Cultural Coastal Habitats

Climate Change Vulnerability Assessment Synthesis for Kaua'i

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for cultural coastal habitats on Kaua'i 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

Cultural coastal habitat types considered in this assessment include lo'i pa'akai (salt ponds), loko i'a (fishponds), lo'i kalo (flooded taro farmland), and iwi kūpuna (ancestral burials). Salt ponds are traditionally used to cultivate pa'akai (sea salt), and one of the only remaining areas where this practice continues is in Hanapēpē on the southwestern coast of Kaua'i (Sproat 2016). Family tend the ponds carefully, allowing them to fill with saltwater, which is allowed to evaporate, then raking and collecting the pa'akai for cooking, food preservation, and ceremonial uses, as well as to sell (Sproat 2016). This process takes many weeks and requires hot, dry weather; bad conditions or a large storm can significantly reduce the harvest or eliminate it altogether (Sproat 2016).

Loko i'a (fishponds) are saltwater, brackish, or freshwater enclosures (natural or artificial) historically used to to cultivate fish, plants, and other freshwater and saltwater food sources in coastal areas (Keala et al. 2007; Honua Consulting 2013). Saltwater fishponds are typically the largest fishpond habitats, and occur in the ocean, bays, or inlets where ocean connectivity is regulated by stone or coral walls and sluice gates (Stone 1988; Honua Consulting 2013). Loko kuapā (rock-walled fishponds) included 'auwai (canals) that ran through the walls and connected the ponds to the sea, allowing fishpond managers to regulate salinity and easily fill, stock, and clean the ponds (Costa-Pierce 1987; Sproat 2016); loko 'umeiki were another type of saltwater fishpond that included permanent fish trap structures (Stone 1988; Honua Consulting 2013). Loko pu'uone are brackish water fishponds enclosed by sand; they are typically connected to the ocean via ditches or channels, and receive freshwater input from streams or groundwater springs (Stone 1988; Honua Consulting 2013). Freshwater fishponds were not connected to the ocean; these included loko i'a kalo (irrigated kalo ponds) and loko wai (natural ponds; Stone 1988). Fishponds range in size from 0.5 to 500 acres and support a variety of marine, estuarine, and freshwater fish species, as well as algae, seaweed, shrimp, crab, and waterbirds (Stone 1988; Keala et al. 2007).

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[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.

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Kalo (*Colocasia esculenta*) is a staple food in Native Hawaiian culture (Sproat 2016), and the Hanalei Valley contains the largest area of kalo cultivation in the state (Hawai'i Department of Land and Natural Resources 2015). Wetland kalo requires a continuous flow of fresh water to cool the plants, which was historically delivered by 'auwai (Gingerich et al. 2007).

Native Hawaiian iwi kūpuna (ancestral burials) are traditionally located along the coast (Sproat 2016); these sites are highly valued and carefully protected within Hawaiian culture because the departed person's mana (spiritual power) remains with the iwi kūpuna after their death (Kane et al. 2012), while the 'uhane (spirit) of the departed person leaves to join the 'aumākua (family gods/deified ancestors; Sproat 2016).

Salt Ponds	Rank	Confidence
Sensitivity	Moderate-High	High
Future Exposure	High	Moderate
Adaptive Capacity	Moderate	High
Vulnerability	**Moderate-High**	**High**

Fishponds	Rank	Confidence
Sensitivity	Moderate	High
Future Exposure	Moderate-High	Moderate
Adaptive Capacity	Moderate	High
Vulnerability	**Moderate**	**High**

Kalo	Rank	Confidence
Sensitivity	Moderate-High	High
Future Exposure	Moderate-High	Moderate
Adaptive Capacity	Moderate	High
Vulnerability	**Moderate**	**High**

Iwi Kūpuna	Rank	Confidence
Sensitivity	High	High
Future Exposure	High	Moderate
Adaptive Capacity	Moderate	High
Vulnerability	**Moderate-High**	**High**

Overall Cultural Coastal Habitats	Rank	Confidence
Sensitivity	Moderate-High	High
Future Exposure	Moderate-High	Moderate
Adaptive Capacity	Moderate	High
Vulnerability	**Moderate**	**High**

Habitat Vulnerability

Cultural coastal habitats on Kaua'i were evaluated within four distinct groups: salt ponds, fishponds, iwi, and kalo. Overall, cultural coastal habitats were evaluated as having moderate vulnerability to climate change due to moderate-high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and moderate adaptive capacity.

