



Shoreline Habitats

Climate Change Vulnerability Assessment Synthesis for Kauaʻi

An Important Note About this Document: This document represents an initial evaluation of vulnerability for shoreline habitats on Kauaʻi based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by habitat experts,¹ relevant references from the literature, and peer-review comments and revisions (see end of document for methods and defining terms). The aim of this document is to expand understanding of habitat vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.

Habitat Description

Kauaʻi has 110 miles of shoreline (O’Connell 2010) featuring a variety of sub-habitats, including rocky shoreline, steep sea cliffs, lava tubes/caves, sandy beach, sand dunes (e.g., Polihale Dunes), and lithified sand dune coast (i.e. Mahaʻulepu; Vuln. Assessment Workshop, pers. comm., 2017; Hawaiʻi Department of Land and Natural Resources 2015). Depending on location, conditions can be arid, mesic, or wet (Warshauer et al. 2009), and shoreline structure and community composition are shaped by wind, waves, storms, and precipitation (Fletcher et al. 2002; Warshauer et al. 2009). In general, Kauaʻi’s shorelines provide habitat for a variety of wildlife, including terrestrial and aquatic invertebrates, migratory shorebirds, seabirds, and nesting or basking marine species (Hawaiʻi Department of Land and Natural Resources 2015).

Habitat Vulnerability

Shoreline habitats on Kauaʻi were evaluated in five sub-groups: sandy beaches, sand dunes, rocky shorelines, cliffs, and caves. Overall, shoreline habitats were evaluated to have high vulnerability to climate change due to high

Overall Shoreline Habitats	Rank	Confidence
Sensitivity	High	High
Future Exposure	High	Moderate
Adaptive Capacity	Low	High
Vulnerability	High	High

sensitivity to climate and non-climate stressors, high exposure to projected future climate changes, and low adaptive capacity. Sandy beach and sand dune habitats were evaluated to have a high vulnerability to climate change due to high sensitivity to climate and non-climate stressors, high exposure to projected future climate changes, and low-moderate (sandy beach) and low (sand dune) adaptive capacity. Rocky shoreline and cliff habitats were evaluated to have a moderate-high vulnerability to climate change due to moderate-high sensitivity to

¹ This information was gathered during a vulnerability assessment and scenario planning workshop in January 2017 (<http://ecoadapt.org/workshops/kauaivulnerabilityworkshop>). Further information and citations can be found in the *Hawaiian Islands Climate Vulnerability and Adaptation Synthesis* and other products available online at www.bit.ly/HawaiiClimate.

climate and non-climate stressors, high exposure to projected future climate changes, and low-moderate adaptive capacity. Cave habitats were evaluated to have a moderate-high vulnerability to climate change due to high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and low adaptive capacity.

Climatic factors including tropical storms, sea level rise, and trade winds significantly affect sediment delivery patterns and shoreline vulnerability to erosion and inundation, potentially reducing overall habitat

availability. Extreme precipitation events, streamflow, and riverine flooding also impact sediment delivery, erosion, and inundation risk, but to a lesser degree. Shoreline habitats are also sensitive to precipitation changes and drought, which affect vegetation communities and habitat conditions (e.g., cave humidity). Non-climate stressors such as pollution, invasive pathogens and parasites, recreation, and invasive vegetation can further alter shoreline vegetative and faunal composition by disturbing, outcompeting, or causing mortality of native species. Additionally, development and shoreline armoring eliminate shoreline habitat, prevent landward migration in response to sea level rise, and often increase erosion.

The adaptive capacity of shoreline habitats is negatively affected by current habitat degradation and alteration as a result of human activities. Shoreline species are typically adapted to variable conditions, but human impacts undermine the natural ability of these habitats to cope with changing conditions. Additionally, shoreline habitats host many endangered, threatened, and climatically vulnerable species, reducing overall resilience. Some shoreline habitats are protected and managed, and shoreline habitats are highly valued by the public and provide many ecosystem services, which may increase overall management opportunities. However,

Sandy Beach and Sand Dune Habitats	Rank	Confidence
Sensitivity	High	High
Future Exposure	High	High
Adaptive Capacity	<i>Sandy Beach: Low-Moderate</i> <i>Sand Dune: Low</i>	High
Vulnerability	High	High

Rocky Shoreline and Cliff Habitats	Rank	Confidence
Sensitivity	Moderate-High	High
Future Exposure	High	High
Adaptive Capacity	Low-Moderate	High
Vulnerability	Moderate-High	High

Cave Habitats	Rank	Confidence
Sensitivity	High	High
Future Exposure	Moderate-High	Moderate
Adaptive Capacity	Low	High
Vulnerability	Moderate-High	High

managers lack funding and face challenges with private land ownership. Additionally, shoreline habitats face continued use interests with development and military activities.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Shoreline habitats are sensitive to climatic factors that increase inundation and erosion and alter sediment delivery, particularly sea level rise, wind, and tropical storms (Table 1). Extreme precipitation events, streamflow, and riverine flooding also influence shoreline inundation and erosion, but to a lesser degree. Increasing inundation and erosion are likely to alter overall shoreline habitat availability, potentially reducing habitat area for valued wildlife and/or driving shifts in community structure. Some shoreline habitats will also be affected by changes in sediment delivery: caves are threatened by increasing siltation, while sandy beach and sand dunes formation and position are affected by wave, wind, and riverine sediment transport. Shoreline habitats are also sensitive to shifts in precipitation and increasing drought, which may affect vegetative community structure, cave humidity, and habitat vulnerability to invasion and wildfire.

Table 1. Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on shoreline habitats. This habitat is sensitive to the climatic factors and disturbance regimes listed below, and will likely be exposed to projected future changes in them. Factors presented below were ranked as having a moderate or higher impact on one of more of the shoreline sub-habitats; additional factors that may influence these habitats to a lesser degree include insects.

Climatic factors and disturbance regimes <i>Sandy beaches, sand dunes, cliffs, caves: High impact (high confidence)</i> <i>Rocky shorelines: Moderate-high impact (high confidence)</i>		
<i>Tropical storms/ hurricanes & extreme precipitation events</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> • Tropical storm frequency was particularly high from 1982–1995, but then decreased slightly from 1995–2000 (Chu 2002) • Overall, tropical storm frequency increased slightly since 1966–1981 (Chu 2002) • On the wet northern coast, slight increase in the intensity and significant decrease in the frequency of extreme precipitation events from 1950–2007; no change on the dry western coast (no information on central Kauaʻi; Chu et al. 2010) <p>Projected future trends</p> <p>Tropical storm projections are highly uncertain because they are influenced by large-scale patterns within the ocean and atmosphere (Murakami et al. 2013). Extreme precipitation projections are also highly uncertain because of the variability associated with precipitation projections. Possible future scenarios include:</p> <ul style="list-style-type: none"> • Increased frequency and strength of tropical storm activity around the Hawaiian Islands due to a northwest shift in storm track and increased strength because of large-scale changes in environmental conditions (Murakami et al. 2013) • Reduced frequency of extreme precipitation events by 2100, particularly in dry areas (Elison Timm et al. 2011, 2013) • Little to no change in the frequency of extreme precipitation events by 2100 (Takahashi et al. 2011) • Significant increase in extreme precipitation events by 2100 	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> • Storms and extreme precipitation events can cause flash flooding in coastal areas and increase runoff-related erosion (Fletcher et al. 2012) • Runoff, altered wave direction, amplified wave energy, and winds associated with storms promote shoreline inundation and accelerate shoreline erosion (Fletcher et al. 2002, 2012) <ul style="list-style-type: none"> ○ Seasonal high waves and storms can drastically alter sandy beach width and grade and can expose and erode rocky shorelines; for example, winter North Pacific swell impacts Kauaʻi's north shore, while Kona storm waves expose and erode Kauaʻi's south shore (Fletcher et al. 2002, 2012) ○ Summer storm wave impacts are typically lower due to smaller wave size; impacts occur primarily on south-facing shorelines (Fletcher et al. 2002) ○ Hurricane-generated waves can be very large and destructive, causing erosion, overwash, and inundation, particularly when combined with storm surge and high tides (Fletcher et al. 2002) <ul style="list-style-type: none"> ▪ For example, southern Kauaʻi experienced inundation up to 300 m (984 ft) inland as a result of Hurricanes Iwa and Iniki (Fletcher

