Food & Fiber

Ecosystem Service Climate Change Vulnerability Assessment Synthesis for Hawai'i

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for food and fiber on the island of Hawai'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 ecosystem service vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.*

Ecosystem Service Description

Food and fiber ecosystem services include non-industrial diversified agriculture that is ecologically and culturally appropriate, intended for local consumption, and carried out within a closed system (Vuln. Assessment Workshop, pers. comm., 2017). Aquaculture, hunting, fishing, and gathering are also used to obtain food and fiber resources, and all of these activities involve many traditional cultural practices such as feral pig (*Sus scrofa*) hunting, kalo (taro; *Colocasia esculenta*) cultivation, fishpond aquaculture, and forest, marine, and shoreline gathering (Keala et al. 2007; Hawai'i Department of Land and Natural Resources 2015). Fiber products include basketry, cordage, textiles important for cultural usage, tools, construction, and lithics (e.g., rock material used for tools; Vuln. Assessment Workshop, pers. comm., 2017).

Many food and fiber products are derived from canoe plants, a group of species that were transported to the Hawaiian Islands by early Polynesian voyagers, and then carefully propagated and cultivated for use as food and fiber (White 1994; Anderson-Fung & Maly 2002). Additionally, people cultivate traditional crops such as taro, a wetland agricultural crop typically grown on alluvial plains (Handy & Handy 1972; Kirch 2000), and construct and utilize coastal fishponds (loko i'a) for aquaculture (Costa-Pierce 1987). Native species utilized for food and fiber include freshwater and reef fish, marine crustaceans, seaweed, snails, and many plant species (Hawai'i Department of Land and Natural Resources 2015; Sproat 2016). Some non-native and invasive species (e.g., pigs, deer) compete with native species for resources, and can change the structure and function of Hawaiian ecosystems, affecting conservation efforts as well as food and fiber availability.

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[1] This information was gathered during a vulnerability assessment and scenario planning workshop in January 2017 (http://ecoadapt.org/workshops/hawaiivulnerabilityworkshop). 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.

Ecosystem Service Vulnerability

Food and fiber ecosystem services on Hawaiʻi were evaluated as having 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 adaptive capacity.

Food & Fiber	Rank	Confidence
Sensitivity	High	High
Future Exposure	High	Low
Adaptive Capacity	Low-Moderate	Moderate
Vulnerability	**High**	**Moderate**

Climate-driven changes and disturbance regimes such as altered precipitation regimes, increased air temperature, tropical storms and flooding, sea level rise, saltwater intrusion, changes in wind and circulation patterns, wildfire, insects, and disease are likely to impact cultivated crops and native species used for food and fiber on Hawaiʻi. These factors may reduce water supply and quality, stressing native ecosystems and limiting crop irrigation and plant growth. Food and fiber species may also be impacted by disturbances that damage habitats and infrastructure and cause direct species injury or mortality (e.g., tropical storms, wildfire, insects, disease). Non-climate stressors reduce habitat extent, introduce pollutants, and diminish surface water and groundwater sources, degrading habitat quality and availability for harvestable plant species. Additionally, invasive plants and wildlife alter native ecosystems that harbor species harvested for food, fiber, and other materials. In many cases, invasive plants and wildlife out-compete native species for resources or lead to the damage or decline of cultivated and/or wild plants and animals.

Although food and fiber ecosystem services are highly valued by the public, societal support is relatively low. The Hawaiian Islands have low food security due to their isolated location and dependence on imported goods and energy, which drives up the price of local agricultural products and in turn increases the competitiveness of cheap imported food. Changes in climate may encourage a shift in focus towards sustainable land use and locally produced food, but little work is being done to specifically alleviate the impacts of climate change on food and fiber ecosystem services.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Food and fiber ecosystem services are vulnerable to climate and climate-driven factors (e.g., altered precipitation regimes, increased air temperature, sea level rise, saltwater intrusion, and changes in wind/circulation patterns) that impact cultivated and native species used for food and fiber on Hawaiʻi (Table 1). Extreme events (e.g., tropical storms and flooding) and disturbance regimes (e.g., wildfire, insects, disease) also impact water resources critical for sustaining food and fiber species, and can additionally cause direct damage or mortality of species that are cultivated or harvested. Warmer air temperatures and other climate changes may increase yield in some cases, but in general are likely to reduce the quality of harvested food and fiber (Vuln. Assessment Workshop, pers. comm., 2017).

