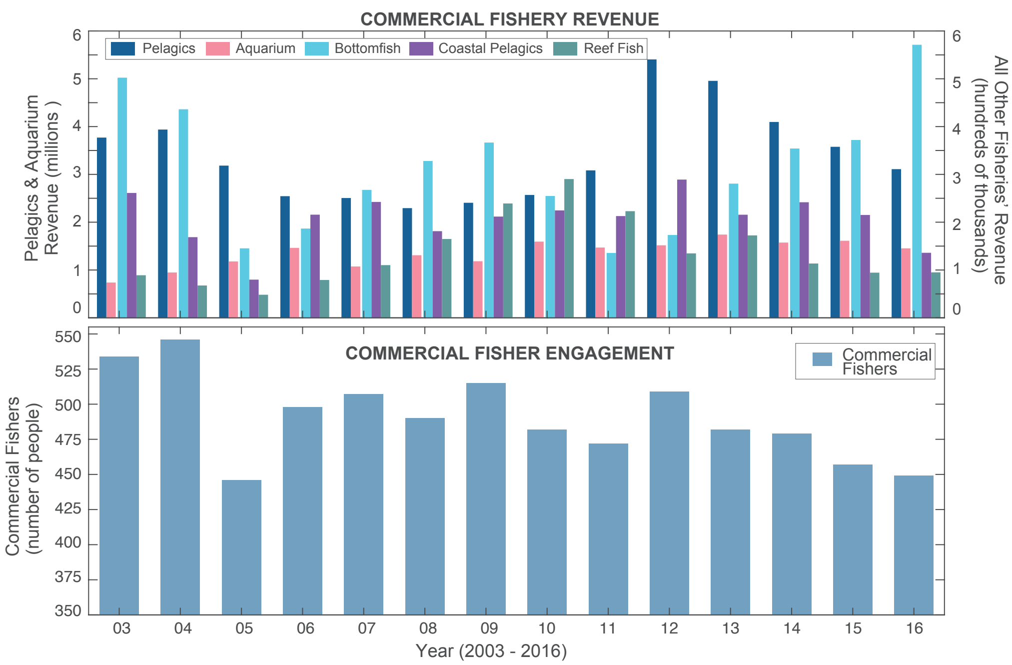


Figure 4.9. The annual revenue generated from commercial fishing activities (top) and the total fishers engaged in commercial fishing (bottom) from 2003 to 2016. Commercial fisheries include those fishing for pelagics, aquarium fishes, bottomfish, coastal pelagics, and reef fish. Note that annual revenue for the commercial pelagics fishery and aquarium fishery are presented in millions of dollars (left y-axis) while all other fisheries are presented in hundreds of thousands of dollars (right y-axis). Annual reported revenues were obtained from the State of Hawaiʻi DAR dealer reports, specifically for fishers that live in West Hawai'i (based on fisher zip code). Revenue values were corrected for inflation to 2016 dollar amounts, using the Bureau of Labor Statistics' Honolulu Consumer Price Index for all urban consumers (*www.bls.gov*). Data Source: NOAA Fisheries (https://inport.nmfs.noaa.gov/inport/5610). Commercial aquarium fishery information was provided by William J. Walsh, State of Hawaiʻi DAR.

fishery is by far the most economically important to the region, generating a total of $47.4 million or 62.3% of the total revenue from all commercial fisheries in West Hawaiʻi over the 14-year time period (Figure 4.9 *Commercial Fishery Revenue*). The commercial collection of aquarium fishes was the second largest fishery in total revenue, accounting for $18.9 million, or 24.9%. Bottomfish, coastal pelagics, and reef fish constituted 5.8%, 3.9%, and 2.5% of the total revenue generated, respectively. Each of the fisheries' revenue exhibited year-to-year differences. For example, bottomfish had over a four-fold change in annual revenue in just six years, increasing from a low of $135,670 in 2011 to a high of $571,114 in 2016.

As with total revenue, the total number of fishers engaged in commercial fishing in West Hawaiʻi varied over the 14-year time period, ranging between 446 and 546 fishers (Figure 4.9 *Commercial Fisher Engagement*). The number of commercial fishers in 2016 was 446, representing an 18% decline from the peak of 546 fishers in 2004.

When comparing the total annual revenue with the total annual catch from each commercial fishery from 2003 to 2016, revenue and catch for pelagics, coastal pelagics, and reef fish were positively correlated (R2 = 0.71, 0.74, and 0.91, respectively; $p < 0.05$), indicating that in general, the greater the total catch, the greater the total revenue generated for a given commercial fishery. The annual revenue and total catch from both the aquarium fishery and the bottomfish fishery were not correlated, indicating that market value is driven by external factors beyond total catch. In addition, no correlation was found between the annual number of commercial fishers and the combined annual catch from all commercial fisheries, indicating that the number of fishers were not a primary driver in year-to-year fluctuations in total catch.