	(Zhang et al. 2016)	<p>et al. 2002)</p> <ul style="list-style-type: none"> ○ Low-gradient, narrow beaches are particularly vulnerable to storm-related inundation (Fletcher et al. 2012) • Wind and wave events associated with storms can damage or kill coastal vegetation (Warshauer et al. 2009; U.S. Fish and Wildlife Service 2016) and/or alter coastal vegetative community composition by changing soil salinity and moisture (Warshauer et al. 2009) • Altered storm frequency and intensity could increase rocky shorelines (i.e. turtle basking habitat) but decrease sandy beaches (i.e. turtle nesting habitat; Vuln. Assessment Workshop, pers. comm., 2017) • Increased wave action as a result of storms may alter rocky shoreline community structure and biodiversity, favoring filter feeders and predators and reducing abundance of grazers and macroalgae (Thompson et al. 2002) • Storms may increase mortality and cause extirpation of cave communities via flooding and/or affect cave food resources by removing vegetation (U.S. Fish and Wildlife Service 2006)
Sea level rise	<p>Historical and current trends</p> <ul style="list-style-type: none"> • At Nawiliwili station, sea levels rose an average of 1.52 mm/year (0.06 in) from 1955–2016 (equivalent to a change of 0.15 m [0.5 ft] in 100 years; NOAA/National Ocean Service 2017) • Rising sea levels over the past century have accelerated beach erosion across the Hawaiian Islands (Fletcher et al. 2012) • Kaua’i beaches eroded by an average of 0.11 m/year (0.36 ft) across all beaches, with 71% of beaches eroding since the early 1900s; in that time, 8% of total beach length (6 km [3.73 miles]) 	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> • Rising sea levels enhance shoreline erosion (Romine et al. 2013) by increasing wave energy reaching the shore (Fletcher et al. 2012; Anderson et al. 2015) and increasing the reach of high wave events, storms, and extreme tides (Fletcher et al. 2012; Eversole & Andrews 2014) • By increasing erosion and altering sediment delivery dynamics from fringing reefs, sea level rise may reduce overall sandy shoreline habitat availability (Anderson et al. 2015; U.S. Fish and Wildlife Service

	<p>was completely lost to erosion and is now seawalls (Romine & Fletcher 2012)</p> <ul style="list-style-type: none"> Sea level rise has contributed to both marine inundation (i.e. flooding in areas with a direct hydrological connection to the ocean) and groundwater inundation (i.e. flooding in areas with an indirect hydrological connection due to elevated water table; Rotzoll & Fletcher 2013) <p>Projected future trends</p> <p>There is high certainty that sea levels will continue to rise at increasing rates, but the magnitude and timing of change is less certain. Possible future scenarios include:</p> <ul style="list-style-type: none"> By 2100, global sea level will likely rise between 0.3 to 2.5 m (0.98 to 8.2 ft); relative sea level may be higher in the Hawaiian Islands compared to global levels, ranging from 0.4 to 3.3 m (1.3 to 10.8 ft; Sweet et al. 2017) Sea level rise will contribute to increased saltwater intrusion, shoreline loss, marine inundation, and groundwater inundation (Ferguson & Gleeson 2012; Cooper et al. 2013; Rotzoll & Fletcher 2013; Kane et al. 2015) Historical rates of beach erosion on Kauaʻi are likely to double with sea level rise by mid-century; 100% of beaches are likely to be eroding by 2050 (Anderson et al. 2015) No projections are available for coastal flooding 	<p>2016), particularly if these habitats are unable to migrate landward (University of Hawaiʻi Sea Grant College Program 2014; Kane et al. 2014)</p> <ul style="list-style-type: none"> Sea level rise will enhance shoreline inundation (Rotzoll & Fletcher 2013); low-lying, low-gradient shorelines (e.g., rocky and sandy beaches) are most vulnerable, while rocky bluffs and headlands are less vulnerable to inundation (Fletcher et al. 2002) Sea level rise may alter overall rocky shoreline habitat availability, which could contribute to shifts in community structure (Thompson et al. 2002) Sea level rise may alter tide pool species composition and distribution by altering habitat availability, connectivity (including sub-tidal connectivity), and wave exposure (Cox et al. 2011) Sea level rise may reduce beach haul-out habitat for ʻIlio-holo-i-ka-uaua (Hawaiian monk seals; <i>Neomonachus schauinslandi</i>; Baker et al. 2006), nesting and basking habitat for honu (green sea turtles; <i>Chelonia mydas</i>) and honuʻea (hawksbill sea turtle; <i>Eretmochelys imbricata</i>), and seabird nesting habitat (Hawaiʻi Department of Land and Natural Resources 2015) Sea level rise may reduce intertidal foraging opportunities, affecting bird populations (Kane et al. 2014) and human foraging opportunities (e.g., for limu [seaweed]; Vuln. Assessment Reviewers, pers. comm., 2017) <p>Geographic variation</p> <ul style="list-style-type: none"> Mahaʻulepu Cave is particularly vulnerable and hosts the cave wolf spider (<i>Adelocosa anops</i>) (Vuln. Assessment Workshop, pers. comm., 2017)
--	--	---

		<p>Potential refugia</p> <ul style="list-style-type: none"> • Sand dunes may become sandy beaches (e.g., Polihale and other undeveloped shoreline areas such as Donkey Beach; Vuln. Assessment Workshop, pers. comm., 2017) • Embayed beaches fronted by sand-filled channels may be more resilient to sea level rise (Romine et al. 2016)
<p><i>Precipitation (amount & timing)</i></p>	<p>Historical and current trends</p> <ul style="list-style-type: none"> • Since 1920, precipitation has decreased across the Hawaiian Islands, with the strongest drying trends occurring over the last 30 years (Frazier et al. 2016; Frazier & Giambelluca 2017) • From 1920 to 2012, dry season (May–Oct.) precipitation on Kauaʻi declined an average of 1.05% per decade across the island, with the largest declines at high elevations Frazier & Giambelluca 2016) • From 1920–2012, wet-season (Nov.–April) precipitation on Kauaʻi declined an average of 0.94% per decade across the island, with the largest declines at high elevations and on the windward side (as much as 4%; Frazier & Giambelluca 2016) <p>Projected future trends</p> <p>Precipitation projections are highly uncertain because they vary in projected direction and magnitude, and will be affected by shifts in the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), as well as the amount of future greenhouse gas emissions. Possible future scenarios include:</p> <ul style="list-style-type: none"> • No change to moderate decrease in precipitation by 2100 (Keener et al. 2013) • Moderate decrease in precipitation across all seasons by 2100 (26% to 41% decrease in wet-season precipitation; 3% to 6% decrease in dry-season precipitation; Elison Timm et al. 2015) • By 2100, increased precipitation at high elevations (up to 20%) 	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> • Changes in moisture availability will likely affect shoreline plant community composition and individual species' distributions (Warshauer et al. 2009) • Precipitation stimulates erosion, which can increase cave sedimentation (U.S. Fish and Wildlife Service 2006) <p>Geographic variation</p> <ul style="list-style-type: none"> • Mahaʻulepu Cave is sensitive to high precipitation (Vuln. Assessment Workshop, pers. comm., 2017)