Many native plants utilized for food and fiber are likely to decline due to changing climate conditions and increasingly frequent disturbances, leading to extirpation or extinction where species are unable to persist in remaining suitable areas or shift upslope (Fortini et al. 2013). In addition, increasing coastal inundation as a result of sea level rise may cause inland expansion of fishponds; for example, Kaloko Fishpond is projected to expand by 2.25 hectares with one meter of sea level rise, 4.25 hectares with 1.5 m of sea level rise, and 6.48 hectares with 1.9 m of sea level rise (Marrack & O'Grady 2014). Eventually, fishponds may be lost where inland habitat migration is not possible due to development and other human land use (Vitousek et al. 2009; Gehrke et al. 2011; Honua Consulting 2013; Marrack & O'Grady 2014). For example, the 'Ai'ōpio Fishtrap is projected to be fully submerged by 2100 (Vitousek et al. 2009). Exposure to seasonal and high wave events are also likely to cause increases in waves that overtop the Kaloko Fishpond seawall. Such waves will occur three to four times more frequently by 2050 and more than 10 times more frequently by 2100 (Vitousek et al. 2009).

Table 1. Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on food and fiber. This ecosystem service is sensitive to the climatic factors and disturbance regimes listed below, and will likely be exposed to projected future changes in them.

Climatic factors and disturbance regimes	High impact (moderate confidence)	
Precipitation (amount) & soil moisture	***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 Hawaiʻi declined an average of 3.19% per decade across the island; declines were greatest leeward side, and declines were at least 6% per decade for most of the Kona region (Frazier & Giambelluca 2017) • From 1920–2012, wet season (Nov.–April) precipitation on Hawaiʻi declined an average of 1.64% per decade across the island, with the largest declines on the leeward side, especially in the Kona region (Frazier & Giambelluca 2017) • Since 1997, dry years were twice as common as wet years on Mauna Kea, and monthly rainfall was lower than normal for 65% of months at Puʻu Lāʻau and 71% of months at Halepōhaku (Banko et al. 2013) ***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: • Slight increase or no change by 2100 (Keener et al. 2013) • Decrease in precipitation across all seasons by 2100 (4% to 6% decrease in wet-season precipitation; 16% to 28% decrease in dry-season precipitation; Elison Timm et al. 2015)	***Potential impacts on ecosystem service*** • Increasingly dry conditions are likely to stress already-limited water resources over the coming century (Barnett et al. 2008) • 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) • Reduced precipitation may degrade the health and integrity of native ecosystems and species (Cristini et al. 2013), reducing their availability for food and fiber • Changes in precipitation will affect where crops can be grown, with some areas becoming less suitable; for instance, increased rainfall in higher-elevation areas on the windward side of the island may contribute to declines in macadamia nut (*Macadamia integrifolia*) productivity (Gross 2014) • Precipitation is closely related to streamflow (Safeeq & Fares 2012; Bassiouni & Oki 2013; Strauch et al. 2015) and water temperature (McIntosh et al. 2008), which can affect water availability and quality for native plants and crop irrigation

	• By 2100, large increase in windward precipitation in the dry season (up to 40%) and moderate increases in wet-season windward precipitation (up to 20%); decreased leeward precipitation in both seasons (up to 40%; Zhang et al. 2016)	
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) • From 1958–2009, the number of freezing days declined from ~4–5 days per year to ~1 day per year at Hilo (3,150 m [10,335 ft] elevation) (Diaz et al. 2011) ***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, with more significant increases at higher elevations (Zhang et al. 2016) • Increase in the mean freezing level height of 600–700 m (1,969–2,296 ft; Zhang et al. 2017) • More frequent and more intense extreme heat days (Keener et al. 2012)	***Potential impacts on ecosystem service*** • Increased air temperatures, especially with decreased precipitation/humidity, are associated with increased evapotranspiration in both forest and agricultural settings, exacerbating water stress in plants (Vose et al. 2016) • Temperature increases may affect crop suitability, decreasing production in areas where warmer temperatures exceed the optimal range; for instance, the lower-elevation farming communities of Pāhoa and Keaʻau may see declines in the productivity of coffee (*Coffea arabica*) and macadamia nut yields, while high-elevation areas around Waimea may see increased productivity (Gross 2014) • Higher air temperature is also related to stream temperature, which can affect taro and other crops (Kurashima 2016) • Increased air temperatures contribute to coral bleaching and reduce fish populations, which may increase gathering pressure on land (Vuln. Assessment Workshop, pers. comm., 2017)
Tropical storms/ hurricanes & riverine flooding	***Historical and current trends*** • 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) ***Projected future trends***	***Potential impacts on ecosystem service*** • Crops are vulnerable to damage from hurricanes and other large storms; for instance, after Hurricane Iniki hit Kauaʻi in September of 1992, there was a large drop in agricultural production due to the loss and damage of crops (Coffman & Noy 2009) • Low-lying crops like taro are vulnerable to inundation