Cultural coastal habitats are vulnerable to changes in climate factors and disturbances that affect water

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availability and quality and increase pollutant and sediment delivery (e.g., saltwater intrusion, increased water temperature, changes in precipitation and streamflow, more drought, tropical storms, wind, and flooding). Sea level rise and associated coastal flooding and erosion are likely to alter habitat extent, and disturbances may also destroy structures (e.g., tropical storms, wind, flooding) or contribute to injury or mortality of crops and fish stocks (e.g., insects, disease). Non-climate stressors, including development, invasive trees/shrubs, recreation, and pollution/poisons, contribute to cultural coastal habitat loss and degradation by damaging structures, increasing sedimentation, introducing nutrients and contaminants, and allowing the establishment of invasive species.

Almost all salt cultivation within the state and over half the area of kalo cultivation occur on Kaua‘i, although the extent of all cultural coastal habitats is much reduced. These habitat types receive relatively low public and societal support, but many constituency groups also influence support and some habitat areas have been protected. The right to continue traditional practices has also been recognized by the state constitution, but enforcement of these rights is low and increased public education and support is necessary for successful habitat management and conservation.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Cultural coastal habitats on Kaua‘i are sensitive to climatic changes and disturbance regimes that affect hydrology and water quality, including saltwater intrusion, increased water temperature, changes in precipitation amount and timing, altered streamflow, more drought, and increased flooding (Table 1). These changes impact water availability, sedimentation/erosion processes, water salinity, and habitat vulnerability to invasive species, potentially reducing the growth and vigor of kalo plants, fish, and other species and materials cultivated within these habitats. Disturbance regimes may also damage cultural coastal habitats, destroying structures (e.g., via sea level rise and associated coastal erosion, tropical storms, wind, and flooding) and causing injury or mortality in crops and fish stocks (e.g., due to storms, insects, and disease), reducing habitat extent and quality and contributing to the loss of valued artifacts and traditional practices.

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Table 1. Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on cultural coastal 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. All factors were ranked as having a moderate or higher impact on these habitats.

Climatic factors and disturbance regimes	**Salt ponds:** High impact (high confidence) **Fishponds:** Moderate impact (high confidence)	**Kalo:** Moderate-high impact (high confidence) **Iwi kūpuna:** High impact (high confidence)
Sea level rise & saltwater intrusion	***Historical and current trends*** • 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]) was completely lost to erosion and is now seawalls (Romine & Fletcher 2012) ***Projected future trends*** 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: • 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) • Historical rates of beach erosion on Kaua‘i 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) • There are no projections available for saltwater intrusion,	***Potential impacts on habitat*** • Flooding associated with sea level rise has shortened the period of time during which salt can be harvested from salt ponds; frequent flooding may completely prevent harvest during some years (Sproat 2016) • Sea level rise at or greater than 2 m (6.5 ft) is likely to inundate existing salt ponds (Vuln. Assessment Reviewer, pers. comm., 2017) • Coastal erosion associated with sea level rise is likely to remove sand deposits and disturb or destroy iwi (Kane et al. 2012; Sproat 2016) • Sea level rise may inundate coastal fishponds, altering pond size, abundance, and distribution (Vitousek et al. 2009; Honua Consulting 2013; Marrack & O’Grady 2014) • Sea level rise will increase fishpond salinity by inundating ponds and enhancing saltwater intrusion into springs (Gehrke et al. 2011; Sproat 2016) • Kalo crops are vulnerable to coastal flooding and saltwater intrusion, which can cause the loss of crops due to increased water salinity and/or soil salinity (Keener et al. 2012; Sproat 2016) • Increased tidal and surface water connectivity may contribute to new exotic species introductions (MacKenzie & Bruland 2012) ***Geographic variation*** • Variation between wet and dry kalo land (Vuln.