	and slightly decreased precipitation at low elevations in the dry season; slight increases at high elevations and slight decreases at low elevations in the wet season (Zhang et al. 2016)	
<i>Drought</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> Drought length increased in 1980–2011 compared to 1950–1979 (Chu et al. 2010) Drought conditions are usually less prevalent during La Niña years, and more prevalent during El Niño years (Dolling et al. 2009; Chu et al. 2010) <p>Projected future trends</p> <p>Drought projections are highly uncertain because they are primarily dependent on precipitation projections, which are variable and have high uncertainty. Possible future scenarios include:</p> <ul style="list-style-type: none"> By 2100, drought risk is likely to increase for low-elevation leeward areas, decrease at high elevations, and remain static elsewhere (Keener et al. 2012) 	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> Drought may confer an advantage to alien vegetation and displace native vegetation (Natural Areas Reserve System 2012) Drought may cause mortality of cave fauna (e.g., Kaua‘i cave amphipod [<i>Spelaeorchestia koloana</i>], cave wolf spider) and/or increase cave vulnerability to invasive species by reducing humidity (U.S. Fish and Wildlife Service 2006) Drought conditions enhance fire risk (Conry & Cannarella 2010) <p>Geographic variation</p> <ul style="list-style-type: none"> Koloa caves/lava tubes may be particularly vulnerable to prolonged drought, which desiccates caves (Vuln. Assessment Workshop, pers. comm., 2017)
<i>Streamflow & riverine flooding</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> From 1943–2008, streamflow declined by 22% and baseflow declined by 23% compared to 1913–1943, with larger declines during the dry season and increased high-flow variability (Bassiouni & Oki 2013) Jan. –March streamflow is typically low following El Niño events, and high following La Niña events; this pattern is enhanced during positive Pacific Decadal Oscillation (PDO) phases (Bassiouni & Oki 2013) Streamflow is typically highest from Jan.–March (wet season) and lowest during July–Sept. (dry season; Bassiouni & Oki 2013) No consistent trends were found in stream peak discharge statewide (Oki et al. 2010) 	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> High streamflow can cause coastal flooding, potentially increasing sandy beach erosion (Fletcher et al. 2012) and/or altering shoreline position (Fletcher et al. 2002); for example, flooding on the Wailua River reshapes Wailua Beach (Fletcher et al. 2002) Streamflow delivers sediment to the coast, which can alter shoreline position (Fletcher et al. 2012) Streamflow and flooding increase pollutant and contaminant delivery to downstream areas (Mead & Wiegner 2010), including shorelines Streamflow and flooding increase lava tube and cave

	<p>Projected future trends</p> <ul style="list-style-type: none"> No regional streamflow or flooding projections are available, but if mean annual precipitation were to decline, streamflow scenarios may include: <ul style="list-style-type: none"> Continuing decline of low flows and baseflow (Strauch et al. 2015) Flashier and/or more variable streamflow (Strauch et al. 2015) 	<p>siltation, shortening the “life” of the tube (Howarth 1972)</p> <p>Geographic variation</p> <ul style="list-style-type: none"> Sensitivity to altered streamflow depends on shoreline hardening (Vuln. Assessment Workshop, pers. comm., 2017) Sand dune sensitivity is highest where there is a dune next to a river mouth (Vuln. Assessment Workshop, pers. comm., 2017) Maha‘ulepu, Hā‘ena caves, and Koloa lava tubes are vulnerable to flooding (Vuln. Assessment Workshop, pers. comm., 2017)
Wind & circulation	<p>Historical and current trends</p> <ul style="list-style-type: none"> Since the 1990s, the Pacific trade winds (both the Walker and Hadley cells) have increased, corresponding with a negative Pacific Decadal Oscillation (PDO) phase (England et al. 2014) Trade wind direction has shifted from predominantly northeast to east from 1973–2009 (Garza et al. 2012), which represents a cyclical shift that is known to complete its cycle approximately every 45 years (Wentworth 1949) The frequency of trade wind inversion (TWI) occurrence increased an average of 16% starting in 1990 (Longman et al. 2015) <p>Projected future trends</p> <p>Projections for the TWI are moderately uncertain due to the influence of large-scale atmospheric patterns (e.g., El Niño–Southern Oscillation [ENSO] and Pacific Decadal Oscillation [PDO]). Possible future scenarios include:</p> <ul style="list-style-type: none"> 8% increase in TWI frequency of occurrence, corresponding to an almost 50% decrease in days without a well-defined TWI (decrease from 17% of days currently to 9% of days by 2100; 	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> Trade wind waves contribute to sandy beach erosion on north, east, and south Kaua‘i (Fletcher et al. 2012) and flooding on east Kaua‘i (Fletcher et al. 2002) Trade wind waves deliver sediment to the Mana Plain, contributing to the extensive sandy shoreline habitat in that area (Fletcher et al. 2012) Trade winds build sand dunes on windward coasts, but can transport beach sediment inland if dunes are not properly managed, affecting beach distribution and erosion (Romine et al. 2013) Trade winds also facilitate inland plant dispersal and prevent seaward colonization of some plant species (Warshauer et al. 2009) Trade winds may help moderate high temperatures in shoreline habitats (Vuln. Assessment Reviewers, pers. comm., 2017)

	<p>Zhang et al. 2016)</p> <ul style="list-style-type: none"> • Possible decrease in TWI base height, ranging from small (Zhang et al. 2016) to more significant (Lauer et al. 2013) <p>Surface wind speed and direction may change, but studies have reached varying conclusions:</p> <ul style="list-style-type: none"> • Nov.–Dec. surface wind speeds across the Hawaiian Islands may decrease strongly by 2100, with small changes in surface wind speed possible in other seasons (Storlazzi et al. 2015) • Surface winds in the Hawaiian Islands may increase modestly, with a very modest increase in frequency of strong wind days (Zhang et al. 2016) 	
--	---	--

Non-Climate Stressors

Sensitivity of the habitat to climate change impacts may be highly influenced by the existence and extent of, and current exposure to, non-climate stressors (Table 2). Development and shoreline armoring reduce shoreline habitat extent, exacerbate erosion risk, and prevent landward shoreline migration in response to sea level rise. Development and recreation also elevate coastal pollution, which can alter community structure or cause native species' mortality. Recreation also facilitates the spread of invasive vegetation, which can outcompete native vegetation and increase vulnerability to cliff failure.

Table 2. Key non-climate stressors that affect the overall sensitivity of shoreline habitats to climate change. All factors were ranked as having a moderate or higher impact on one or more of the shoreline sub-habitats.