	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)	by large waves during storm events, causing the loss of crops due to increased water and/or soil salinity (Keener et al. 2012) • Flooding can introduce large amounts of sediment and contaminants into fishponds and downstream areas (Honua Consulting 2013; Hawaiʻi Department of Land and Natural Resources 2015), including lowland and coastal habitats where many food and fiber products are cultivated or collected ○ Nutrient inputs can support blooms of phytoplankton and nuisance algae, altering food webs (Hoover et al. 2006; Mead & Wiegner 2010; Atwood et al. 2012) • 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); waves and runoff can result in the destruction of some structures (Sproat 2016) • Large storms (e.g., Kona storms, hurricanes) can impact fisheries by damaging boats, docks, and storage/processing facilities (Barnett 2011) • High winds associated with storms may cause damage to forest vegetation (e.g., large trees) (Gerrish 1980; Richmond et al. 2001; Jokiel 2006), accelerating invasion by non-native species on disturbed sites (Loope & Giambelluca 1998) and reducing the availability of native forest species utilized for food and fiber
Sea level rise & saltwater intrusion	***Historical and current trends*** • At Hilo station, sea levels rose an average of 3.01 mm/year (0.12 in) from 1927–2016 (equivalent to a change of 0.3 m [0.99 ft] in 100 years; NOAA/National Ocean Service 2017)	***Potential impacts on ecosystem service*** • Increasing coastal inundation as a result of sea level rise may cause shifts in estuary and fishpond habitat abundance and distribution (Vitousek et al. 2009; Marrack & O'Grady 2014)

	• Rising sea levels over the past century have accelerated beach erosion across the Hawaiian Islands (Fletcher et al. 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 rise 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) • No projections available for saltwater intrusion, but it is likely to increase due to SLR, drought, and groundwater withdrawals (Rotzoll et al. 2010; Ferguson & Gleeson 2012)	○ Increasing inundation could initially cause inland expansion of fishponds (Marrack & O'Grady 2014) ○ An overall loss in fishpond and estuarine area may be experienced if inland habitat migration is not possible due to development or other human land uses (Vitousek et al. 2009; Gehrke et al. 2011; Honua Consulting 2013; Marrack & O'Grady 2014) • Sea level rise will exacerbate exposure to and impacts of seasonal and high wave events (Vitousek et al. 2009) • Sea level rise will increase fishpond salinity by inundating ponds and enhancing saltwater intrusion into springs (Gehrke et al. 2011; Sproat 2016) • Taro 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)
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	***Potential impacts on ecosystem service*** • Drought significantly limits water availability for taro cultivation, which depends on surface water for flooding (Sproat 2016) • Drought conditions may reduce fishpond water levels and/or impair water quality by reducing freshwater input and flushing (Honua Consulting 2013) • Drought conditions impact aquatic species by reducing or eliminating streamflow and groundwater recharge (Bassiouni & Oki 2013), which also contribute to increased water temperature (Gingerich

	include: • By 2100, drought risk is likely to increase for low- and mid-elevation leeward areas, decrease for mid-elevation windward slopes, and remain static elsewhere (Keener et al. 2012)	& Wolff 2005); these conditions impact the health, survival, and successful recruitment of freshwater aquatic organisms harvested for food (Hau 2007) • Drought decreases soil moisture and increases evaporative demand, causing limited production and potential mortality in plants harvested for food (Gomes & Prado 2007) • Plants experiencing drought stress are also more likely to be damaged by insect outbreaks (Jones et al. 2006) • Drought-induced loss of native forest is likely to reduce cloud interception, water infiltration and aquifer recharge (Scholl et al. 2007; Giambelluca et al. 2011; Perkins et al. 2012, 2014), likely impacting streams and irrigation water supply
Streamflow	***Historical and current trends*** • Streamflow is typically highest from Jan.–March (wet season) and lowest during July–Sept. (dry season; Bassiouni & Oki 2013) • 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) ***Projected future trends*** • In the North Hilo-Hamakua area, a 29% reduction in streamflow would likely occur under warmer, drier conditions, with the greatest declines occurring in areas with higher precipitation levels (MacKenzie et al. 2014) • If mean annual rainfall decreases within a given watershed, it	***Potential impacts on ecosystem service*** • Taro is dependent on flows of fresh water through the fields; low flows due to the combined impacts of climate change and agricultural water diversions threatens the survival of crops (Sproat 2016) • High flows can deliver significant sediment and contaminants to fishponds, which can reduce fishpond depth (Honua Consulting 2013)

