



Food & Fiber

Ecosystem Service Climate Change Vulnerability Assessment Synthesis for Maui, Lānaʻi, and Kahoʻolawe

An Important Note About this Document: This document represents an initial evaluation of vulnerability for food & fiber on Maui Nui¹ based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by habitat experts,² 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 Description³

In Hawaiʻi, agriculture, aquaculture, hunting, fishing, and gathering are used to obtain food and fiber resources, and 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; Hawaiʻi Department of Land and Natural Resources 2015). Commercial food production was dominated by sugarcane and pineapple plantations for most of the twentieth century; however, both of these crops have declined significantly over the last several decades (Perroy et al. 2016). Since 1980, the production of macadamia nuts (*Macadamia integrifolia*), coffee (*Coffea arabica*), and diversified agriculture (e.g., fruits and vegetables) has increased dramatically (Perroy et al. 2016).

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 fibers (White 1994; Anderson-Fung & Maly 2002). Notable canoe plants used for fiber include the hala tree (*Pandanus tectorius*), wauke (*Broussonetia papyrifera*), olonā (*Touchardia latifolia*), and hau bush (*Hibiscus tiliaceus*). Canoe plants used for food include ʻolena (turmeric; *Curcuma domestica*), niu (coconut palm; *Cocos nucifera*), ko (sugarcane; *Saccharum officinarum*), and maiʻa (banana; *Musa acuminata*) (White 1994). Native

¹ Molokaʻi is considered separately from this assessment. The vulnerability assessment workshop approach was not applied to Molokaʻi as the PICCC funded Ka Honua Momona between 2014-2016 to host a workshop series to identify climate-related risks and vulnerabilities, and brainstorm potential solutions and partnerships. EcoAdapt and PICCC were invited to participate in a one-day workshop with the Molokaʻi Climate Change Network in April 2017 to discuss adaptation options.

² This information was gathered during a vulnerability assessment and scenario planning workshop in August 2016 (<http://ecoadapt.org/workshops/maui/vulnerabilityworkshop>). 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.

³ Food and fiber ecosystem services includes traditional and/or subsistence practices and commercial industries; for this assessment, workshop participants focused primarily on traditional and subsistence practices.

Hawaiians also cultivated taro, a wetland agricultural crop typically grown on coastal plains (Fletcher 2010).

Most native forest species were used for ethnobotanical purposes such as construction, tools, and hula, among others (Medeiros et al. 1998). For example, of the 50 species of native trees in the dryland forest at Auwahi, all but nine have a documented use within native Hawaiian culture (Medeiros et al. 1998). Native species historically and currently harvested for these purposes are critical links to bridge past and present Hawaiian culture (Vuln. Assessment Reviewer, pers. comm., 2017).

Native Hawaiians also historically constructed and utilized coastal fishponds (loko i'a) for aquaculture, although fishpond use and distribution has declined over time (Maui has 44 remnant fishponds; Sylva 2010). Remnant loko i'a in Hawai'i are used to raise and harvest the following traditional native species: 'ama'ama (mullet; *Mugil cephalus*), awa (milkfish; *Chanos chanos*), āholehole (Hawaiian flagtail; *Kuhlia sandvicensis*), moi (threadfin; *Polydactylus sexfilis*), pāpio (jack; *Carangidae* spp.), 'ō'io (bonefish; *Albula vulpes*), awa 'aua (ladyfish; *Elops machnata*), and various edible limu (seaweeds) (Keala et al. 2007). Additionally, fishponds are used to raise some harvestable non-native species, including ogo (seaweed; *Gracilaria* spp.), rainbow trout (*Oncorhynchus mykiss*), tilapia (*Oreochromis mossambicus*), and ornamental carp (order Cyprinidae) (Keala et al. 2007).

Ecosystem Service Vulnerability

Food and fiber on Maui Nui were evaluated within two distinct groups: 1) canoe plants, other moveable plants, and non-native animals; and 2) reef/nearshore ecosystems and native forest plants. Overall, food and fiber ecosystem services were

Overall Food & Fiber	Rank	Confidence
Sensitivity	Moderate	High
Future Exposure	High	Moderate ⁴
Adaptive Capacity	Moderate	High
Vulnerability	Moderate-High	High

evaluated as having moderate-high vulnerability to climate change due to moderate sensitivity to climate and non-climate stressors, high exposure to projected future climate changes, and moderate adaptive capacity.

⁴ Workshop participants identified relevant future climate exposure factors and evaluated their confidence in the projected degree of exposure to these factors. After reviewing the scientific literature, EcoAdapt scientists evaluated and modified confidence rankings as needed to reflect uncertainties related to future climate projections. For example, future projections for precipitation are highly variable, with some models showing no change and others showing significant decreases or increases in precipitation. For more information on climate trends and future projections, please see the *Hawaiian Islands Climate Vulnerability and Adaptation Synthesis*.

Climatic changes such as water temperature, ocean acidification, and drought are likely to impact water supply and quality, increasing stress in cultivated and native species. These species may also be directly impacted by extreme events (e.g., storms) or disturbances (e.g., wildfire, insects, disease), which can impact water resources and damage infrastructure. Non-climate stressors introduce pollutants and diminish surface water and groundwater sources, degrading habitat quality and availability for harvestable 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 outcompete native species for resources or lead to the damage or decline of cultivated and/or wild plants and animals. This can change the structure and function of Hawaiian ecosystems, affecting conservation efforts as well as food and fiber availability.

Canoe plants, other moveable plants, & non-native animals	Rank	Confidence
Sensitivity	Low-Moderate	High
Future Exposure	High	Moderate
Adaptive Capacity	Moderate	High
Vulnerability	Moderate	High

Reef/nearshore ecosystems & native forest plants	Rank	Confidence
Sensitivity	High	High
Future Exposure	High	Moderate
Adaptive Capacity	Moderate	High
Vulnerability	Moderate-High	High

Although food and fiber ecosystem services are highly valued by the public, societal support for management is relatively low, and little funding is available. Food security in the Hawaiian Islands is low, but some efforts to restore fishponds and increase traditional taro cultivation have been successful.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Food and fiber ecosystem services are vulnerable to climate and climate-driven factors that impact water quality and/or supply, such as water temperature, ocean acidification, and drought (Table 1). Extreme events (e.g., storms) 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.

Many native plants utilized for food and fiber may 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). Overall, it is likely that large-scale agriculture on Maui will continue to decline (Perroy et al. 2016).