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	but it is likely to increase due to SLR, drought, and groundwater withdrawals (Rotzoll et al. 2010; Ferguson & Gleeson 2012)	Assessment Workshop, pers. comm., 2017) • Fishpond exposure may vary based on location (Vuln. Assessment Workshop, pers. comm., 2017)
Air temperature	***Historical and current trends*** • From 1975–2006, the rate of air temperature increases has accelerated to 0.2°C (0.36°F) per decade, compared to overall increases of 0.04°C (0.07°F) per decade for all records from 1919–1975; the strongest warming is found at high elevations and in winter minimum temperatures (Giambelluca et al. 2008) ***Projected future trends*** Projections that air temperature will increase are highly certain, although the magnitude of change is less certain. Possible future scenarios include: • Air temperature increases by 2.0°C (3.6°F) to 3.5°C (6.3°F) across the Hawaiian Islands by 2100 (Zhang et al. 2016) • More frequent and more intense extreme heat days (Keener et al. 2012)	***Potential impacts on habitat*** • Air temperature affects germination in wetland plants and crops, and high temperatures may reduce germination under saline conditions (Brimacombe 2003) • Warmer, drier conditions may benefit salt ponds by speeding evaporation (Sproat 2016; Vuln. Assessment Workshop, pers. comm., 2017)
Streamflow	***Historical and current trends*** • 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)	***Potential impacts on habitat*** • Lo‘i kalo are dependent on flows of fresh water through the fields; low flows due to the combined impacts of climate change and agricultural water diversions threatens crop survival (Sproat 2016) • High flows can deliver significant sediment and contaminants to fishponds, which can reduce fishpond depth (Honua Consulting 2013)

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	Projected future trends
	• No regional streamflow projections are available, but if mean annual precipitation were to decline, streamflow scenarios may include:
	  ○ Continuing decline of low flows and baseflow (Strauch et al. 2015)
	  ○ Flashier and/or more variable streamflow (Strauch et al. 2015)	

Drought	***Historical and current trends*** • 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) ***Projected future trends*** Drought projections are highly uncertain because they are primarily dependent on precipitation projections, which are variable and have high uncertainty. Possible future scenarios include: • 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)	***Potential impacts on habitat*** • Drought significantly limits water availability for kalo cultivation, which depends on surface water for flooding the lo‘i kalo (Oki et al. 2010b; Sproat 2016) • Drought conditions may reduce fishpond water levels and/or impair water quality by reducing freshwater input and flushing (Honua Consulting 2013) • Drought may favor invasive vegetation by promoting dry conditions (Bantilan-Smith et al. 2009) • Drought may benefit salt ponds by speeding evaporation (Vuln. Assessment Workshop, pers. comm., 2017) ***Geographic variation*** • The Halele‘a moku may have more problems with drought (Vuln. Assessment Workshop, pers. comm., 2017)
Water temperature (freshwater & sea surface temperature)	***Historical and current trends*** *Sea surface temperature* • Sea surface temperatures (SST) in the Pacific Ocean increased by 0.07°C to 0.23°C (0.13°F to 0.41°F) increase per decade from 1970–2010 (Australian Bureau of Meteorology & CSIRO 2011; IPCC 2013) • In the Northeast Pacific, temperatures increased by 0.12°C (0.22°F) per decade from 1960–1990 (Casey & Cornillon 2001)	***Potential impacts on habitat*** • Water temperatures over 27°C (80.6°F) may increase the likelihood of fungal and rotting diseases in kalo (Gingerich et al. 2007) • Warmer water temperatures may alter feeding behavior, growth, reproduction, disease immunity, and survival of fishpond species, ultimately affecting community composition (Keala et al. 2007)

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	Freshwater temperature
	• No regional stream temperature trends are available; however, the following patterns typically occur:
	  ○ Stream temperatures are lower in forested areas compared to urban areas (Brasher 2003)
	  ○ Stream temperatures are lower in the wet season than during the dry season (MacKenzie et al. 2013)
	