Non-climate stressors <i>All sub-habitats: Moderate-high impact (high confidence)</i>	
<i>Residential & commercial development</i>	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> • Development can destroy and fragment shoreline habitats and degrade remnant habitats by increasing disturbance and vulnerability to invasive species, exacerbating erosion, and contributing to pollution (Hawai'i Department of Land and Natural Resources 2015) • Development can prevent landward migration of shoreline habitats in response to sea level rise and coastal erosion (Fletcher et al. 1997; Romine & Fletcher 2013) • Shoreline development can affect erosion patterns; for example, Kīkīāola Harbor disrupts alongshore sediment transport and prevents sediment delivery to 'Ō'ōmanō Beach (Fletcher et al. 2012) • Coastal lighting associated with development can negatively impact seabirds and sea turtles (Hawai'i Department of Land and Natural Resources 2015) • Urbanization increases surface and sediment runoff, which may increase rocky shoreline sedimentation and alter community structure by favoring sediment-tolerant organisms (e.g., turf algae, anemones; Thompson et al. 2002) • Development can directly destroy cave habitats by opening or filling them during construction, reduce cave humidity via groundwater recharge reductions, and/or affect sediment processes and ecology by removing surface vegetation and associated root systems (Howarth 1972; U.S. Fish and Wildlife Service 2006) • Cave habitat fragmentation caused by development may increase the vulnerability of cave fauna to drought by trapping them in areas without moisture refugia (U.S. Fish and Wildlife Service 2006) • <i>Pattern of exposure:</i> Consistent across habitat, although overall, development on Kaua'i is concentrated on the east and south shores and around several towns on the north shore (Hawai'i Department of Land and Natural Resources 2015)
<i>Recreation</i>	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> • Pedestrian and off-road vehicle use can trample and degrade dune, beach, cave, and other shoreline vegetation, contribute to erosion, and reduce habitat for nesting seabirds (U.S. Fish and Wildlife Service 2006; Warshauer et al. 2009; Hawai'i Department of Land and Natural Resources 2015); vegetation impacts are particularly acute at Polihale State Park and near the Pacific Missile Range Facility

	<p>(Warshauer et al. 2009)</p> <ul style="list-style-type: none"> • Recreation may introduce non-native vegetation, exacerbating associated impacts (Conry & Cannarella 2010) • Recreation can also introduce pollutants (e.g., bathroom, sanitation, and parking lot runoff, trash; Vuln. Assessment Workshop, pers. comm., 2017) • Cave species are sensitive to smoke from cigarettes and campfires (U.S. Fish and Wildlife Service 2006) • <i>Pattern of exposure:</i> Consistent across habitat
<i>Invasive/ problematic trees & shrubs</i>	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> • Without restoration intervention, invasive plants such as mangroves (<i>Bruguiera gymnorhiza</i>, <i>Rhizophora mangle</i>), ironwood (<i>Casuarina equisetifolia</i>), and haole koa (<i>Leucaena leucocephala</i>) can displace native species in beach, coastal strand, and cliff habitats (e.g., by shading out low-growing vegetation; Warshauer et al. 2009) and degrade wildlife habitat quality (Mālama Hulē'ia & Hawai'i Sea Grant 2015) • Invasive trees (e.g., ironwood) can increase the likelihood of cliff and/or bluff area collapse, which can smother native vegetation (Warshauer et al. 2009) • Non-native plants may not have adequate/deep enough root systems to sustain cave species (U.S. Fish and Wildlife Service 2006) • <i>Pattern of exposure:</i> Consistent across habitat
<i>Seawalls</i>	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> • Shoreline hardening (e.g., seawalls, revetments, groins) built to protect development and infrastructure contributes to erosion, narrowing, and loss of fronting beach, and flanking erosion on adjacent beaches (O'Connell 2010; Fletcher et al. 2012) • Shoreline hardening affects natural patterns of beach accretion and erosion by altering alongshore sediment transport and restricting upland sediment contributions (O'Connell 2010; Fletcher et al. 2012; Romine et al. 2013) • Shoreline armoring (e.g., seawalls, breakwaters, groins) may provide some artificial rocky shoreline habitat and increase habitat connectivity by providing hard surfaces between isolated rocky shoreline segments (Thompson et al. 2002) • <i>Pattern of exposure:</i> Localized; 10% of Kaua'i's shoreline is armored (11 miles; University of Hawai'i Sea Grant College Program 2014 and citations therein)
<i>Pollution & poisons</i>	<p>Potential impacts on habitat</p> <ul style="list-style-type: none"> • Pollutants degrade shoreline habitats, reducing habitat suitability for valued wildlife including seabirds, shorebirds (Hawai'i Department of Land and Natural Resources 2015), and cave specialists (U.S. Fish and Wildlife Service 2006); pollutants can remain in sand/sediment for long periods of time (Thompson et al. 2002) • Pollutants and poisons (e.g., oil spills, nutrient loading) can affect rocky shoreline community structure (Thompson et al. 2002) • Marine debris (e.g., abandoned fishing gear, trash) can be deposited on Hawai'i's beaches and cause monk seal or turtle mortality via entanglement or ingestion (NOAA 2010) • Some caves were historically lost or degraded due to their use as garbage pits (U.S. Fish and Wildlife Service 2006) • <i>Pattern of exposure:</i> Localized around streams and developed areas

<i>Invasive/ problematic pathogens & parasites</i>	Potential impacts on habitat <ul style="list-style-type: none"> Cesspools and other on-site sewage disposal systems can elevate pathogens in groundwater, surface water, and nearshore environments, with potential negative effects on wildlife and humans (Whittier & El-Kadi 2014) <i>Pattern of exposure:</i> Localized around rivers
--	--

Adaptive Capacity

Although Kauaʻi has extensive shoreline area, many shoreline habitats have been lost, degraded, or altered by human activity, and face continued use conflicts with development and military activities (Table 3). Although coastal species are generally tolerant of variable conditions, Kauaʻi's shoreline habitats have many endangered, threatened, or particularly vulnerable species, reducing overall resilience. Additionally, human impacts on shoreline communities impair the inherent resiliency of shoreline species and make it difficult for shoreline habitats to resist and respond to sea level rise and coastal erosion. Workshop participants indicated that shoreline habitats have high public value and high constituency group support for habitat conservation and management. Additionally, the protected status of several shoreline areas may bolster overall habitat management potential. Additional funding and coordination with private landowners would further improve shoreline management opportunities.

Table 3. Adaptive capacity factors that influence the ability of shoreline habitats to adapt to projected future climate changes. Factors that receive a ranking of “High” enhance adaptive capacity for this habitat (+), while factors that receive a ranking of “Low” undermine adaptive capacity (-).