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 Canoe plants, other moveable plants, & non-native animals: Moderate sensitivity (high confidence) Reef/nearshore ecosystems & native forest plants: High sensitivity (high confidence)		
<p><i>Stream temperature</i></p>	<p>Historical and current trends</p> <ul style="list-style-type: none"> No regional stream temperature trends are available, however, the following patterns typically occur: <ul style="list-style-type: none"> 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) <p>Projected future trends</p> <ul style="list-style-type: none"> No regional stream temperature projections are available, but temperatures are likely to increase over the coming century (Gehrke et al. 2011) 	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Higher water temperatures (>27–29°C [>81–84°F]) may increase likelihood of <i>Pythium</i> rot or undermine new plant root growth in taro (Oki et al. 2010) Higher water temperatures may alter the growth, assemblages, distribution, and abundance of aquatic species used for food, such as the endemic snail hīhīwai (<i>Neritina granosa</i>; Brasher 2003; Gingerich & Wolff 2005; Oki et al. 2010), and fishpond species (Keala et al. 2007) Higher water temperatures may also favor invasive aquatic species (Brasher 2003) Higher water temperatures may contribute to decreased agricultural productivity by elevating environmental stress (Perroy et al. 2016)
<p><i>Ocean acidification</i></p>	<p>Historical and current trends</p> <ul style="list-style-type: none"> Globally, ocean surface pH has decreased by 30% (0.1 unit) since the pre-industrial era, creating more acidic conditions (IPCC 2013) In the Central North Pacific, ocean surface pH decreased by 0.0019 to 0.0002 per year (Dore et al. 2009) <p>Projected future trends</p> <p>There is high certainty that ocean pH will decline because changes in pH correspond very closely to the amount of atmospheric CO₂ absorbed by oceans (e.g., a ~30% increase in CO₂ absorbed by oceans has been associated with a ~30%</p>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Lower coral calcification rates due to ocean acidification increase reef fragility, alter reef structure, and impact coral diversity, recruitment, and abundance, which ultimately affects habitat suitability for other harvestable reef fish species (Keener et al. 2012) Ocean acidification also impacts shellfish and other marine organisms with calcium carbonate shells or skeletons by interfering with calcification processes (Eversole & Andrews 2014); many of these species are harvested directly (such as ‘opihi [<i>Cellana</i> spp.]) or support harvested species at higher levels of the food chain (Fletcher 2010)

	<p>drop in pH since pre-industrial times; IPCC 2013; Bopp et al. 2013; Gattuso et al. 2015).</p> <ul style="list-style-type: none"> By 2090–2099, ocean surface pH may decline by an additional 0.07–0.33 units compared to 1990–1999 (Bopp et al. 2013) 	
<i>Drought</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> Drought length increased in 1980–2011 compared to 1950–1979 (Chu et al. 2010) Drought conditions are usually less prevalent during La Niña years, and more prevalent during El Niño years (Dolling et al. 2009; Chu et al. 2010) <p>Projected future trends</p> <p>Drought projections are highly uncertain because they are primarily dependent on precipitation projections, which are variable and have high uncertainty. Possible future scenarios include:</p> <ul style="list-style-type: none"> Maui drought risk is likely to increase by 2100 for low- and mid-elevation leeward slopes, decrease on mid-elevation windward Haleakalā slopes and the summit of Mauna Kahālāwai, and remain static elsewhere (Keener et al. 2012) Drought risk is likely to increase by 2100 for Lānaʻi and Kahoʻolawe, except for the summit of Lānaʻi, which may not experience a change in drought risk (Keener et al. 2012) 	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Drought conditions impact aquatic species by reducing or eliminating streamflow (Grubert 2010; Bassiouni & Oki 2013) and groundwater recharge (Bassiouni & Oki 2013), which in turn contribute to increased water temperature (Gingerich & Wolff 2005); these conditions impact the health, survival, and successful recruitment of freshwater aquatic organisms harvested for food (Hau 2007) Drought impacts irrigation water availability for crops like sugarcane (King 2013) and taro, which depends on surface water from the Nā Wai ʻEhā area (Oki et al. 2010) 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 decrease 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
<i>Precipitation (amount & timing)</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> Since 1920, precipitation has decreased across the Hawaiian Islands, with the strongest drying trends occurring over the last 30 years (Frazier et al. 2016; Frazier & Giambelluca 2017) From 1920 to 2012, dry season (May–Oct.) precipitation 	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Increasingly dry conditions, especially on the leeward side of Maui, are likely to stress already-limited water resources over the coming century (King 2013) Reduced precipitation may degrade the health and integrity of native ecosystems and species (Cristini et al. 2013),

	<p>declined 1% to 5% per decade for most areas on Maui and Lānaʻi, particularly in leeward areas; Kahoʻolawe experienced more modest declines of up to 1.2% per decade (Frazier & Giambelluca 2017)</p> <ul style="list-style-type: none"> • From 1920–2012, Maui experienced the most significant wet season (Nov.–April) precipitation declines of any island in the state, decreasing 27.6 mm per decade, which ranged from 2% to 5% per decade in East Maui (Frazier & Giambelluca 2017) • The frequency of trade wind inversion (TWI) occurrence increased an average of 20% since 1990, resulting in a 31% reduction in wet-season rainfall and a 16% reduction in dry-season rainfall at nine high-elevation sites on Maui (over 1,900 m [6,234 ft]; Longman et al. 2015) <p><i>Projected future trends</i></p> <p>Precipitation projections are highly uncertain because they vary in projected direction and magnitude, and will be affected by shifts in the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), as well as the amount of future greenhouse gas emissions. Possible future scenarios include:</p> <ul style="list-style-type: none"> • Little to no change in average precipitation by 2100 (Keener et al. 2012) • Significant decreases in precipitation across all seasons by 2100, particularly in leeward areas (30% to 80% decrease in wet-season leeward precipitation and -20% to +20% change in wet-season windward precipitation; 10% to 90% decrease in dry-season precipitation) (Elison Timm et al. 2015) • By 2100, increased rainfall on windward slopes of Maui (up to 30% in the dry season), and decreased rainfall on 	<p>reducing their availability for food and fiber</p>
--	------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	-------------------------------------------------------