	Projected future trends
	Sea surface temperature
	There is high certainty that SST will increase, but the magnitude of change is less certain and depends on large-scale patterns of ocean mixing and atmospheric processes (e.g., El Niño-Southern Oscillation [ENSO] and Pacific Decadal Oscillation [PDO]). Possible future scenarios include:
	• By 2100, increase between 1.3°C and 2.7°C (2.3°F and 4.9°F) in SST compared to 1970–2010 (Australian Bureau of Meteorology & CSIRO 2011)
	
	Freshwater temperature
	• Stream temperatures are likely to increase over the coming century (Gehrke et al. 2011)	

Precipitation (amount & timing)	***Historical and current trends*** • 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 Kaua‘i declined an average of 1.05% per decade across the island, with the largest declines at high elevations (Frazier & Giambelluca 2017) • From 1920–2012, wet-season (Nov.–April) precipitation on Kaua‘i declined an average of 0.94% per decade across	***Potential impacts on habitat*** • Salt cultivation is dependent on dry conditions, and changes in the amount and/or timing of precipitation may impact season length and harvest amount (Sproat 2016); increased precipitation would likely have a negative impact on salt ponds, while decreased precipitation may benefit them (Vuln. Assessment Workshop, pers. comm., 2017) • Rainfall stimulates water delivery to coastal habitats (e.g., fishponds, kalo cultivation areas) by increasing surface runoff and groundwater discharge (Pacific Coast Joint

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	the island, with the largest declines at high elevations and on the windward side (as much as 4%; Frazier & Giambelluca 2017) ***Projected future trends*** 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: • 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%) 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)	Venture Hawai'i 2006) • Fishponds rely on rainfall for fresh water delivery; drier conditions may impair fishpond water quality by reducing freshwater contributions and flushing, allowing sediment buildup (Honua Consulting 2013) ***Geographic variation*** • Increased precipitation in Kona moku (salt pond) is problematic (Vuln. Assessment Workshop, pers. comm., 2017)
Tropical storms/ hurricanes, wind, & riverine flooding	***Historical and current trends*** *Tropical storms/hurricanes* • 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) *Wind* • Since the 1990s, the Pacific trade winds (both the Walker and Hadley cells) have increased, corresponding with a	***Potential impacts on habitat*** • Storm waves and runoff can inundate fishponds, damage fishpond walls, and/or deposit sand and rock on pond bottoms, reducing pond depth (Keala et al. 2007; Honua Consulting 2013; Sproat 2016); this can result in the destruction of some structures (Sproat 2016) • Storm surge may exacerbate sea level rise impacts (e.g., increase salinity by extending tidal reach; Kane et al. 2015) • Hurricanes may promote the spread of invasive vegetation by causing significant disturbance (Hawai'i

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	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) *Riverine flooding* • No consistent trends were found in stream peak discharge statewide (Oki et al. 2010a) ***Projected future trends*** *Tropical storms/hurricanes* Tropical storm projections are highly uncertain because they are influenced by large-scale patterns within the ocean and atmosphere (Murakami et al. 2013). Possible future scenarios include: • 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) *Wind* Surface wind speed and direction may change, but studies have reached varying conclusions: • Nov.–Dec. surface wind speeds across the Hawaiian Islands may decrease greatly by 2100, with small changes in surface wind speed possible in other seasons (Storlazzi et al. 2015)	Department of Land and Natural Resources 2015) • Flooding and debris associated with storms may overwhelm and damage and clog irrigation systems for kalo, impacting water delivery on both an immediate (i.e. damaged infrastructure may need to be repaired) and longer-term basis, because water temperature may increase while flows are reduced due to damage and/or repair (Gingerich et al. 2007) • Kalo crops are vulnerable to damage from hurricanes and other large storms; Hurricane Iniki, which occurred in September of 1992, was associated with a large drop in agricultural production due to crop damage (Coffman & Noy 2009)