5. SUMMARY AND NEXT STEPS

Ecosystem indicators provide the ability to track the status of West Hawaiʻi's marine ecosystem. Here, we compiled 30 individual indicators identified via a combination of community and expert opinions, 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 including social, ecological, climatic, and oceanic drivers of ecosystem change. From this synthesis of information, a number of key findings have emerged:

Ecological Indicators

- The number of juvenile yellow tang has significantly increased between 60 and 80% in the last 14 years across all three management designations in West Hawaiʻi.
- The total abundance of nearshore fishes has shown a positive trend in all management areas, increasing since 2003 by 28.9%, 36.0%, and 34.9% in MPAs, FRAs, and open areas, respectively.
- The estimated annual average non-commercial reef fish catch was nearly 406,000 pounds from 2003 to 2013, representing an 11.5-, 2.7-, and 24-fold increase over the annual average commercial catch of bottomfish, coastal pelagics, and reef fish, respectively.
- Herbivorous fishes showed no change in FRAs or open areas, but increased by nearly 1/3 since 2003 in MPAs.
- Herbivores constitute about 50% of the total fish biomass in West Hawaiʻi.
- All reef fish indicators—total abundance and biomass, adult fish length, species richness, herbivore

biomass, juvenile yellow tang—were 1.1–2 times higher in MPAs than open areas in 2017.

- The total cover of hard coral across West Hawaiʻi was approximately 18% in 2017, representing a relative decrease of 50% since 2003.

Climate and Ocean Indicators

- Long-term sea level measurements from Kawaihae indicate a clear positive trend, increasing by 0.27 m (0.89 ft) in the past 28 years.
- Rainfall patterns are shifting towards dryer conditions across West Hawaiʻi. The total number of months exceeding the *very dry* threshold was 1.9–2.6 times higher during most recent 20-year time period (1997–2016) compared to the previous 20 years (1976–1996).
- Ocean temperatures in 2015 were the warmest on record in West Hawaiʻi.
- As a result of climate change, ocean temperatures are projected to substantially increase in the coming decades, causing severe coral bleaching similar to that experienced in 2015 to occur on an annual basis starting in 2040 in West Hawaiʻi.

Social Indicators

- The population of Hawaiʻi Island is currently 200,000 residents. Over 25% live 1 mile or less to the coast, and over 80% live within 5 miles.
- Since 2003, the total catch from the pelagics commercial fishery was over six times the combined commercial catch (by weight) of all other commercial fisheries representing 62.3% of the total revenue generated in West Hawaiʻi.
- The aquarium fishery is the most economically valuable inshore commercial fishery and the second most economically valuable commercial fishery in West Hawaiʻi, averaging nearly $1.6 million per year over the past 5 years.
- Tourism represents the single largest source of economic activity in West Hawaiʻi, exceeding $2.1 billion in spending in 2016. December spending, which is the highest single month of visitor spending each year, increased 75%, or from $133 million to $233 million in the past 15 years.
- An estimated 680 million gallons of wastewater was released into the coastal environment in 2017 from on-site sewage disposal systems. The highest concentration of OSDS (>800 OSDS/km^2) is located in the vicinity of Kailua-Kona, where 125 million gallons of wastewater and 87,500 pounds of nitrogen enter the nearshore waters each year.

NEXT STEPS

We have assembled a suite of relevant ecosystem indicators to help track changes in key social-ecological processes in West Hawaiʻi; however, many gaps remain. Our understanding of ecosystem dynamics and the myriad of social-ecological interactions occurring in the region continues to evolve. The evaluation and synthesis of information and development of ecosystem indicators is an adaptive and iterative process that will continue to evolve beyond this publication.

In the coming years, the West Hawaiʻi IEA will focus on human well-being in West Hawaiʻi. Simply stated: ecosystems are fundamentally intertwined with human well-being and ignoring this important connection can undermine the sustainability of an ecosystem and related resource management goals (Millennium Ecosystem Assessment 2005).

Previous efforts with stakeholders in West Hawaiʻi identified the potential impacts of ecosystem change onto ecosystem services (Ingram et al. 2018). Importantly, a majority of ecosystem services perceived as the most vulnerable to ecosystem change were found to be *cultural ecosystem services*, which are considered critical to human well-being. Cultural services foster and maintain a connection to place, identity, values, and experiences (Chan et al. 2012, Fish et al. 2016, Pascua et al. 2017). Cultural services are often intertwined and interconnected with other ecosystem services (Chan et al. 2011, Pascua et al. 2017). Therefore, attempting to manage a complex cultural service specifically and individually, without accounting for other services such as provisioning or supporting (Chan et al. 2012, Gould et al. 2015) is challenging. Hawaiʻi's non-commercial nearshore fishery is a clear example as it contributes to both subsistence (provisioning ecosystem service) and cultural ecosystem services such as knowledge transfer and social cohesion (Grafeld et al. 2017).