Adaptive capacity factors <i>Sand dunes, caves:</i> Low adaptive capacity (high confidence) <i>Sandy beaches, rocky shorelines, cliffs:</i> Low-moderate adaptive capacity (high confidence)	
<i>Extent & integrity</i> <i>Sand dunes, caves:</i> Low (high confidence) <i>Sandy beaches, rocky shorelines, cliffs:</i> Moderate-high (high confidence)	<p>+/- Rocky shoreline and cliff habitats have a high extent and moderate habitat integrity; the most pristine cliff habitat occurs on the Nā Pali Coast, away from development (Vuln. Assessment Workshop, pers. comm., 2017), although the Nā Pali Coast is also a dynamic natural system with high level of erosion (Vuln. Assessment Reviewers, pers. comm., 2017)</p> <p>+/- Sandy beach habitats have a high extent but low-moderate habitat integrity (Vuln. Assessment Workshop, pers. comm., 2017); Kauaʻi has 75 miles of sandy shoreline but some beaches (e.g., Waimea Beach, near Ōʻōmanō Point) have experienced accelerated erosion or been otherwise negatively impacted by human shoreline activities (Fletcher et al. 2012)</p> <p>- Sand dunes have a low extent and low habitat integrity (Vuln. Assessment Workshop, pers. comm., 2017); sand dune habitat is restricted to the Mahaʻulepu sub-region of south Kauaʻi and backing the beaches of Mana Plain in west Kauaʻi (Fletcher et al. 2012)</p> <p>- Caves have a low-moderate extent and low habitat integrity (Vuln. Assessment Workshop, pers. comm., 2017); caves have experienced significant loss and degradation over time (U.S. Fish and Wildlife Service 2006)</p>

	<ul style="list-style-type: none"> - Some shoreline habitats on Kaua'i have been modified; for example, the Mana coastal plain used to be a wetland, but was drained and is now managed by the Department of Fish and Wildlife (Vuln. Assessment Workshop, pers. comm., 2017)
<p><i>Habitat isolation</i></p> <p><i>All sub-habitats:</i> High (high confidence)</p>	<ul style="list-style-type: none"> + Larvae of many rocky shoreline species are easily re-distributed via tidal and water action (Thompson et al. 2002) - Barriers to shoreline habitat dispersal include roads, agriculture, alien vegetation, residential and commercial development, and geologic, atmospheric, and water features (Vuln. Assessment Workshop, pers. comm., 2017)
<p><i>Resistance & recovery</i></p> <p><i>All sub-habitats:</i> Low (high confidence)</p>	<ul style="list-style-type: none"> + Sandy shorelines are very dynamic, so fauna may be adapted to some degree of variability (Thompson et al. 2002; Fletcher et al. 2012) + Rocky shorelines may be more resistant to climatic changes (e.g., erosion) due to hard substrates, and typically recover rapidly from disturbance via recruitment from unaffected areas (Thompson et al. 2002) + Many rocky shoreline species are tolerant of extreme conditions, which may make them more resilient to some stressors (e.g., pollution; Thompson et al. 2002) + Sea cliffs may have lower exposure to mammalian predators and human disturbance, making them refugia for native species (U.S. Fish and Wildlife Service 2016) - Coastal systems (e.g., beaches) have a limited capacity to accrete sediment and keep pace with sea level rise due to small tidal ranges (<2 m [<6.5 ft]; Kane et al. 2015) - Hawaiian beach sand is primarily marine-derived carbonate skeletal material, not terrestrially sourced material (Anderson et al. 2015), but armoring reduces any potential terrestrially sourced sediment accretion and prevents beaches from migrating landward (Romine & Fletcher 2013), increasing sandy shoreline vulnerability to erosion as sea levels rise - Human-driven degradation of coastal areas impairs shorelines' ability to recover from natural stressors such as drought, storms, and landslides by reducing seed sources (Warshauer et al. 2009) and by physically limiting space needed for natural processes associated with these dynamic ecosystems (Vuln. Assessment Reviewers, pers. comm., 2017) - Small populations make cave species vulnerable to extirpation, and paired with low reproductive potentials, undermine reproduction and colonization opportunities following disturbance (U.S. Fish and Wildlife Service 2006)
<p><i>Habitat diversity</i></p> <p><i>All sub-habitats:</i> Low (high confidence)</p>	<ul style="list-style-type: none"> + Kaua'i has a variety of different sandy beach types, including embayed beaches, pocket beaches, wide and steep beaches, and narrow and gentle sloping beaches; these beach types will likely exhibit variable vulnerability (Fletcher et al. 2012) +/- Shoreline habitats support a variety of wildlife, including several rare and endemic cave species (e.g., Kaua'i cave wolf spider; Kaua'i cave amphipods; U.S. Fish and Wildlife Service 2006), seabirds (Hawai'i Department of Land and Natural Resources 2011), and nesting or basking marine species (Hawai'i Department of Land and Natural Resources 2015)

	<ul style="list-style-type: none"> - Shoreline habitats have several species and species groups that are particularly vulnerable to climate change, including rare plants and endangered/threatened wildlife (e.g., Hawaiian monk seal, green sea turtle, wedge-tailed shearwaters; Vuln. Assessment Reviewers, pers. comm., 2017) - Several shoreline bird species have been lost in the past (Olson & James 2004) - Endemic cliff vegetation has increased risk of extinction or endangerment because restricted distributions may enhance component species' vulnerability to climate and non-climate impacts (Sakai et al. 2002)
<p><i>Management potential</i></p> <p><i>All sub-habitats: Moderate (high confidence)</i></p>	<ul style="list-style-type: none"> + High public value: Shoreline habitats provide subsistence, recreation, hazard buffers, scenic and cultural benefits, and support the economy (Vuln. Assessment Workshop, pers. comm., 2017) + Shoreline habitats provide a variety of ecosystem services, including food provisioning, tourism/recreation, storm protection, flood and erosion control, water filtration, and cultural services (Kane et al. 2012, 2015; Hawai'i Department of Land and Natural Resources 2015) + Several shoreline areas have some type of protected status and management (e.g., Kīlauea Point National Wildlife Refuge, Koloa Caves), which may help buffer some habitat impacts (U.S. Fish and Wildlife Service 2006, 2016) + There are several constituency groups that support shoreline habitats and have positive impacts on shoreline conservation, including environmental groups, native Hawaiian groups, and tourism agencies (Vuln. Assessment Workshop, pers. comm., 2017) +/- Low-moderate societal support for habitat management: There is strong governance support, but managers need more local landowner support and financial support to take action (Vuln. Assessment Workshop, pers. comm., 2017) +/- Extreme events could increase societal support for habitat management and conservation: Chronic beach erosion could increase support, while hurricanes could increase or decrease support depending on impacts (Vuln. Assessment Workshop, pers. comm., 2017) - Low-moderate likelihood of managing or alleviating climate change impacts: Managers have the technical knowledge, but alleviating impacts is very hard financially and socially due to private property issues (e.g., little incentive to adapt due to multiple landowners, high property values, and absentee residents; private property rights inhibit regulatory oversight; Vuln. Assessment Workshop, pers. comm., 2017) - Low manager capacity/ability to cope with habitat impacts: There are not enough managers, funding support, expertise, and infrastructure, and managers cannot manage private property (Vuln. Assessment Workshop, pers. comm., 2017) - Shoreline habitats face conflicting interests with development and military operations (i.e. the military keeps Mana Plain drained on west side; Vuln. Assessment Workshop, pers. comm., 2017)

Recommended Citation

Reynier WA, Hilberg LE, Kershner JM, Gregg RM. 2018. Shoreline Habitats: A Habitat Climate Change Vulnerability Assessment Synthesis for Kauaʻi. EcoAdapt, Bainbridge Island, WA.

Produced in cooperation with the Pacific Islands Climate Change Cooperative, with funding from the U.S. Fish and Wildlife Service.