	Lānaʻi and leeward slopes of Maui in both seasons (Zhang et al. 2016)	
<i>Air temperature</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> 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) The annual number of freezing days on Haleakalā has declined since 1958 (Hamilton 2013) <p>Projected future trends</p> <p>Projections that air temperature will increase are highly certain, although the magnitude of change is less certain. Possible future scenarios include:</p> <ul style="list-style-type: none"> Air temperature increases of 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) More frequent and more intense extreme heat days (Keener et al. 2012) 	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> 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) Higher temperatures may elevate environmental stress, potentially decreasing agricultural productivity (Perroy et al. 2016) <ul style="list-style-type: none"> Higher temperatures are unlikely to increase productivity in many species on the Hawaiian Islands, which are limited by moisture rather than temperature (Pau et al. 2010; Crausbay et al. 2014; Krushelnycky et al. 2016)
<i>Sea level rise & shoreline change</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> At Kahului station, sea levels rose an average of 2.1 mm/year (0.08 in) from 1947–2016 (equivalent to a change of 0.21 m [0.69 ft] in 100 years; NOAA/National Ocean Service 2017) Rising sea levels over the past century have accelerated beach erosion; Maui beaches are the most erosive in Hawaiʻi (Fletcher et al. 2012) Maui beaches eroded by an average of 0.17 m/year (0.56 ft) across all beaches, with 85% of beaches eroding and 	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Coastal food and fiber sources are likely to continue being affected by erosion, flooding, and saltwater intrusion driven by sea level rise (Rooney & Fletcher 2005; Eversole & Andrews 2014; Kane et al. 2014) 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

	<p>14% to 18% of beaches accreting since the early 1900s; in that time, 11% of total beach length (6.8 km [4.23 miles]) was completely lost to erosion and is now seawalls (Romine & Fletcher 2012)</p> <ul style="list-style-type: none"> No historical/current trends are available for Lānaʻi and Kahoʻolawe <p>Projected future trends</p> <p>There is high certainty that sea levels will continue to rise at increasing rates, but the magnitude and timing of change is less certain. Possible future scenarios include:</p> <ul style="list-style-type: none"> By 2100, global sea level will likely rise between 0.3 to 2.5 m (0.98 to 8.2 ft); relative sea level may be higher in the Hawaiian Islands compared to global levels, ranging from 0.4 to 3.3 m (1.3 to 10.8 ft; Sweet et al. 2017); no regional sea level rise projections are available Sea level rise will contribute to increased saltwater intrusion, shoreline loss, coastal inundation, and groundwater inundation (Ferguson & Gleeson 2012; Cooper et al. 2013; Rotzoll & Fletcher 2013; Kane et al. 2015) Historical rates of beach erosion on Maui are likely to double with sea level rise by mid-century; 87% of beaches are likely to be eroding by 2050 (Anderson et al. 2015) No projected future trends are available for Lānaʻi and Kahoʻolawe 	<p>(Gehrke et al. 2011; Sproat 2016)</p> <ul style="list-style-type: none"> 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)
<i>Tropical storms/ hurricanes</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> Tropical storm frequency was particularly high from 1982–1995, but then decreased slightly from 1995–2000 (Chu 2002) Overall, tropical storm frequency increased slightly since 1966–1981 (Chu 2002) 	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Crops are vulnerable to damage from hurricanes and other large storms; for instance, Hurricane Iniki, which hit Kauaʻi in September of 1992, was associated with a large drop in agricultural production due to the loss and damage of crops on the island (Coffman & Noy 2009)

	<p>Projected future trends</p> <p>Tropical storm projections are highly uncertain because they are influenced by large-scale patterns within the ocean and atmosphere (Murakami et al. 2013). Possible future scenarios include:</p> <ul style="list-style-type: none"> Increased frequency and strength of tropical storm activity around the Hawaiian Islands due to a northwest shift in storm track and increased strength due to large-scale changes in environmental conditions (Murakami et al. 2013) 	<ul style="list-style-type: none"> Low-lying crops like taro are vulnerable to inundation by large waves during storm events, causing the loss of crops due to increased water and/or soil salinity (Keener et al. 2012) Storms and associated flooding can introduce large amounts of sediment and contaminants into fishponds and downstream areas (Honua Consulting 2013; Hawai'i Department of Land and Natural Resources 2015), including lowland and coastal habitats where many food and fiber products are cultivated or collected <ul style="list-style-type: none"> Nutrient inputs can support blooms of phytoplankton and nuisance algae, altering food webs (Hoover et al. 2006; Mead & Wiegner 2010; Atwood et al. 2012) Increased trace elements such as lead, zinc, and arsenic can cause direct species mortality 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 may cause damage to forests 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
Wildfire	<p>Historical and current trends</p> <ul style="list-style-type: none"> 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 	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> 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

	<p>et al. 2015)</p> <ul style="list-style-type: none"> The majority of wildfires on Maui occur during summer (June–Aug.), when conditions are warm and dry, accounting for 57% of the annual area burned (Chu et al. 2002) No wildfire data is available for Lānaʻi and Kahoʻolawe <p>Projected future trends</p> <ul style="list-style-type: none"> No regional wildfire projections are available, but increased wildfire is likely if drier conditions and more drought occur (Trauernicht et al. 2015) 	<p>spread because cattle grazing reduces fuel biomass (Blackmore & Vitousek 2000)</p> <ul style="list-style-type: none"> 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
<i>Insects</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> No information is available about trends in insect outbreaks <p>Projected future trends</p> <ul style="list-style-type: none"> 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) <ul style="list-style-type: none"> 12,000 acres across the Hawaiian Islands are at risk due to Erythrina gall wasp (<i>Quadrastichus erythrinae</i>); on Kauaʻi, the greatest threat is in mid-elevation forests on the leeward side (Krist et al. 2014) 61,000 acres across the Hawaiian Islands are at risk due to myoporum thrips (<i>Klambothrips myopori</i>; Krist et al. 2014) 	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Insects can cause extensive damage to agricultural crops and native forest species; for instance, the two-spotted leafhopper (<i>Sophonia rufofascia</i>) impacts tropical fruits and vegetables, as well as ʻōhiʻa trees and many other native plants (Lenz & Taylor 2001; Jones et al. 2006) Impacts of invasive insects such as bruchid beetles (<i>Specularius impressithorax</i>) and Erythrina gall wasp on wiliwili (<i>Erythrina sandwicensis</i>) trees (Medeiros et al. 2008; Docola et al. 2009; Rubinoff et al. 2010) can damage fibers as well as surfboard and lei materials (Vuln. Assessment Reviewer, pers. comm., 2017) Large areas of insect-killed vegetation within a 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 impact on species used for food and fiber Plants stressed by drought or other causes may be more