	is likely that there will be: ◦ Continuing decline of low flows and baseflow (Strauch et al. 2015) ◦ Flashier and/or more variable streamflow (Strauch et al. 2015)	
Wind & circulation	***Historical and current trends*** • Since the 1990s, the Pacific trade winds (both the Walker and Hadley cells) have increased, corresponding with a negative 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) ***Projected future trends*** 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: • An 8–9% 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; Zhang et al. 2016, 2017) • Possible decrease in TWI base height, ranging from small (Zhang et al. 2016, 2017) to more significant (Lauer et al. 2013) Surface wind speed and direction may change, but studies have reached varying conclusions: • Nov.–Dec. surface wind speeds across the Hawaiian Islands may decrease strongly by 2100, with small changes in surface	***Potential impacts on ecosystem service*** • Changes in the frequency and/or mean height of the TWI drastically reduce rainfall and relative humidity at higher elevations in Maui (Crausbay et al. 2014; Longman et al. 2015); this may drive native plant mortality and changes in species distribution that would alter montane forests (Crausbay et al. 2014; Crausbay & Hotchkiss 2015), and similar impacts are likely to be seen on Hawaiʻi. • Wind speed significantly influences potential evapotranspiration, impacting irrigation efficiency and water use (Osorio et al. 2014)

	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)	
Wildfire	***Historical and current trends*** • From 1904–2011, the overall trend has been towards increases in area burned across all of the Hawaiian Islands, but with high interannual variability (Trauernicht et al. 2015) ***Projected future trends*** • The probability of fire occurrence in grassland, shrubland, and forest areas on the leeward side of the island is expected to roughly double; wildfire risk is highest at mid-elevation sites and in grasslands (Wada et al. 2017) • Increased wildfire is likely if drier conditions and more drought occur (Trauernicht et al. 2015)	***Potential impacts on ecosystem service*** • Wildfires are larger and more severe in areas dominated by non-native grasses, which provide ample fuel; however, wildfires in grazed areas are less severe and slower to spread because cattle grazing reduces fuel biomass (Blackmore & Vitousek 2000) • Severe wildfires have the potential to convert forest area to non-native grasslands (Blackmore & Vitousek 2000; D'Antonio et al. 2011; Ellsworth et al. 2014; Trauernicht et al. 2015), reducing the availability of native forest species utilized for food and fiber and perpetuating more frequent fires • Wildfire increases runoff and erosion by removing vegetation, which can negatively affect freshwater, coastal and nearshore systems (Trauernicht et al. 2015) that harbor species utilized for food and fiber
Insects	***Historical and current trends*** • No information is available about trends in insect outbreaks ***Projected future trends*** • 0.4 million forested acres across the Hawaiian Islands are at risk of experiencing a 25% decrease in standing live basal area by 2027 due to the combined threat of insects and disease (not taking climatic changes into account; Krist et al. 2014) ○ 61,000 acres across the Hawaiian Islands are at risk due to myoporum thrips (*Klambothrips myopori*); on Hawaiʻi, the greatest threat is on the leeward side of the island, especially in low-elevation coastal forests and high-elevation forests on Mauna Kea (Krist et al. 2014)	***Potential impacts on ecosystem service*** • Insects can cause extensive damage to agricultural crops and native forest species; for instance, the two-spotted leafhopper (*Sophonia rufofascia*) impacts tropical fruits and vegetables, as well as ʻōhiʻa (*Metrosideros polymorpha*) trees and many other native plants (Lenz & Taylor 2001; Jones et al. 2006) • Impacts of invasive insects such as bruchid beetles (*Specularius impressithorax*) and Erythrina gall wasp on wiliwili (*Erythrina sandwicensis*) trees (Doccola et al. 2009; Rubinoff et al. 2010) can damage species used for fiber and other materials • Large areas of insect-killed vegetation within a