Literature Cited

- Anderson TR, Fletcher CH, Barbee MM, Frazer LN, Romine BM. 2015. Doubling of coastal erosion under rising sea level by mid-century in Hawaiʻi. *Natural Hazards* **78**:75–103.
- Baker JD, Littnan CL, Johnston DW. 2006. Potential effects of sea level rise on the terrestrial habitats of endangered and endemic megafauna in the Northwestern Hawaiian Islands. *Endangered Species Research* **4**:1–10.
- Bassiouni M, Oki DS. 2013. Trends and shifts in streamflow in Hawaiʻi, 1913–2008. *Hydrological Processes* **27**:1484–1500.
- Chu P-S. 2002. Large-scale circulation features associated with decadal variations of tropical cyclone activity over the Central North Pacific. *Journal of Climate* **15**:2678–2689.
- Chu P-S, Chen YR, Schroeder TA. 2010. Changes in precipitation extremes in the Hawaiian Islands in a warming climate. *Journal of Climate* **23**:4881–4900.
- Conry PJ, Cannarella RJ. 2010. Hawaiʻi statewide assessment of forest conditions and resource strategy. Hawaiʻi Department of Land and Natural Resources - Division of Forestry and Wildlife, Honolulu, HI. Available from <http://dlnr.hawaii.gov/forestry/files/2013/09/SWARS-Entire-Assessment-and-Strategy.pdf>.
- Cooper HM, Chen Q, Fletcher CH, Barbee MM. 2013. Assessing vulnerability due to sea-level rise in Maui, Hawaiʻi using LiDAR remote sensing and GIS. *Climatic Change* **116**:547–563.
- Cox TE, Baumgartner E, Philippoff J, Boyle KS. 2011. Spatial and vertical patterns in the tidepool fish assemblage on the island of Oʻahu. *Environmental Biology of Fishes* **90**:329–342.
- Dolling K, Chu P-S, Fujioka F. 2009. Natural variability of the Keetch–Byram Drought Index in the Hawaiian Islands. *International Journal of Wildland Fire* **18**:459–475.
- Elison Timm O, Diaz HF, Giambelluca TW, Takahashi M. 2011. Projection of changes in the frequency of heavy rain events over Hawaiʻi based on leading Pacific climate modes. *Journal of Geophysical Research: Atmospheres* **116**:D04109.
- Elison Timm O, Giambelluca TW, Diaz HF. 2015. Statistical downscaling of rainfall changes in Hawaiʻi based on the CMIP5 global model projections. *Journal of Geophysical Research: Atmospheres* **120**:2014JD022059.
- Elison Timm O, Takahashi M, Giambelluca TW, Diaz HF. 2013. On the relation between large-scale circulation pattern and heavy rain events over the Hawaiian Islands: Recent trends and future changes. *Journal of Geophysical Research: Atmospheres* **118**:4129–4141.
- England MH, McGregor S, Spence P, Meehl GA, Timmermann A, Cai W, Gupta AS, McPhaden MJ, Purich A, Santoso A. 2014. Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. *Nature Climate Change* **4**:222–227.
- Eversole D, Andrews A. 2014. Climate change impacts in Hawaiʻi: A summary of climate change and its impacts to Hawaiʻi's ecosystems and communities. UNHI-SEAGRANT-TT-12-04. University of Hawaiʻi at Mānoa Sea Grant College Program.
- Ferguson G, Gleeson T. 2012. Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change* **2**:342–345.

- Fletcher CH, Grossman EE, Richmond BM, Gibbs AE. 2002. Atlas of natural hazards in the Hawaiian coastal zone. USGS Geologic Investigations Series I-2761. United States Printing Office.
- Fletcher CH, Mullane RA, Richmond BM. 1997. Beach loss along armored shorelines on O‘ahu, Hawaiian Islands. *Journal of Coastal Research* **13**:209–215.
- Fletcher CH, Romine BM, Genz AS, Barbee MM, Dyer M, Anderson TR, Lim SC, Vitousek S, Bochicchio C, Richmond BM. 2012. National assessment of shoreline change: Historical shoreline change in the Hawaiian Islands. USGS Numbered Series 2011–1051, Open-File Report. U.S. Geological Survey, Reston, VA.
- Frazier AG, Giambelluca TW. 2017. Spatial trend analysis of Hawaiian rainfall from 1920 to 2012. *International Journal of Climatology* **37**:2522–2531.
- Frazier AG, Giambelluca TW, Diaz HF, Needham HL. 2016. Comparison of geostatistical approaches to spatially interpolate month-year rainfall for the Hawaiian Islands. *International Journal of Climatology* **36**:1459–1470.
- Garza JA, Chu P-S, Norton CW, Schroeder TA. 2012. Changes of the prevailing trade winds over the islands of Hawai‘i and the North Pacific. *Journal of Geophysical Research: Atmospheres* **117**:D11109.
- Hawai‘i Department of Land and Natural Resources. 2011. Hono O Nā Pali Natural Area Reserve Management Plan. Hawai‘i Department of Land and Natural Resources, Honolulu, HI. Available from <http://dlnr.hawaii.gov/ecosystems/files/2013/07/Hono-O-Na-Pali-Management-Plan-2012-.pdf>.
- Hawai‘i Department of Land and Natural Resources. 2015. Hawai‘i’s State Wildlife Action Plan (SWAP). Prepared by H. T. Harvey and Associates, Honolulu, HI. Available from <http://www.state.hi.us/dlnr/dofaw/swap/> (accessed November 2, 2016).
- Howarth FG. 1972. Ecological studies on Hawaiian lava tubes. Technical Report 16. Bernice P. Bishop Museum. Available from <https://scholarspace.manoa.hawaii.edu/bitstream/handle/10125/25993/16.pdf?sequence=1>.
- Kane HH, Fletcher CH, Frazer LN, Anderson TR, Barbee MM. 2015. Modeling sea-level rise vulnerability of coastal environments using ranked management concerns. *Climatic Change* **131**:349–361.
- Kane HH, Fletcher CH, Frazer LN, Barbee MM. 2014. Critical elevation levels for flooding due to sea-level rise in Hawai‘i. *Regional Environmental Change* **15**:1679–1687.
- Kane HH, Fletcher CH, Romine BM, Anderson TR, Frazer NL, Barbee MM. 2012. Vulnerability assessment of Hawai‘i’s cultural assets attributable to erosion using shoreline trend analysis techniques. *Journal of Coastal Research*:533–539.
- Keener VW, Hamilton K, Izuka SK, Kunkel KE, Stevens LE, Sun L. 2013. Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 8. Climate of the Pacific Islands. NOAA Technical Report NESDIS 142-8. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C.
- Keener VW, Marra JJ, Finucane ML, Spooner D, Smith MH. 2012. Climate change and Pacific Islands: Indicators and impacts. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Island Press, Washington, D.C.
- Lauer A, Zhang C, Elison Timm O, Wang Y, Hamilton K. 2013. Downscaling of climate change in the Hawai‘i region using CMIP5 results: On the choice of the forcing fields. *Journal of Climate* **26**:10006–10030.
- Longman RJ, Diaz HF, Giambelluca TW. 2015. Sustained increases in lower-tropospheric subsidence over the central tropical North Pacific drive a decline in high-elevation rainfall in Hawai‘i. *Journal of Climate* **28**:8743–8759.