		vulnerable to insect-related damage and mortality (Lenz & Taylor 2001; Jones et al. 2006)
<i>Disease</i>	<p>Historical and current trends</p> <ul style="list-style-type: none"> No information is available for plant disease <p>Projected future trends</p> <ul style="list-style-type: none"> 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) <ul style="list-style-type: none"> On Maui, the greatest threat from ‘ōhi’a rust (<i>Austropuccinia psidii</i>) is on mid-elevation windward slopes (Krist et al. 2014) 53,000 acres across the Hawaiian Islands are at risk due to koa wilt (<i>Fusarium oxysporum</i> f. sp. <i>koa</i>); on Maui, the greatest threat is on mid-elevation windward slopes Krist et al. 2014) Little change is expected in the suitable climatic space for ‘ōhi’a rust (Hanna et al. 2012) 	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Increasing sea surface temperatures may make corals more susceptible to disease, which ultimately may affect habitat availability for harvestable reef fish species (Hawai’i Department of Land and Natural Resources 2015) Warming air and water temperatures and changes in precipitation may alter the distribution and severity of root rot, fungal diseases, vector-borne diseases (e.g., avian malaria, dengue fever), and other pathogens that can impact wildlife and human populations (Conry & Cannarella 2010; Kolivras 2010; Sturrock et al. 2011; Hawai’i Department of Land and Natural Resources 2015), including humans who hunt and gather in forest areas (Vuln. Assessment Reviewer, pers. comm., 2017) Diseases such as koa wilt, caused by a soil-borne disease organism, and banana bunchy top disease, caused by a virus carried by aphids (<i>Pentalonia nigronervosa</i>), can cause extensive damage to both cultivated and native plants, resulting in widespread damage and economic loss (Nelson 2004; Conry & Cannarella 2010) Rapid ‘ōhi’a death (caused by the fungal pathogen <i>Ceratocystis</i>) has caused extensive tree mortality in ‘ōhi’a stands on Hawai’i and is spreading to other islands (Keith et al. 2015; Loope 2016) Parasite infections in native freshwater fish may increase if climate and human-driven changes reduce streamflows (Gagne & Blum 2016) Increasing temperatures and UV radiation may make corals more susceptible to disease, which ultimately may affect habitat availability for other harvestable reef species (Hawai’i 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, roads and highways) introduce nutrients and pollutants 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 surface- and groundwater availability 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, fish, and social insects) 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 and fiber to climate change.

Non-climate stressors	
Canoe plants, other moveable plants, & non-native animals: Moderate-high sensitivity (high confidence)	
Reef/nearshore ecosystems & native forest plants: High sensitivity (high confidence)	
<i>Residential & commercial development</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Extensive land-use conversion from agriculture (e.g., sugarcane, pineapple) to residential and resort development has occurred over the past decade, especially around Mānele Bay on Lānaʻi and in West Maui (Hawaiʻi Department of Land and Natural Resources 2015) Development has also caused many anchialine ponds to be filled (Hawaiʻi Department of Land and Natural Resources 2015), reducing sources of shrimp used for ʻōpelu (<i>Decapтерus macarellus</i>) and akule (<i>Selar crumenophthalmus</i>) fishing (Conservation Council for Hawaiʻi 2011) Development has also caused the loss (Wolanski et al. 2009) and sedimentation of some fishpond systems (Sylva 2010) Development contributes to contaminant runoff, affecting water quality in freshwater, coastal, and nearshore systems (Sylva 2010; Hawaiʻi Department of Land and Natural Resources 2015)
<i>Pollution & poisons</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> 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 (<i>Hypnea musciformis</i>, <i>Ulva fasciata</i>) that lower water quality and have negative impacts on fish and invertebrate species (Dailer et al. 2010) that may be harvested for food Urban areas are associated with particularly high nutrient inputs; on Maui, the highest are in Lahaina, Kihei, and Kahului where wastewater treatment plants are located (Dailer et al. 2010)
<i>Roads, highways, & trails</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Runoff from roads, highways, and trails increases erosion and can contain contaminants, affecting water quality (Conry & Cannarella 2010; Hawaiʻi Department

	<p>of Land and Natural Resources 2015) and the health and survival of aquatic species utilized for food (Keala et al. 2007)</p> <ul style="list-style-type: none"> 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)
<i>Groundwater development</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Groundwater withdrawals from the Īao aquifer, which supplies most water for non-agricultural use in Maui, doubled between 1970 and 2005; this occurred during a period of drought and declining agricultural irrigation (Engott & Vana 2007) Agricultural irrigation increases local groundwater recharge on Maui due to the additional surface runoff in a small area, but more efficient irrigation methods and reduced acreage have led to an overall decline in irrigation since 1970 (Engott & Vana 2007); irrigation declines combined with periods of low precipitation and drought could decrease aquifer recharge (Engott & Vana 2007), although there is no net gain for the island if the irrigation water source is in a different aquifer or watershed, and more efficient irrigation methods are more useful for mitigating water consumption (Vuln. Assessment Reviewer, pers. comm., 2017) Increasing groundwater withdrawals may increase water salinity by shrinking the freshwater lens, potentially damaging crops that depend on fresh water, such as taro (Rotzoll et al. 2010; Gingerich & Engott 2012) Pasture irrigation for beef cattle uses large amounts of groundwater, as well as energy for pumping (King 2013)
<i>Water diversions</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Maui has the highest streamflow diversions statewide (Hawai'i Department of Land and Natural Resources 2015); diversions are most prevalent at lower elevations (Brasher 2003), and exist in all Nā Wai 'Ehā streams (Oki et al. 2010) Diverted water supports some food production via crop and pastureland irrigation, although diverted water is also utilized for golf courses and other human landscapes; historically, sugarcane used the vast majority of diverted water (Oki et al. 2010) Surface water diversions decrease water delivery to downstream areas; during the dry season, diversions can cause intermittent flows or cause downstream reaches to dry up completely (Oki et al. 2010) Reduced streamflow negatively affects traditional taro cultivation (Oki et al. 2010; Gingerich & Engott 2012) and reduces habitat availability and suitability for aquatic wildlife harvested for food (McIntosh et al. 2002; Benbow et al. 2004; Hau 2007)
<i>Invasive/ problematic parasites & pathogens</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> Reduced precipitation and resulting lower streamflows are associated with an increase in non-native parasites that use native 'o'opu (gobies) 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); for instance, rapid 'ōhi'a death can cause high rates of tree mortality, potentially shifting forest species composition (Mortenson et al. 2016), impacting native forest resources and watershed integrity (Loope 2016)