	○ 12,000 acres across the Hawaiian Islands are at risk due to Erythrina gall wasp (*Quadrastichus erythrinae*); on Hawaiʻi, the greatest threat is in the Kona district (Krist et al. 2014)	watershed can increase erosion and allow the establishment of invasive plants (Jones et al. 2006), potentially impacting species utilized for food and fiber • Warmer temperatures may alter insect development, reproduction, survival, and distribution (Régnière et al. 2012), exacerbating the above effects • Plants stressed by drought or other causes may be more vulnerable to insect-related damage and mortality (Lenz & Taylor 2001; Jones et al. 2006)
Disease	***Historical and current trends*** • No information is available for plant disease ***Projected future trends*** • Warming temperatures are expected to increase the distribution of avian diseases spread by mosquitos, such as avian malaria (*Plasmodium* spp.; Fortini et al. 2015) ○ Within the Hakalau National Wildlife Refuge, areas of montane forest where birds are at low risk of contracting malaria will be nearly eliminated by 2100 (Benning et al. 2002) • 0.4 million forested acres across the Hawaiian Islands are at risk of experiencing a 25% decrease in standing live basal area by 2027 due to the combined threat of insects and disease (not taking climatic changes into account; Krist et al. 2014) ○ Koa wilt (*Fusarium oxysporum* f. sp. *koae*) and ʻōhiʻa rust (*Austropuccinia psidii*) are the greatest disease threats on Hawaiʻi, primarily on mid-elevation windward slopes (Krist et al. 2014) ○ 53,000 acres across the Hawaiian Islands are at risk due to koa wilt (Krist et al. 2014) • Little change is expected in the suitable climatic space for ʻōhiʻa rust (Hanna et al. 2012)	***Potential impacts on ecosystem service*** • Diseases such as koa wilt and banana bunchy top disease — caused by a virus carried by aphids (*Pentalonia nigronervosa*) — can cause extensive damage to cultivated crops and native plants, resulting in widespread damage and economic loss (Nelson 2004; Conry & Cannarella 2010) • Warming air and water temperatures and changes in precipitation may alter the distribution and severity of root rot, fungal diseases, and other pathogens that can affect both native and cultivated non-native species (Gingerich et al. 2007; Conry & Cannarella 2010; Sturrock et al. 2011; Hawaiʻi Department of Land and Natural Resources 2015) • Increasing sea surface temperatures and UV radiation may make corals more susceptible to disease, which ultimately may affect habitat availability for other harvestable reef species (Hawaiʻi Department of Land and Natural Resources 2015)

Non-Climate Stressors

Sensitivity of the ecosystem service 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 (e.g., development, agriculture and aquaculture, roads/highways, energy production, recreation) reduce habitat extent, consume valuable resources, and introduce nutrients and pollutants, especially into lowland, coastal, and nearshore habitats where many species are sensitive to contaminants. These stressors, as well as groundwater development and water diversions, also impact the availability of surface water and groundwater, which are used for irrigation and habitat by native aquatic and marine species. Invasive species (e.g., pathogens/parasites, flammable grasses, reptiles and amphibians, mammalian predators, ungulates, trees and shrubs, fish, and social insects) also compete with native species for resources, alter predator/prey dynamics, and can change the structure and function of Hawaiian ecosystems, affecting food and fiber availability.

Table 2. Key non-climate stressors that affect the overall sensitivity of food & fiber ecosystem services to climate change.

Non-climate stressors	High impact (high confidence)
Residential & commercial development	***Potential impacts on ecosystem service*** • Extensive land-use conversion from agriculture (e.g., sugarcane, pineapple) to urban development has occurred over the past decade (Hawaiʻi Department of Land and Natural Resources 2015) • Development has also caused many anchialine ponds and traditional fishponds to be filled (Hawaiʻi Department of Land and Natural Resources 2015), reducing sources of shrimp used for ʻōpelu (*Decapterus macarellus*) and akule (*Selar crumenophthalmus*) fishing (Conservation Council for Hawaiʻi 2011) • 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); contaminated runoff also affects water quality in freshwater, coastal, and nearshore systems (Hawaiʻi Department of Land and Natural Resources 2015) • Development has replaced many taro fields, dryland cultivation, and other traditional agricultural systems, contributing to the loss of the majority of the historically cultivated area (Stone 1988; Kurashima 2016) • Development is strongly associated with the introduction of invasive plants, wildlife, pests, and disease (Conry & Cannarella 2010)
Agriculture & aquaculture	***Potential impacts on ecosystem service*** • Lowland areas were converted to large-scale sugarcane and pineapple plantations beginning in the 19th century (Perroy et al. 2016); over the last several decades these plantations have closed, and the plantation areas have been developed or converted to forestry, pasture, or other agricultural uses (e.g., macadamia, coffee, tropical fruit, diversified agriculture; Hawaiʻi Department of Land and Natural Resources 2015; Perroy et al. 2016) • Water diversions for crop irrigation reduce instream flows necessary for the