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	• Surface winds in the Hawaiian Islands may increase modestly, with a very modest increase in frequency of strong wind days (Zhang et al. 2016) *Riverine Flooding* • No regional stream/river flooding projections are available, but flows may become more variable/flashy if mean annual precipitation declines (Strauch et al. 2015)	
Disease	***Historical and current trends*** • No information is available about trends in diseases that impact cultural coastal habitats ***Projected future trends*** • No regional projections are available for diseases that impact cultural coastal habitats	***Potential impacts on habitat*** • Warming temperatures and changes in precipitation may alter the distribution and severity of fungal diseases and other pathogens (Hawai'i Department of Land and Natural Resources 2015), including those that impact kalo (Gingerich et al. 2007) and fish (Keala et al. 2007)
Insects	***Historical and current trends*** • No information is available about trends in insect outbreaks ***Projected future trends*** • No projections are available for insects that impact cultural coastal habitats	***Potential impacts on habitat*** • Warmer temperatures may alter the development, reproduction, survival, and distribution of insects (Régnière et al. 2012), including those that impact kalo crops

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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). Non-climate stressors, including development, invasive trees/shrubs, recreation, and pollution/poisons, contribute to cultural coastal habitat loss and degradation by damaging structures, increasing sedimentation, introducing nutrients and contaminants, and allowing the establishment of invasive species.

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

Non-climate stressors	**Salt ponds:** Moderate impact (high confidence) **Fishponds:** Moderate-high impact (high confidence) **Kalo:** Moderate-high impact (high confidence) **Iwi kūpuna:** High impact (high confidence)
Residential & commercial development	***Potential impacts on habitat*** • Development is a significant threat to the Hanapēpē salt ponds, which have been impacted by an airfield runway, a beach park and access route, and a road that runs through the salt beds; these activities increase polluted runoff into the ponds, block pond drainage, and can directly contribute to pond loss (Sproat 2016) • Impermeable surfaces associated with development degrade fishpond water quality by increasing contaminant and sediment delivery (Honua Consulting 2013; Duarte et al. 2013; Hawaiʻi Department of Land and Natural Resources 2015) • Development has contributed to the destruction of many historic fishponds (Honua Consulting 2013) • Development has replaced many loʻi kalo, contributing to the loss of the majority of the historically cultivated area (Stone 1988) • Development is strongly associated with the introduction of invasive plants, wildlife, pests, and disease (Conry & Cannarella 2010) • *Pattern of exposure:* Consistent across habitat
Invasive/ problematic trees & shrubs	***Potential impacts on habitat*** • Mangroves (e.g., *Rhizophora mangle*) can damage fishponds (Honua Consulting 2013); for example, the walls of Alekoko Fishpond have been damaged by mangrove roots (El-Kadi et al. 2008) • Mangroves can reduce fishpond depth by enhancing sedimentation (Honua Consulting 2013) • Mangroves can decrease oxygen circulation in fishponds (Honua Consulting 2013) • *Pattern of exposure:* Consistent across habitat
Recreation	***Potential impacts on habitat*** • Salt ponds may be impacted by tourism and improper public relations and education about cultural assets (Vuln. Assessment Workshop, pers. comm., 2017) • *Pattern of exposure:* Consistent across habitat
Pollution & poisons	***Potential impacts on habitat*** • Pollutants associated with runoff from roads and nearby development threaten the Hanapēpē salt ponds (Sproat 2016) • Nutrient loading (e.g., nitrogen, phosphorous) can cause phytoplankton blooms that

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	rapidly deplete dissolved oxygen (Martinez et al. 2012), threatening fish species (Mitchell et al. 2005) • Nutrient loading and toxic pollutants (e.g., organic chemicals, heavy metals) reduce habitat suitability for cultivated and native species (Hawai'i Department of Land and Natural Resources 2015) • *Pattern of exposure:* Consistent across habitat

Adaptive Capacity

Although much reduced, the extent of cultural coastal habitats on Kaua'i is relatively high, and a high proportion of Hawaiian kalo cultivation and almost all salt cultivation occurs on the island (Table 3). These habitat types receive relatively low public and societal support, but many constituency groups also influence support and some habitat areas have been placed on the Hawai'i State Register of Historic Places. The right to land access and natural resources (e.g., water rights), as well as the right to continue traditional cultural practices such as kalo and salt cultivation, have been protected by the state constitution; however, enforcement of these rights is low and education of the public is needed to increase recognition of cultural assets, rights, and practices.