<i>Invasive/ problematic flammable grasses</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> • 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)
<i>Invasive/ problematic reptiles & amphibians</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> • Coqui frogs (<i>Eleutherodactylus coqui</i>) threaten Hawaiian ecosystems by competing with native species for food, as well as reducing pollinators necessary for food production (Hawai'i Department of Land and Natural Resources 2015; Hawai'i Invasive Species Council 2016)
<i>Invasive/ problematic mammalian predators</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> • Non-native rats (<i>Rattus</i> spp.) 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; Hawai'i 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) 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., <i>Leptospira</i>, <i>Toxoplasma</i>; Dubey & Jones 2008; Buchholz et al. 2016)
<i>Invasive/ problematic ungulates</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> • 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; Hawai'i 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)
<i>Invasive/ problematic trees</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> • Invasive trees (e.g., <i>Morella faya</i>, <i>Falcataria moluccana</i>, <i>Prosopis pallida</i>) displace native species and can alter soil biochemical processes, favoring further invasion of non-natives and potentially altering stream food webs, aquifers and nearshore

	<p>coastal waters (Vitousek & Walker 1989; Atwood et al. 2010; Miyazawa et al. 2016)</p> <ul style="list-style-type: none"> • In native forests, strawberry guava (<i>Psidium cattleianum</i>) reduces cloud water interception, canopy water storage, and the amount of rain that reaches the forest floor in native forests (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 (<i>Rhizophora mangle</i>) 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 fishponds (Keala et al. 2007)
<i>Invasive/ problematic fish</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> • Invasive fish, including mosquitofish (<i>Gambusia affinis</i>), guppies (<i>Poecilia reticulata</i>), and tilapia 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, rainbow trout, carp; Keala et al. 2007)
<i>Invasive/ problematic social insects</i>	<p>Potential impacts on ecosystem service</p> <ul style="list-style-type: none"> • 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), influencing native plant reproductive potentials (Vuln. Assessment Reviewer, pers. comm., 2017) • 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 (<i>Vespula pensylvanica</i>) 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

Adaptive Capacity

Although food and fiber ecosystem services are highly valued by the public, societal support is relatively low, with little funding available to support managing this service to alleviate some climate change impacts (Table 3). Overall, the Hawaiian Islands have low food security due to their remote location and dependence on imported products. However, taro cultivation has increased, and some fishpond restoration efforts have been successful and could support native and introduced species harvested for food.

Table 3. Adaptive capacity factors that influence the ability of food and fiber 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	
Canoe plants, other moveable plants, & non-native animals: Moderate sensitivity (high confidence)	
Reef/nearshore ecosystems & native forest plants: Moderate sensitivity (high confidence)	
<i>Intrinsic value & management potential</i>	<ul style="list-style-type: none"> + High public value (Vuln. Assessment Workshop, pers. comm., 2016) + The cultivation of taro and other traditional crop has increased over the last decade (Vuln. Assessment Reviewer, 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 Hawai'i 2006; Hawai'i Department of Land and Natural Resources 2015) - Low-moderate human willingness to change behavior (Vuln. Assessment Workshop, pers. comm., 2016) - Low-moderate societal support for management (Vuln. Assessment Workshop, pers. comm., 2016) - Low-moderate likelihood of alleviating climate change impacts: There is limited funding available to address the impacts of climate change on this ecosystem service (Vuln. Assessment Workshop, pers. comm., 2016) - The Hawaiian Islands have relatively low food security, due to the dependence on imported products (Perroy et al. 2016) <ul style="list-style-type: none"> 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) - 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)

Recommended Citation

Hilberg LE, Reynier WA, Kershner JM, Gregg RM. 2018. Food & Fiber: An Ecosystem Service Climate Change Vulnerability Assessment Synthesis for Maui, Lānaʻi, and Kahoʻolawe. EcoAdapt, Bainbridge Island, WA.

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

Literature Cited

- Anderson TR, Fletcher CH, Barbee MM, Frazer LN, Romine BM. 2015. Doubling of coastal erosion under rising sea level by mid-century in Hawai'i. *Natural Hazards* **78**:75–103.
- Anderson-Fung PO, Maly K. 2002. Hawaiian ecosystems and culture: Why growing plants for lei helps to preserve Hawai'i's natural and cultural heritage. Pages 177–205 in J. R. Hollyer, editor. *Growing Plants for Hawaiian Lei; 85 Plants for Gardens, Conservation, and Business*. College of Tropical Agriculture and Human Resources, University of Hawai'i at Mānoa, Honolulu, HI.
- Athens JS, Toggle HD, Ward JV, Welch DJ. 2002. Avifaunal extinctions, vegetation change, and Polynesian impacts in prehistoric Hawai'i. *Archaeology in Oceania* **37**:57–78.
- Atwood TB, Wiegner TN, MacKenzie RA. 2012. Effects of hydrological forcing on the structure of a tropical estuarine food web. *Oikos* **121**:277–289.
- Atwood TB, Wiegner TN, Turner P, MacKenzie RA. 2010. Potential effects of an invasive nitrogen-fixing tree on a Hawaiian stream food web. *Pacific Science* **64**:367–379.
- Barnett J. 2011. Dangerous climate change in the Pacific Islands: food production and food security. *Regional Environmental Change* **11**:229–237.
- Bassiouni M, Oki DS. 2013. Trends and shifts in streamflow in Hawai'i, 1913–2008. *Hydrological Processes* **27**:1484–1500.
- Benbow ME, Burky AJ, Way CM. 2004. The use of two modified Breder traps to quantitatively study amphidromous upstream migration. *Hydrobiologia* **527**:139–151.
- Blackmore M, Vitousek PM. 2000. Cattle grazing, forest loss, and fuel loading in a dry forest ecosystem at Pu'u Wa'aWa'a Ranch, Hawai'i. *Biotropica* **32**:625–632.
- Bopp L et al. 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences* **10**:6225–6245.
- Brasher AMD. 2003. Impacts of human disturbances on biotic communities in Hawaiian streams. *BioScience* **53**:1052–1060.
- Buchholz AE, Katz AR, Galloway R, Stoddard RA, Goldstein SM. 2016. Feral swine *Leptospira* seroprevalence survey in Hawai'i, USA, 2007–2009. *Zoonoses and Public Health* **63**:584–587.
- Chu P-S. 2002. Large-scale circulation features associated with decadal variations of tropical cyclone activity over the Central North Pacific. *Journal of Climate* **15**:2678–2689.
- Chu P-S, Chen YR, Schroeder TA. 2010. Changes in precipitation extremes in the Hawaiian Islands in a warming climate. *Journal of Climate* **23**:4881–4900.
- Chu P-S, Yan W, Fujioka F. 2002. Fire-climate relationships and long-lead seasonal wildfire prediction for Hawai'i. *International Journal of Wildland Fire* **11**:25–31.
- Coffman M, Noy I. 2009. In the eye of the storm: Coping with future natural disasters in Hawai'i. University of Hawai'i at Mānoa. Available from http://www.economics.hawaii.edu/research/workingpapers/wp_09-4.pdf.
- Cole RJ, Litton CM. 2014. Vegetation response to removal of non-native feral pigs from Hawaiian tropical montane wet forest. *Biological Invasions* **16**:125–140.
- Conry PJ, Cannarella RJ. 2010. Hawai'i statewide assessment of forest conditions and resource strategy. Hawai'i Department of Land and Natural Resources - Division of Forestry and Wildlife, Honolulu, HI. Available from <http://dlnr.hawaii.gov/forestry/files/2013/09/SWARS-Entire-Assessment-and-Strategy.pdf>.