	cultivation of taro (Oki & Brasher 2003) • Industrialized agriculture has resulted in the diversion of water from windward areas to dry leeward fields, altering the natural distribution of water resources and limiting the cultivation of water-intensive crops on the windward side of the island (Vuln. Assessment Reviewer, pers. comm., 2017) • Pasture now covers many areas (e.g., Kohala, Kaʻū) that were traditionally Hawaiian dryland field systems of ʻuala (sweet potato) (Kurashima 2016)
Pollutions & poisons	***Potential impacts on ecosystem service*** • Wastewater effluent from treatment plants and agricultural/urban runoff introduce large amounts of nitrogen into coastal and nearshore waters, which can contribute to algal blooms (*Hypnea musciformis, Ulva fasciata*) that lower water quality and have negative impacts on fish and invertebrate species (Dailer et al. 2010) that may be harvested for food • Nutrient loading (e.g., nitrogen, phosphorous) can cause phytoplankton blooms that 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 (Hawaiʻi Department of Land and Natural Resources 2015)
Energy production	***Potential impacts on ecosystem service*** • Competition between land use for food crops or fuel crops can occur; however, the type of biofuel technology used can minimize this issue (e.g., if byproducts of food production are used; Kim et al. 2015)
Roads, highways, & trails	***Potential impacts on ecosystem service*** • Runoff from roads, highways, and trails increases erosion and can contain contaminants, affecting water quality (Conry & Cannarella 2010; Hawaiʻi Department of Land and Natural Resources 2015) and the health and survival of aquatic species utilized for food (Keala et al. 2007) • Roads, highways, and trails are also associated with the spread of invasive species (Daehler 2005) and an increased risk of wildfire ignitions associated with increased human activity (Trauernicht et al. 2015)
Groundwater development	***Potential impacts on ecosystem service*** • Increasing groundwater withdrawals may increase water salinity by shrinking the freshwater lens (Rotzoll et al. 2010), potentially damaging crops that depend on fresh water, such as taro (Keener et al. 2012)
Water diversions	***Potential impacts on ecosystem service*** • Seventy-four streams on Hawaiʻi have been diverted, primarily to provide water for agricultural and urban use (Hawaiʻi Department of Land and Natural Resources 2015); stream modifications are most prevalent at lower elevations (Brasher 2003) • Surface water diversions decrease water delivery to downstream areas, and during the dry season, diversions can cause intermittent flows or cause downstream reaches to dry up completely (Benbow et al. 2004; Oki et al. 2010), affecting traditional taro cultivation (Oki et al. 2010; Gingerich & Engott 2012) and reducing habitat availability and suitability for aquatic wildlife harvested for food (McIntosh et al. 2002; Benbow et al. 2004; Hau 2007)

	• Studies on other Hawaiian Islands indicate that agricultural water diversions may exacerbate future climate-driven hydrological shifts and/or declines in water availability (Oki et al. 2006, 2010)
Recreation	***Potential impacts on ecosystem service*** • Recreation can degrade native habitats by increasing erosion, introducing invasive species, increasing trash and pollution, and creating other impacts associated with overuse (Sutherland et al. 2001; Conry & Cannarella 2010)
Invasive/ problematic parasites & pathogens	***Potential impacts on ecosystem service*** • Reduced precipitation and resulting lower streamflows are associated with an increase in non-native parasites that use native fish as hosts (Gagne & Blum 2016) • Introduced pathogens can spread rapidly from island to island, damaging native species with no history of exposure (Conry & Cannarella 2010)
Invasive/ problematic flammable grasses	***Potential impacts on ecosystem service*** • Areas cleared for agriculture are vulnerable to invasion by flammable grasses and other invasive species (Rovzar 2016), which increase wildfire severity and area burned (Trauernicht et al. 2015) and decrease water infiltration and aquifer recharge (Perkins et al. 2012, 2014)
Invasive/ problematic amphibians & reptiles	***Potential impacts on ecosystem service*** • Coqui frogs (*Eleutherodactylus coqui*) threaten Hawaiʻi ecosystems by competing with native species for food, as well as reducing pollinators necessary for food production (Hawaiʻi Department of Land and Natural Resources 2015; Hawaiʻi Invasive Species Council 2016) • Jackson's chameleons (*Trioceros jacksonii*) consume many native insects, arthropods, and snails, putting many endemic invertebrate species at risk of extinction (Kraus et al. 2012)
Invasive/ problematic mammalian predators	***Potential impacts on ecosystem service*** • Non-native rats (*Rattus* spp.) and mongooses consume native arthropods, land snails, terrestrial and marine avifauna as well as seeds, stems and flowers of native plant species, reducing seedling recruitment (Athens et al. 2002; Hadfield & Saufler 2009; Hawaiʻi Department of Land and Natural Resources 2015; Shiels et al. 2017) • Without management, rats will proliferate in restored Hawaiian forest and influence their restoration trajectories (Shiels et al. 2017) • Rats have also been shown to damage the bark of adult koa trees (Scowcroft & Conrad 1992) • Exotic mammalian predators (e.g., rats, cats, mongooses) may contribute to degraded water quality, impacting water-based food production efforts, by elevating fecal indicator bacteria (Dunkell et al. 2011) and shedding parasites (e.g., *Leptospira*, *Toxoplasma*; Dubey & Jones 2008; Buchholz et al. 2016)
Invasive/ problematic ungulates	***Potential impacts on ecosystem service*** • Ungulate browsing and rooting impact forest habitats and native species that may be utilized for food and fiber by reducing species richness, native abundance, stem density and cover, ground litter and epiphyte cover, increasing the area of bare ground, and contributing to the introduction and establishment of invasive plant species (Weller et al. 2011; Cole & Litton 2014; Murphy et al. 2014; Hawaiʻi