- Mālama Hulē'ia, Hawai'i Sea Grant. 2015. Red Mangrove Invasive Species Action Plan for the Hulē'ia. Available from https://malamahuleia.files.wordpress.com/2015/06/red-mangrove-invasive-species-action-plan_final.pdf.
- Mead LH, Wiegner TN. 2010. Surface water metabolism potential in a tropical estuary, Hilo Bay, Hawai'i, USA, during storm and non-storm conditions. *Estuaries and Coasts* **33**:1099–1112.
- Murakami H, Wang B, Li T, Kitoh A. 2013. Projected increase in tropical cyclones near Hawai'i. *Nature Climate Change* **3**:749–754.
- Natural Areas Reserve System. 2012. 'Ahihi-Kina'u Natural Area Reserve Management Plan. Department of Land and Natural Resources, Honolulu, HI. Available from <http://dlnr.hawaii.gov/ecosystems/files/2013/07/Ahihi-Kinau-NAR-Management-Plan.pdf>.
- NOAA. 2010. Hawai'i marine debris action plan. NOAA Office of Response and Restoration, Marine Debris Program. Available from <https://marinedebris.noaa.gov/sites/default/files/publications-files/2010%20HI%20MDAP.pdf>.
- NOAA/National Ocean Service. 2017. NOAA Tides and Currents: Sea Level Trends. Available from <http://tidesandcurrents.noaa.gov/sltrends/sltrends.html> (accessed July 13, 2017).
- O'Connell JF. 2010. Shoreline armoring impacts and management along the shores of Massachusetts and Kaua'i, Hawai'i. Puget Sound Shorelines and Impacts of Armoring - Proceedings of State of the Science Workshop. Available from http://www.realignhonoapiilani.com/uploads/8/0/4/8/80483190/oconnel_2010.pdf.
- Oki DS, Rosa SN, Yeung CW. 2010. Flood-frequency estimates for streams on Kaua'i, O'ahu, Moloka'i, Maui, and Hawai'i, State of Hawai'i. U.S. Geological Survey Scientific Investigations Report 2010–5035. U.S. Geological Survey, Reston, VA.
- Olson SL, James. 2004. Fossil birds from the Hawaiian Islands: evidence for wholesale extinction by man before western contact [reprint of *Science* 217:633–35]. Pages 1023–1025 in D. Lomolino, F. Sax, and J. H. Brown, editors. *Foundations of Biogeography: Classic Papers with Commentaries*. University of Chicago Press, Chicago and London.
- Romine BM, Fletcher CH. 2012. A summary of historical shoreline changes on beaches of Kaua'i, O'ahu, and Maui, Hawai'i. *Journal of Coastal Research* **29**:605–614.
- Romine BM, Fletcher CH. 2013. Armoring on eroding coasts leads to beach narrowing and loss on O'ahu, Hawai'i. Page in J. A. G. Cooper and O. H. Pilkey, editors. *Pitfalls of shoreline stabilization: Selected case studies*. Springer Science and Business Media, Dordrecht, Netherlands. Available from <http://www.soest.hawaii.edu/coasts/publications/Romine%20Fletcher%202013%20Oahu%20Armoring.pdf>.
- Romine BM, Fletcher CH, Barbee MM, Anderson TR, Frazer LN. 2013. Are beach erosion rates and sea-level rise related in Hawai'i? *Global and Planetary Change* **108**:149–157.
- Romine BM, Fletcher CH, Frazer LN, Anderson TR. 2016. Beach erosion under rising sea-level modulated by coastal geomorphology and sediment availability on carbonate reef-fringed island coasts. *Sedimentology*:n/a–n/a.
- Rotzoll K, Fletcher CH. 2013. Assessment of groundwater inundation as a consequence of sea-level rise. *Nature Climate Change* **3**:477–481.
- Sakai AK, Wagner WL, Mehrhoff LA. 2002. Patterns of endangerment in the Hawaiian flora. *Systematic Biology* **51**:276–302.
- Storlazzi CD, Shope JB, Erikson LH, Hegermiller CA, Barnard PL. 2015. Future wave and wind projections for United States and United States-affiliated Pacific Islands. Page 455. USGS Numbered Series Open-File Report 2015-1001, Open-File Report. U.S. Geological Survey, Reston, VA. Available from <http://pubs.er.usgs.gov/publication/ofr20151001> (accessed May 24, 2016).

- Strauch AM, MacKenzie RA, Giardina CP, Bruland GL. 2015. Climate driven changes to rainfall and streamflow patterns in a model tropical island hydrological system. *Journal of Hydrology* **523**:160–169.
- Sweet WV, Kopp RE, Weaver CP, Obeysekera J, Horton RM, Thieler ER, Zervas C. 2017. Global and regional sea level rise scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. National Oceanic and Atmospheric Administration, Silver Spring, MD.
- Takahashi M, Elison Timm O, Giambelluca TW, Diaz HF, Frazier AG. 2011. High and low rainfall events in Hawai'i in relation to large-scale climate anomalies in the Pacific: Diagnostics and future projections. American Geophysical Union, Fall Meeting 2011, Abstract #GC51D-1024 **51**. Available from <http://adsabs.harvard.edu/abs/2011AGUFMGC51D1024T> (accessed June 2, 2016).
- Thompson RC, Crowe TP, Hawkins SJ. 2002. Rocky intertidal communities: past environmental changes, present status and predictions for the next 25 years. *Environmental Conservation* **29**:168–191.
- University of Hawai'i Sea Grant College Program. 2014. Kaua'i Climate Change and Coastal Hazard Assessment. Kaua'i General Plan Update Technical Study. Available from <http://seagrant.soest.hawaii.edu/sites/default/files/publications/web-8-18-14-kc3ha-final.pdf>.
- U.S. Fish and Wildlife Service. 2006. Recovery plan for the Kaua'i Cave Arthropods: Kaua'i Cave Wolf Spider (*Adelocosa anops*) and the Kaua'i Cave Amphipod (*Spelaeorchestia koloana*). U.S. Fish and Wildlife Service, Portland, OR. Available from https://ecos.fws.gov/docs/recovery_plan/060719.pdf.
- U.S. Fish and Wildlife Service. 2016. Kilauea Point National Wildlife Refuge comprehensive conservation plan. U.S. Fish & Wildlife Service, Kilauea, Hawai'i. Available from https://www.fws.gov/uploadedFiles/Region_1/NWRS/Zone_1/Kauai_Complex/Kilauea_Point/Documents/Kilauea%20Point%20NWR%20fCCP.pdf.
- Warshauer FR, Jacobi JD, Price JP. 2009. Native coastal flora and plant communities in Hawai'i: Their composition, distribution, and status. Technical Report HCSU-014. Hawai'i Cooperative Studies Unit, University of Hawai'i at Hilo, Hilo, HI. Available from https://www.researchgate.net/profile/James_Jacobi/publication/239601172_NATIVE_COASTAL_FLORA_AND_PLANT_COMMUNITIES_IN_HAWAII_THEIR_COMPOSITION_DISTRIBUTION_AND_STATUS/links/5535dfa0cf20ea35f10ebab.pdf.
- Wentworth CK. 1949. Directional shift of trade winds at Honolulu. Available from <http://scholarspace.manoa.hawaii.edu/handle/10125/8917> (accessed March 24, 2017).
- Whittier RB, El-Kadi AI. 2014. Human health and environmental risk ranking of on-site sewage disposal systems for the Hawaiian Islands of Kaua'i, Moloka'i, Maui, and Hawai'i. State of Hawai'i Department of Health, Honolulu, HI. Available from http://health.hawaii.gov/wastewater/files/2015/09/OSDS_NI.pdf.
- Zhang C, Wang Y, Hamilton K, Lauer A. 2016. Dynamical downscaling of the climate for the Hawaiian Islands. Part II: Projection for the late twenty-first century. *Journal of Climate* **29**:8333–8354.