- Conservation Council for Hawai'i. 2011. Anchialine pools: Windows to Hawai'i's underground labyrinth - Loko 'Ōpae 'Ula: 'Īpuka I Ke Kaiaola Malalo Honua. Available from http://www.conservehi.org/documents/CCH_PosterGuide11.pdf.
- Cooper HM, Chen Q, Fletcher CH, Barbee MM. 2013. Assessing vulnerability due to sea-level rise in Maui, Hawai'i using LiDAR remote sensing and GIS. *Climatic Change* **116**:547–563.
- Crausbay SD, Frazier AG, Giambelluca TW, Longman RJ, Hotchkiss SC. 2014. Moisture status during a strong El Niño explains a tropical montane cloud forest's upper limit. *Oecologia* **175**:273–284.
- Cristini L, Cox LJ, Konan DE, Eversole D. 2013. Climate change and the visitor industry: People, place, culture, and the Hawai'i experience. University of Hawai'i Sea Grant College Program. Available from http://seagrantsoest.hawaii.edu/sites/default/files/publications/web-hita-climatechange-visitorindustry_0.pdf.
- Daehler CC. 2005. Upper-montane plant invasions in the Hawaiian Islands: Patterns and opportunities. *Perspectives in Plant Ecology, Evolution and Systematics* **7**:203–216.
- Dailer ML, Knox RS, Smith JE, Napier M, Smith CM. 2010. Using $\delta^{15}\text{N}$ values in algal tissue to map locations and potential sources of anthropogenic nutrient inputs on the island of Maui, Hawai'i, USA. *Marine Pollution Bulletin* **60**:655–671.
- D'Antonio CM, Hughes RF, Tunison JT. 2011. Long-term impacts of invasive grasses and subsequent fire in seasonally dry Hawaiian woodlands. *Ecological Applications* **21**:1617–1628.
- Doccola JJ, Smith SL, Strom BL, Medeiros AC, von Allmen E; 2009. Systemically applied insecticides for treatment of Erythrina gall wasp, *Quadrastichus erythrinae* Kim (Hymenoptera: Eulophidae). *Arboriculture & Urban Forestry*, Vol **35**:173–181.
- Dolling K, Chu P-S, Fujioka F. 2009. Natural variability of the Keetch–Byram Drought Index in the Hawaiian Islands. *International Journal of Wildland Fire* **18**:459–475.
- Dore JE, Lukas R, Sadler DW, Church MJ, Karl DM. 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proceedings of the National Academy of Sciences* **106**:12235–12240.
- Dubey JP, Jones JL. 2008. *Toxoplasma gondii* infection in humans and animals in the United States. *International Journal for Parasitology* **38**:1257–1278.
- Dunkell DO, Bruland GL, Evensen CI, Walker MJ. 2011. Effects of feral pig (*Sus scrofa*) exclusion on enterococci in runoff from the forested headwaters of a Hawaiian watershed. *Water, Air, & Soil Pollution* **221**:313–326.
- Elison Timm O, Giambelluca TW, Diaz HF. 2015. Statistical downscaling of rainfall changes in Hawai'i based on the CMIP5 global model projections. *Journal of Geophysical Research: Atmospheres* **120**:2014JD022059.
- Ellsworth LM, Litton CM, Dale AP, Miura T. 2014. Invasive grasses change landscape structure and fire behaviour in Hawai'i. *Applied Vegetation Science* **17**:680–689.
- Engott JA, Vana TT. 2007. Effects of agricultural land-use changes and rainfall on ground-water recharge in central and West Maui, Hawai'i, 1926–2004. USGS Numbered Series 2007–5103, Scientific Investigations Report. Geological Survey (U.S.). Available from <http://pubs.er.usgs.gov/publication/sir20075103> (accessed November 4, 2016).
- Eversole D, Andrews A. 2014. Climate change impacts in Hawai'i: A summary of climate change and its impacts to Hawai'i's ecosystems and communities. UNIH-SEAGRANT-TT-12-04. University of Hawai'i at Mānoa Sea Grant College Program.
- Ferguson G, Gleeson T. 2012. Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change* **2**:342–345.
- Fletcher C. 2010. Hawai'i's changing climate. Briefing Sheet. Center for Island Climate Adaptation and Policy, University of Hawai'i Sea Grant College Program.