	Department of Land and Natural Resources 2015; Hess 2016) • Wild pigs also root in the soil, degrading aquatic habitats by increasing runoff, soil erosion, and fecal indicator bacteria (FIB), especially in native forests (Hess 2016; Strauch et al. 2016); pigs can also degrade water quality by shedding parasites (Buchholz et al. 2016), transmit diseases to livestock (e.g., leptospirosis; Witmer et al. 2003) and their wallows can create breeding habitat for mosquito vectors (LaPointe et al. 2016) • Many non-native ungulates are utilized as game species in Hawai'i; hunting is an important aspect of cultural identity and is practiced for subsistence, as well as being a recreational opportunity (Hawai'i Department of Land and Natural Resources 2015)
Invasive/ problematic trees & shrubs	***Potential impacts on ecosystem service*** • Invasive trees and shrubs (e.g., *Morella faya*, *Falcataria moluccana*, *Prosopis pallida, Schinus terebinthifolius*) displace native species and can alter soil biochemical processes, favoring further invasion of non-natives and potentially altering the structure and function of native ecosystems (Vitousek & Walker 1989; Atwood et al. 2010; Miyazawa et al. 2016; Vuln. Assessment Reviewer, pers. comm., 2017) • In native forests, strawberry guava (*Psidium cattleianum*) reduces cloud water interception, canopy water storage, and the amount of rain that reaches the forest floor (Takahashi et al. 2011), potentially increasing water stress in native species that are harvested for food • Strawberry guava trees also reduce streamflow, affecting surface water available for irrigation (MacKenzie et al. 2014) • Mangroves (*Rhizophora mangle*) can reduce food and fiber resources by encroaching on and altering coastal habitats (MacKenzie & Kryss 2013; Hawai'i Department of Land and Natural Resources 2015) and reducing fishponds (Keala et al. 2007) ○ Mangroves reduce fishpond depth (by enhancing sedimentation), decrease oxygen circulation, and damage structural components (Honua Consulting 2013)
Invasive/ problematic fish	***Potential impacts on ecosystem service*** • Invasive fish, including mosquitofish (*Gambusia affinis*), guppies (*Poecilia reticulata*), and tilapia (*Oreochromis mossambicus*) can displace native aquatic species utilized for food or fishing bait (Brasher 2003; Havird et al. 2013; Hawai'i Department of Land and Natural Resources 2015) • Some non-native fish are utilized as food (e.g., tilapia; Keala et al. 2007)
Invasive/ problematic social insects	***Potential impacts on ecosystem service*** • Social insects were not historically present in Hawaiian ecosystems (Wilson 1996) and their introduction has affected native insect (e.g., pollinators) and bird populations through predation and/or competition for food (Wilson & Holway 2010) • Introduced ants protect aphids and other piercing/sucking insects, allowing them to thrive (Conry & Cannarella 2010), impacting many native forest plants utilized for food and fiber • Highly invasive western yellowjackets (*Vespula pensylvanica*) prey on pollinators (both introduced and endemic) and rob nectar, significantly decreasing pollination and seed set of 'ōhi'a (Hanna et al. 2013) and probably other food and fiber plants

Population growth	***Potential impacts on ecosystem service*** • Population growth drives development and tourism, increasing impacts to ecosystems and natural resources of cultural importance by accelerating the expansion of agriculture and aquaculture, groundwater development, invasive species, and the introduction of contaminants, among other impacts (Trust for Public Land & Office of Hawaiian Affairs 2015; Vuln. Assessment Workshop, pers. comm., 2016)

Adaptive Capacity

Although food and fiber ecosystem services are highly valued by the public, societal support is relatively low, in part due to the availability of cheap imported food (Table 3). This dependence on imported products, in addition to the isolated location of the Hawaiian Islands, has resulted in low food security, which is exacerbated by fluctuating global markets, declining fishery production, and rising fuel costs. However, climate change may encourage a shift in focus towards sustainable land use and locally produced food. Some increases in taro cultivation and successful fishpond restoration efforts have occurred, but little work is being done to specifically alleviate the impacts of climate change on food and fiber ecosystem services.