Hawaiian Islands Climate Synthesis Project: Vulnerability Assessment Methods and Application

Defining Terms

Exposure: A measure of how much of a change in climate or climate-driven factors a resource is likely to experience (Glick et al. 2011).

Sensitivity: A measure of whether and how a resource is likely to be affected by a given change in climate or factors driven by climate (Glick et al. 2011).

Adaptive Capacity: The ability of a resource to accommodate or cope with climate change impacts with minimal disruption (Glick et al. 2011).

Vulnerability: A function of the sensitivity of a particular resource to climate changes, its exposure to those changes, and its capacity to adapt to those changes (IPCC 2007).

Vulnerability Assessment Model

The vulnerability assessment model applied in this process was developed by EcoAdapt² (Hutto et al. 2015, EcoAdapt 2014a, EcoAdapt 2014b, Kershner 2014), and includes evaluations of relative vulnerability by local stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats and ecosystem services. Stakeholders evaluated vulnerability of each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Habitat exposure was evaluated by EcoAdapt using future climate projections from the scientific literature; ecosystem service exposure was evaluated by workshop participants using the climate impacts table provided by EcoAdapt. Each vulnerability component (i.e. sensitivity, adaptive capacity, and exposure) was divided into specific elements. For example, habitats included three elements for assessing sensitivity and five elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

Stakeholders assigned one of five rankings (High, Moderate-high, Moderate, Low-moderate, or Low) for sensitivity and adaptive capacity. Stakeholder-assigned rankings for each component were then converted into scores (High-5, Moderate-high-4, Moderate-3, Low-moderate-2, or Low-1) and the scores averaged (mean) to generate an overall score. For example, scores for each element of habitat sensitivity were averaged to generate an overall habitat sensitivity score. Scores for exposure were weighted less than scores for sensitivity and adaptive capacity; this was due to greater uncertainty about the magnitude and rate of future change. Sensitivity, adaptive capacity, and exposure scores were combined into an overall vulnerability score calculated as:

$$\text{Vulnerability} = [(\text{Climate Exposure} \times 0.5) \times \text{Sensitivity}] - \text{Adaptive Capacity}$$

² Sensitivity and adaptive capacity elements were informed by Glick et al. 2011, Manomet Center for Conservation Sciences 2013, and Lawler 2010.

Elements for each component of vulnerability were also assigned one of three confidence rankings (High, Moderate, or Low). Confidence rankings were converted into scores (High-3, Moderate-2, or Low-1) and the scores averaged (mean) to generate an overall confidence score. These approximate confidence levels were based on the Manomet Center for Conservation Sciences (2013) 3-category scale, which collapsed the 5-category scale developed by Moss and Schneider (2000) for the IPCC Third Assessment Report. The vulnerability assessment model applied here assesses the confidence associated with individual element rankings, and uses these rankings to estimate the overall level of confidence for each component of vulnerability as well as overall vulnerability.

Rankings and scores presented should be considered measures of relative vulnerability and confidence (i.e. comparing the level of vulnerability between the focal resources evaluated in this project).

Vulnerability and confidence rankings and scores for a given element were supplemented with information from the scientific literature. The final vulnerability assessment summaries for a given resource include stakeholder-assigned rankings, confidence evaluations, and narratives summarizing expert opinions and information from the scientific literature.

Habitat & Ecosystem Service Elements

Sensitivity & Exposure (Applies to Habitats and Ecosystem Services)

- 1. Climate and Climate-Driven Factors:** e.g., air temperature, precipitation, freshwater temperature, sea surface temperature, sea level rise, soil moisture, altered streamflows, etc.
- 2. Disturbance Regimes:** e.g., wildfire, flooding, drought, insect and disease outbreaks, wind, etc.
- 3. Future Climate Exposure:** e.g., consideration of projected future climate changes (e.g., temperature and precipitation) as well as climate-driven changes (e.g., altered fire regimes, altered flow regimes, shifts in vegetation types). Experts were provided with a summary of historical, current, and projected future climate changes for the main Hawaiian Islands.
- 4. Non-Climate Stressors:** e.g., land-use conversion (e.g., residential or commercial development), agriculture and/or aquaculture, transportation corridors (e.g., roads, railroads, trails), water diversions, invasive and other problematic species, pollution and poisons, etc. For non-climate stressors, experts were asked to evaluate sensitivity, whether the habitat or ecosystem service is currently exposed to that stressor, and whether the pattern of exposure is widespread and/or consistent across the study area or is highly localized (e.g., exposure to aquaculture is highly localized but exposure to invasive grasses is often widespread).

Adaptive Capacity (Habitats)

- 1. Extent and Integrity:** e.g., habitats that occur in multiple locations vs. single, small areas; high integrity vs. degraded habitats
- 2. Habitat Isolation:** e.g., adjacent to other native habitat types vs. isolated habitats, barriers to dispersal (e.g., development, energy productions, roads, water diversions, etc.)

3. Resistance and Recovery: e.g., *resistance* refers to the stasis of a habitat in the face of change, *recovery* refers to the ability to “bounce back” more quickly from stressors once they do occur

4. Habitat Diversity: e.g., diversity of component native species and functional groups in the habitat

5. Management Potential: e.g., ability of resource managers to alter the adaptive capacity and resilience of a habitat to climatic and non-climate stressors (societal value of habitats, ability to alleviate impacts)

Adaptive Capacity (Ecosystem Services)

1. Intrinsic Value and Management Potential: e.g., ability of managers to alter the adaptive capacity and resilience of a service to climatic and non-climate stressors (societal value of ecosystem services, ability to alleviate impacts)

Literature Cited

- EcoAdapt. 2014a. A climate change vulnerability assessment for aquatic resources in the Tongass National Forest. EcoAdapt, Bainbridge Island, WA.
- EcoAdapt. 2014b. A climate change vulnerability assessment for resources of Nez Perce-Clearwater National Forests. Version 3.0. EcoAdapt, Bainbridge Island, WA.
- Glick P, Stein BA, Edelson NA. 2011. Scanning the conservation horizon: A guide to climate change vulnerability assessment. National Wildlife Federation, Washington, D.C.
- Hutto SV, Higgason KD, Kershner JM, Reynier WA, Gregg DS. 2015. Climate change vulnerability assessment for the north-central California coast and ocean. Page 473. ONMS-15-02, Marine Sanctuaries Conservation Series. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD.
- Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.
- Kershner JM, editor. 2014. A climate change vulnerability assessment for focal resources of the Sierra Nevada. Version 1.0. EcoAdapt, Bainbridge Island, WA.
- Lawler J. 2010. Pacific Northwest Climate Change Vulnerability Assessment. Available from <http://climatechangesensitivity.org/>.
- Manomet Center for Conservation Science, National Wildlife Federation. 2013. The vulnerabilities of fish and wildlife habitats in the Northeast to climate change. A report to the Northeastern Association of Fish and Wildlife Agencies and the North Atlantic Landscape Conservation Cooperative. Manomet Center for Conservation Sciences, Plymouth, MA.
- Moss R, Schneider S. 2000. Towards consistent assessment and reporting of uncertainties in the IPCC TAR. In R. Pachauri and T. Taniguchi, editors. Cross-cutting issues in the IPCC Third Assessment Report. Global Industrial and Social Progress Research Institute (for IPCC), Tokyo.
-