- Fletcher CH, Romine BM, Genz AS, Barbee MM, Dyer M, Anderson TR, Lim SC, Vitousek S, Bochicchio C, Richmond BM. 2012. National assessment of shoreline change: Historical shoreline change in the Hawaiian Islands. USGS Numbered Series 2011–1051, Open-File Report. U.S. Geological Survey, Reston, VA.
- Fortini L, Price J, Jacobi J, Vorsino A, Burgett J, Brinck KW, Amidon F, Miller S, Gon III S, Koob G, Paxton E. 2013. A landscape-based assessment of climate change vulnerability for all native Hawaiian plants. Technical Report HCSU-044. Hawai'i Cooperative Studies Unit, University of Hawai'i at Hilo. Available from https://dspace.lib.hawaii.edu/bitstream/10790/2620/1/TR44_Fortini_plant_vulnerability_assessment.pdf.
- Frazier AG, Giambelluca TW. 2017. Spatial trend analysis of Hawaiian rainfall from 1920 to 2012. *International Journal of Climatology* **37**:2522–2531.
- Frazier AG, Giambelluca TW, Diaz HF, Needham HL. 2016. Comparison of geostatistical approaches to spatially interpolate month-year rainfall for the Hawaiian Islands. *International Journal of Climatology* **36**:1459–1470.
- Gagne RB, Blum MJ. 2016. Parasitism of a native Hawaiian stream fish by an introduced nematode increases with declining precipitation across a natural rainfall gradient. *Ecology of Freshwater Fish* **25**:476–486.
- Gattuso J-P et al. 2015. Contrasting futures for ocean and society from different anthropogenic CO₂ emissions scenarios. *Science* **349**:aac4722.
- Gehrke PC, Sheaves MJ, Boseto D, Figa BS, Wani J. 2011. Chapter 10: Vulnerability of freshwater and estuarine fisheries in the tropical Pacific to climate change. Page in J. D. Bell, J. E. Johnson, and A. J. Hobday, editors. *Vulnerability of tropical Pacific fisheries and aquaculture to climate change*. Secretariat of the Pacific Community, Noumea, New Caledonia.
- Gerrish G. 1980. Photometric monitoring of foliage loss from a wind storm, Island of Hawai'i. Cooperative National Park Resources Studies Unit, University of Hawai'i at Mānoa, Department of Botany.
- Giambelluca TW, DeLay JK, Nullet MA, Scholl MA, Gingerich SB. 2011. Canopy water balance of windward and leeward Hawaiian cloud forests on Haleakalā, Maui, Hawai'i. *Hydrological Processes* **25**:438–447.
- Giambelluca TW, Diaz HF, Luke MSA. 2008. Secular temperature changes in Hawai'i. *Geophysical Research Letters* **35**:L12702.
- Gingerich SB, Engott JA. 2012. Groundwater availability in the Lahaina District, west Maui, Hawai'i. Page 90. Scientific Investigations Report 2012–5010. U.S. Geological Survey. Available from <http://pubs.usgs.gov/sir/2012/5010/>.
- Gingerich SB, Wolff RH. 2005. Effects of surface-water diversions on habitat availability for native macrofauna, northeast Maui, Hawai'i. U.S. Geological Survey Scientific Investigations Report 2005–5213. U.S. Geological Survey. Available from <http://pubs.usgs.gov/sir/2005/5213/>.
- Gomes FP, Prado CHBA. 2007. Ecophysiology of coconut palm under water stress. *Brazilian Journal of Plant Physiology* **19**:377–391.
- Grubert E. 2010. Maui's freshwater: Status, allocation, and management for sustainability. Master of Arts. The University of Texas at Austin, Austin, TX. Available from <https://repositories.lib.utexas.edu/bitstream/handle/2152/ETD-UT-2010-08-1835/GRUBERT-THESIS.pdf?sequence=1&isAllowed=y>.
- Hadfield MG, Saufler JE. 2009. The demographics of destruction: Isolated populations of arboreal snails and sustained predation by rats on the island of Moloka'i 1982–2006. *Biological Invasions* **11**:1595–1609.

- Hamilton K. 2013. High resolution dynamical projections of climate change for Hawai'i and other Pacific islands. University of Hawai'i, Honolulu, HI. Available from <https://www.sciencebase.gov/catalog/item/54b82e9ee4b03ff52703c95e>.
- Hanna C, Foote D, Kremen C. 2013. Invasive species management restores a plant–pollinator mutualism in Hawai'i. *Journal of Applied Ecology* **50**:147–155.
- Hanna JW, Graca RN, Kim MS, Ross-Davis AL, Hauff RD, Uchida JW. 2012. A bioclimatic approach to predict global regions with suitable climate space for *Puccinia psidii*. In S. Zeglen & P. Palacios (Eds.), *Proc. 59th Annual Western International Forest Disease Work Conference* (pp. 131–136). Leavenworth, WA, US: Department of Agriculture, Forest Service, Forest Health Protection. October 11-14, 2011.
- Hau S. 2007. Hīhīwai (*Neritina granosa* Sowerby) recruitment in 'īao and Honomanū streams on the island of Maui, Hawai'i. *Bishop Museum Bulletin in Cultural and Environmental Studies* **3**:171–181.
- Havird JC, Weeks JR, Hau S, Santos SR. 2013. Invasive fishes in the Hawaiian anchialine ecosystem: investigating potential predator avoidance by endemic organisms. *Hydrobiologia* **716**:189–201.
- Hawai'i Department of Land and Natural Resources. 2015. Hawai'i's State Wildlife Action Plan (SWAP). Prepared by H. T. Harvey and Associates, Honolulu, HI. Available from <http://www.state.hi.us/dlnr/dofaw/swap/> (accessed November 2, 2016).
- Hawai'i Invasive Species Council. 2016. Coqui Frog (*Elsotherodactylus coqui*). Available from <http://dlnr.hawaii.gov/hisc/info/invasive-species-profiles/coqui/> (accessed December 6, 2016).
- Hess SC. 2016. A tour de force by Hawai'i's invasive mammals: establishment, takeover, and ecosystem restoration through eradication. *Mammal Study* **41**:47–60.
- Honua Consulting. 2013. Final Environmental Assessment/Finding of No Significant Impact: Statewide Programmatic General Permit and Programmatic Agreement for the restoration, repair, maintenance and reconstruction of traditional Hawaiian fishpond systems across Hawai'i. Hawai'i Department of Land and Natural Resources, Honolulu, HI. Available from <http://dlnr.hawaii.gov/occl/files/2013/08/Loko-Ia-Final-EA1.pdf>.
- Hoover RS, Hoover D, Miller M, Landry MR, DeCarlo EH, Mackenzie FT. 2006. Zooplankton response to storm runoff in a tropical estuary: bottom-up and top-down controls. *Marine Ecology Progress Series* **318**:187–201.
- Intergovernmental Panel on Climate Change (IPCC). 2013. Summary for Policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jokiel P. 2006. Impact of storm waves and storm floods on Hawaiian reefs. Pages 390–398 *Proc 10th Int Coral Reef Symp.*
- Jones VP, Fukuda MT, Ullman DE, Hu JS, Borth WB. 2006. *Sophonia rufofascia*. Available from http://www.extento.hawaii.edu/kbase/crop/Type/s_rufofa.htm (accessed November 22, 2016).
- Kane HH, Fletcher CH, Frazer LN, Anderson TR, Barbee MM. 2015. Modeling sea-level rise vulnerability of coastal environments using ranked management concerns. *Climatic Change* **131**:349–361.
- Kane HH, Fletcher CH, Frazer LN, Barbee MM. 2014. Critical elevation levels for flooding due to sea-level rise in Hawai'i. *Regional Environmental Change* **15**:1679–1687.
- Keala G, Hollyer JR, Castro L. 2007. *Loko I'a: A manual on Hawaiian fishpond restoration and management*. College of Tropical Agriculture and Human Resources, University of Hawai'i at Mānoa. Available from <http://www.ctahr.hawaii.edu/oc/freepubs/pdf/Loko%20I%27a%20Full%20Publication.pdf>.