Table 3. Adaptive capacity factors that influence the ability of cultural coastal 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	**Salt ponds, fishponds, kalo, and iwi kūpuna:** Moderate adaptive capacity (high confidence)
Extent & integrity **Salt pond:** Low-moderate (high confidence) **Fishpond & kalo:** Moderate-high (high confidence) **Iwi kūpuna:** Moderate-high (moderate confidence)	+ Kalo cultivation in the Hanalei River Valley (including the Hanalei National Wildlife Refuge) represents 60% of Hawai'i's kalo production (Pacific Coast Joint Venture Hawai'i 2006) +/- Pa'akai cultivation in salt ponds has largely been eliminated on the Hawaiian Islands; one of the only remaining areas is in Hanapēpē on the southwestern coast of Kaua'i (Sproat 2016) - Only 500 acres of kalo are cultivated today, a 97.5% decline from a peak of over 20,000 acres (Sproat 2016) - Many historical fishponds have been degraded or eliminated over time (Honua Consulting 2013) - Many lo'i kalo and fishponds have become degraded by invasive species without active human management (e.g., Lawai Kai Fishpond, Waimea River and Wailua River lo'i kalo; Pacific Coast Joint Venture Hawai'i 2006) - Salt ponds are geographically restricted to flat, seasonally inundated areas of impermeable clay (Vuln. Assessment Reviewers, pers. comm., 2017) - The location of many iwi kūpuna is unknown (Vuln. Assessment Workshop, pers. comm., 2017)
Habitat isolation **Salt pond & iwi**	+/- Fishponds are isolated and fragmented by roads, geologic/water/atmospheric features, water diversions, and development (Vuln. Assessment Workshop, pers. comm., 2017)

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kūpuna: Low (high confidence) **Fishpond & kalo:** Moderate (high confidence)	+/- Lo‘i kalo are isolated and fragmented by geologic features, development, roads, water diversions, and energy production (Vuln. Assessment Workshop, pers. comm., 2017)
Resistance & recovery **Salt pond & iwi kūpuna:** Low (high confidence) **Fishpond & kalo:** Moderate-high (high confidence)	- Wetland habitats, including artificial habitats such as lo‘i kalo and fishponds, appear less resilient to human-induced hydrological alterations and invasive vegetation (Pacific Coast Joint Venture Hawai‘i 2006; Van Rees & Reed 2014) - Human-driven degradation of coastal habitats impairs their ability to recover from natural stressors like drought, storms, and landslides by reducing seed sources (Warshauer et al. 2009)
Habitat diversity **Fishpond & kalo:** Low-moderate (high confidence) **Salt pond & iwi kūpuna:** No scores provided	+ Although kalo cultivation focuses on one species, over 300 varieties have been recorded (Gingerich et al. 2007) + Native aquatic fauna, such as those found in fishponds and lo‘i kalo, is typically highly endemic, rare, and unique (Brasher 2003; Pacific Coast Joint Venture Hawai‘i 2006) + Taro fields, fishponds, and salt ponds support many endangered plants and provide important habitat for endemic waterbirds, migratory shorebirds and waterfowl, fish, and invertebrates (Stone 1988; Underwood et al. 2013; Hawai‘i Department of Land and Natural Resources 2015) +/- Salt pond habitat diversity may also be affected by physical geography (Vuln. Assessment Workshop, pers. comm., 2017) +/- Fishpond habitat diversity is highly dependent on the type of fishpond, as they have different requirements (Vuln. Assessment Workshop, pers. comm., 2017)
Management potential **Salt pond & iwi kūpuna:** Low-moderate (high confidence) **Fishpond & kalo:** Moderate (high confidence)	+ Adaptive capacity will be affected by the education of the general public and tourists and by societal recognition of cultural assets, rights, and practices (Vuln. Assessment Workshop, pers. comm., 2017) + The Hanapēpē salt ponds and five Kaua‘i fishponds were added to the Hawai‘i Register of Historic Places in 1988 (Honua Consulting 2013; Sproat 2016); inclusion on the State Register means that potential development must be approved by state agencies and Native Hawaiian organizations, and an environmental assessment must be completed when the site could be affected (Sproat 2016) + A preservation plan for management and protection of iwi kūpuna is required by the Hawai‘i State Historic Preservation District before disturbance of land is permitted; the preservation plan may include landscaping, buffers, consultation with known descendants, and relocation (Kane et al. 2012) + The Hanalei Watershed Management Plan and Hanalei to Ha‘ena: Community Disaster Resilience Plan address ecosystem conditions in the region and provide guidance on potential climate change threat mitigation (Sustainable Resources Group International Inc.. 2012; Henly-Shepard 2014) +/- Moderate public value for kalo, low-moderate public value for salt ponds and fishponds, and low public value for iwi: Cultural coastal habitats provide many