Table 3. Adaptive capacity factors that influence the ability of food and fiber ecosystem services to adapt to projected future climate changes. Factors that receive a ranking of "High" enhance adaptive capacity for this ecosystem service (+), while factors that receive a ranking of "Low" undermine adaptive capacity (-).

Adaptive capacity factors	Low-moderate adaptive capacity (moderate confidence)
Intrinsic value & management potential	+ Moderate-high public value: Food is a universal human need, and local food will be increasingly valued during future food shortages (Vuln. Assessment Workshop, pers. comm., 2017) + High willingness to change behavior to continue accessing this ecosystem service: The ability to import food will be reduced under climate change, so the focus should be shifted to current and potential future agricultural areas (Vuln. Assessment Workshop, pers. comm., 2017) + Climate change is implicitly included in goals related to community capacity building around disaster response, recovery, resiliency, and climate-based management (Vuln. Assessment Workshop, pers. comm., 2017). + Climate change may force people to be more flexible, and may encourage a return to management based on ahupuaʻa, a holistic concept of land use that also includes marine food sources and people's livelihoods and is at the intersection of Native Hawaiian cultural perpetuation, environmental conservation, and sustainable and self-reliant agriculture (Vuln. Assessment Workshop, pers. comm., 2017) + Some traditional agroecosystems have been shown to be resilient, and therefore their restoration could be advantageous under climate change (Kurashima 2016) +/- Climate change necessitates long-term planning for sustained food production

	(e.g., land use, sea level rise modeling studies; Vuln. Assessment Workshop, pers. comm., 2017)
	+/- Conflicts and/or areas of mutual benefit with other ecosystem services: Tourism (conflicts with money allocation and land use), regulatory services, cultural services (has mutual benefits and conflicts; 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 fishpond restoration efforts have been successful (Keala et al. 2007)
	+/- Taro fields, fishponds, and salt ponds can support endangered waterbird species, which can increase incentives for habitat management and conservation (Stone 1988; Underwood et al. 2013); however, waterbirds can also present management challenges because they feed on valued crops (Pacific Coast Joint Venture Hawaiʻi 2006; Hawaiʻi Department of Land and Natural Resources 2015)
	+/- Potential actions that could potentially increase adaptive capacity for food and fiber ecosystem services include using new technology and education, including the use of GMOs, new crop varieties and mixes, soil management, and planning to grow crops in innovative locations under future climate conditions (Vuln. Assessment Workshop, pers. comm., 2017)
	- Low-moderate societal support for managing and conserving this ecosystem service: Society often values cheap, imported food more than local and sustainably produced food; however, community-driven partnerships exist to support this ecosystem service (e.g., South Kohala Coastal Partnership, Kai Kuleana Network, Ala Kahakai Trail Association, and Puako Community Association; Vuln. Assessment Workshop, pers. comm., 2017)
	- Low-moderate likelihood of alleviating climate change impacts on this ecosystem service: There is very little work being done on alleviating climate impacts at the Department of Agriculture or landowner levels, and there is little research on the topic thus far; potential actions could include using new technology and education, including the use of GMOs, new crop varieties and mixes, soil management, and planning to grow crops in innovative locations under future climate conditions (Vuln. Assessment Workshop, pers. comm., 2017)
	- Taro 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)
	    o Only 500 acres of taro are cultivated today, a 97.5% decline from a peak of over 20,000 acres (Sproat 2016)
	- The Hawaiian Islands have low food security due to their isolated location and dependence on imported goods and energy (Loke & Leung 2013; Perroy et al. 2016), which drives up the price of local agricultural products and in turn increases the competitiveness of cheap imported food (McGregor et al. 2009)
	    o Because of the dependence on imported food and fuel, increases in global prices may exacerbate economic stress and reduce food security (McGregor

	et al. 2009; Keener et al. 2012) o Changes in import/export restrictions, excise taxes, and other regulations may affect the economic viability of food production (Perroy et al. 2016) - Loss of local-level fisheries management has resulted in statewide fisheries regulations that are unable to take small-scale variability (e.g., geology, habitats and species, timing of spawning) and local traditional knowledge into account (Vaughan & Ayers 2016), and overfishing has heavily impacted small-scale and subsistence fisheries (Vaughan & Ayers 2016) - Increases in the cost of fuel directly increase the cost of food production (McGregor et al. 2009), and rising fuel costs may interact with climate impacts such as sea level rise and storms to exacerbate economic stress (Keener et al. 2012); for instance, increased climate variability may increase fuel costs for fisherman (Barnett 2011) o Rising fuel costs may increase the production of biofuel crops, especially those that use water and nutrients efficiently (e.g., Napier grass [*Pennisetum purpureum*]; Pawlowski et al. 2017)

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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

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[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)

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