As part of the West Hawaiʻi IEA, we have begun to identify domains of cultural ecosystem services related to human well-being, associated attributes (i.e., definitions or examples) of each domain, and potential indicators of cultural services (see Appendix A). We are currently conducting interviews with community members in West Hawaiʻi to refine this information and ensure its validity, relevancy, and applicability for West Hawaiʻi. It is our intention to develop a more robust suite of indicators that track the overall status of West Hawaiʻi's social ecological system, including the cultural services and human well-being within the region.

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APPENDICES

Consolidated list of human well-being domains, attributes, and cultural ecosystem services in relation to cultural ecosystem services in West Hawaiʻi

DOMAINS	ATTRIBUTES	POTENTIAL INDICATORS OF CULTURAL ECOSYSTEM SERVICES
Heritage	Multi-generational interactions/connections with natural resources	Transmission of knowledge or practices around deified ancestral guardians (e.g., ʻaumakua); use or transmission of stories and verbal histories (e.g., mo’olelo); birth place and family burial sites; ceremonial practices, practices of respect, and other practices related to connection with place and resources
	Archaeological and historic sites	
	Cultural resources	
	Acceptable historical change	
Spirituality	Interacting with the landscape to perpetuate spiritual beliefs and practices (e.g., divine power)	Formal ceremonial practices (e.g., oli, pule, other cultural protocols); perpetuation of songs, chants, dances, and prayers of/for place; protocols for place-specific gathering and harvesting practices
	Presence and recognition of plants, animals, and elements that represent/symbolize deities	Creation and use of ceremonial garlands (e.g., lei); ceremonial offerings such as fresh water, rain, salt, and turmeric
	Presence and recognition of familial guardians/ancestors; resources themselves recognized as kin	Recognition of deified ancestral guardians that are cared for by and take care of specific families (e.g., ʻaumakua)

DOMAINS	ATTRIBUTES	POTENTIAL INDICATORS OF CULTURAL ECOSYSTEM SERVICES
Sense of Place & Identity	Sense of self, community, and/or home related to the coastal and marine environment	Activities on the landscape; heritage, social, and emotional connections to places
	Presence of historical place-based names which describe the past and present of the coastal and marine environment	Place names; landscape terms; species names; environmental process names (e.g., rain names, wind names); transmission of existing or creation of new cultural proverbs to describe these observations
	Engagement of families in coastal and marine resource based activities	Existence and availability of activities such as fishing or harvesting for livelihood or enjoyment
	Presence on and interaction with lands that will remain secure (formally or informally) for future generations	Presence by lease, physical access, ownership, and/or occupation; customary rights and tenure
Education	Local knowledge about the coastal and marine environment	Language and/or culture encoded knowledge of seasonal weather patterns, timing, and intensity of rain, plant/animal behavior and reproductive cycles; place-specific practices associated with storied landscapes
	Knowledge transmission (place-based, observational, formal, informal, etc.)	Scientific research, experiential, land-based education, learning from elders, culture-based education (e.g., gathering salt from natural pools and making salt in raised ponds)
	Presence of environmental signs or indicators (e.g., bioindicators) and the ability to recognize them	Species or environmental processes that signal the cycles of another plant/animal species (e.g., types of rainbows to signal events)
Social Relations	Perpetuation of practices/skills that allow individuals to provide for and share with their families and community	Goods for household, sharing, and income; jobs that require knowledge of traditional practices or the discipline required; formal and informal apprenticeships; place-based fishing/gathering practices; community fishing endeavors; acknowledgement of young leaders
	Presence of strong social ties or networks; sense of community; trust in neighbors	Network of people to share with and receive from; gifting/exchanging of goods; joint family endeavors; communal child care; community spaces
Stewardship	Ability to care for resources and environment	Contributions of time, labor, and/or monetary support towards maintenance of public or private lands or specific sites; restoration and maintenance of sacred sites (e.g., wahi pana), civic activities around public spaces
	Customary rights and responsibilities are locally known, practiced, and respected	Recognition and use of access restrictions, gathering rights, and easements related to traditional ownership or harvesting practices (e.g., kapu)

DOMAINS	ATTRIBUTES	POTENTIAL INDICATORS OF CULTURAL ECOSYSTEM SERVICES
Existence	Aesthetics	Recognition and practices around the appropriate maintenance of specific sacred sites; pride in community parks and coastal areas; beach clean-up activities
	Inspiration	Broadly circulating public discourse about collective responsibilities (e.g., caring for place or *malama ʻaina*)
	Creativity	Local artistic or creative practices; moralization; poster competitions in schools
Governance & Management	Political participation and equity	Participation in marine management decision-making processes and leadership; stakeholder processes; exercising rights/interest in politics; management reflects local and traditional values
	Effectiveness of management	Perceptions of management, permits, and regulation; adequate funding and staff capacity for achieving management objectives; partners and collaboration
Health	Physical and nutritional health	Outdoor activities that promote health and strength of body and mind
	Mental and emotional health	
Safety & Security	Security and safety related to real or perceived environmental risks	Protection from threats of natural disasters (hurricanes, tsunamis, earthquakes, etc.), e.g., level of social preparedness for natural disasters; access to social nets; availability and application of traditional knowledge to mitigate environmental risks.


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