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	public benefits including food, land conservation, spiritual, health, cultural, preservation, and medicine (Vuln. Assessment Workshop, pers. comm., 2017) +/- Constituency groups that influence support for cultural coastal habitats include Hue Hana Paʻakai o Hanapēpē (salt ponds), Kuaʻāina Ulu ʻAuamo (KUA; fishponds and kalo), Hui loko iʻa (fishponds), Onipaa Na Hui Kalo (kalo), Kauaʻi Taro Growers Association (kalo), Hanalui Watershed (kalo), Burial Council (iwi), Hui Malapua (iwi), and Na Hui Kupuna (iwi; Vuln. Assessment Workshop, pers. comm., 2017) +/- Moderate societal support for management and conservation of fishpond, kalo, and iwi habitat and low-moderate societal support for salt pond habitat: Societal support for these habitats is limited, and there is much room for improvement (e.g., funding, policy implementation; Vuln. Assessment Workshop, pers. comm., 2017) +/- There is increasing interest in restoring fishpond systems for their cultural, ecological, and economic benefits, but restoration projects face significant permitting, regulatory, and financial barriers (Honua Consulting 2013) +/- Some taro fields and fishponds have protected status (e.g., Hanalei National Wildlife Refuge), which may help buffer some climate impacts; other areas are not currently protected or highly managed (e.g., Wainiha Valley; Pacific Coast Joint Venture Hawaiʻi 2006) +/- Taro fields, fishponds, and salt ponds can support endangered waterbird species, and this can increase incentives for habitat management and conservation (Stone 1988; Underwood et al. 2013); however, waterbirds can also generate management challenges as waterbirds feed on valued crops (Pacific Coast Joint Venture Hawaiʻi 2006; Hawaiʻi Department of Land and Natural Resources 2015) +/- Extreme events (e.g., hurricanes) would likely have a moderate-high (salt ponds and fishponds) to high (kalo and iwi) impact on societal support for the management and conservation of this habitat (Vuln. Assessment Workshop, pers. comm., 2017) +/- Native Hawaiian access to land and natural resources (including water rights) for the purpose of engaging in traditional subsistence/cultural practices are protected within the Hawai'i State Constitution; however, these protections are not well-implemented, especially the Water Code meant to ensure a supply of fresh water for kalo cultivation (Sproat 2016) - Low-moderate manager capacity and ability to cope with habitat impacts and low (iwi) to moderate (fishponds and kalo) likelihood of managing or alleviating climate change impacts on these habitat types (Vuln. Assessment Workshop, pers. comm., 2017) - Kalo cultivation is a vital part of community self-sufficiency and food security; historical use of water diversions for large-scale agriculture limited cultivation by native communities, forcing them to depend on a western diet that relies largely on imported foods (Sproat 2016)

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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 EcoAdapt[2] (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:

Vulnerability = [(Climate Exposure*0.5) x Sensitivity] - Adaptive Capacity

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

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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.)

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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)

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