- Keener VW, Marra JJ, Finucane ML, Spooner D, Smith MH. 2012. Climate change and Pacific Islands: Indicators and impacts. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Island Press, Washington, D.C.
- Keith LM, Hughes RF, Sugiyama LS, Heller WP, Bushe BC, Friday JB. 2015. First report of *Ceratocystis* Wilt on 'ōhi'a (*Metrosideros polymorpha*). Plant Disease **99**:1276.
- King CW. 2013. A systems approach for investigating water, energy, and food scenarios in east-central Maui. The University of Texas at Austin, Austin, TX. Available from http://mauisierraclub.org/wp-content/uploads/2015/12/ULUPONO-WATER-REPORT-11_13.pdf (accessed November 23, 2016).
- Kolivras KN. 2010. Changes in dengue risk potential in Hawai'i, USA, due to climate variability and change. Climate Research **42**:1–11.
- Krist FJ, Ellenwood JR, Woods ME, McMahan AJ, Cowardin JP, Ryerson DE, Sapio FJ, Sweifler MO, Romero SA. 2014. 2013–2027 National Insect and Disease Forest Risk Assessment. FHTET 14-01. USDA Forest Service Forest Health Technology Enterprise Team, Fort Collins, CO.
- Krushelnycky P, Loope L, Fortini L, Felts J, Drake D, Starr F, Starr K, Giambelluca T, Brown M. 2016. Understanding how climate change is affecting Hawai'i's high-elevation ecosystems: an assessment of the long-term viability of Haleakalā silverswords and associated biological communities. PICCC Final Project Report. University of Hawai'i at Mānoa.
- LaPointe DA, Gaudioso-Levita JM, Atkinson CT, Egan A, Hayes K. 2016. Changes in the prevalence of avian disease and mosquito vectors at Hakalau Forest National Wildlife Refuge: A 14-year perspective and assessment of future risk. University of Hawai'i at Hilo.
- Lenz L, Taylor JA. 2001. The influence of an invasive tree species (*Myrica faya*) on the abundance of an alien insect (*Sophonia rufofascia*) in Hawai'i Volcanoes National Park. Biological Conservation **102**:301–307.
- Longman RJ, Diaz HF, Giambelluca TW. 2015. Sustained increases in lower-tropospheric subsidence over the central tropical North Pacific drive a decline in high-elevation rainfall in Hawai'i. Journal of Climate **28**:8743–8759.
- Loope L. 2016. Guidance document for Rapid 'Ōhi'a Death: Background for the 2017–2019 ROD Strategic Response Plan. Coordinating Group on Alien Pest Species, Pacific Cooperative Studies Unit, University of Hawai'i at Mānoa.
- Loope LL, Giambelluca TW. 1998. Vulnerability of island tropical montane cloud forests to climate change, with special reference to East Maui, Hawai'i. Climatic Change **39**:503–517.
- MacKenzie R, Giardina CP, Povak N, Hessburg P, Reynolds KM, Heider C, Salminen E, Kimball H. 2014. Development of a decision support tool for watershed management in the tropics. Institute of Pacific Islands Forestry, USDA Forest Service.
- MacKenzie RA, Bruland GL. 2012. Nekton communities in Hawaiian coastal wetlands: The distribution and abundance of introduced fish species. Estuaries and Coasts **35**:212–226.
- MacKenzie RA, Kryss CL. 2013. Impacts of exotic mangroves and chemical eradication of mangroves on tide pool fish assemblages. Marine Ecology Progress Series **472**:219–237.
- MacKenzie RA, Wiegner TN, Kinslow F, Cormier N, Strauch AM. 2013. Leaf-litter inputs from an invasive nitrogen-fixing tree influence organic-matter dynamics and nitrogen inputs in a Hawaiian river. Freshwater Science **32**:1036–1052.
- Marrack L, O'Grady P. 2014. Predicting impacts of sea level rise for cultural and natural resources in five national park units on the island of Hawai'i. Pacific Cooperative Studies Unit, University of Hawai'i at Mānoa. Available from <http://scholarspace.manoa.hawaii.edu/handle/10125/34111> (accessed June 15, 2016).

- McGregor A, Bourke RM, Manley M, Tubuna S, Deo R. 2009. Pacific island food security: Situation, challenges and opportunities. *Pacific Economic Bulletin* **24**:24–42.
- McIntosh MD, Benbow ME, Burky AJ. 2002. Effects of stream diversion on riffle macroinvertebrate communities in a Maui, Hawai'i, stream. *River Research and Applications* **18**:569–581.
- Mead LH, Wiegner TN. 2010. Surface water metabolism potential in a tropical estuary, Hilo Bay, Hawai'i, USA, during storm and non-storm conditions. *Estuaries and Coasts* **33**:1099–1112.
- Medeiros AC, Davenport CF, Chimera CG. 1998. Auwahi: ethnobotany of a Hawaiian dryland forest. Report. Cooperative National Park Resources Studies Unit, University of Hawai'i at Mānoa, Department of Botany. Available from <http://scholarspace.manoa.hawaii.edu/handle/10125/7355> (accessed March 26, 2017).
- Medeiros AC, Von Allmen E, Fukada M, Samuelson A, Lau T. 2008. Impact of the newly arrived seed-predating beetle *Specularius impressithorax* (Coleoptera: Chrysomelidae: Bruchinae) in Hawai'i. *Pacific Conservation Biology* **14**:6.
- Miyazawa Y, Dudley BD, Hughes RF, Vandemark J, Cordell S, Nullet MA, Ostertag R, Giambelluca TW. 2016. Non-native tree in a dry coastal area in Hawai'i has high transpiration but restricts water use despite phreatophytic trait. *Ecohydrology* **9**:1166–1176.
- Mortenson LA, Flint Hughes R, Friday JB, Keith LM, Barbosa JM, Friday NJ, Liu Z, Sowards TG. 2016. Assessing spatial distribution, stand impacts and rate of *Ceratocystis fimbriata* induced 'ōhi'a (*Metrosideros polymorpha*) mortality in a tropical wet forest, Hawai'i Island, USA. *Forest Ecology and Management* **377**:83–92.
- Murakami H, Wang B, Li T, Kitoh A. 2013. Projected increase in tropical cyclones near Hawai'i. *Nature Climate Change* **3**:749–754.
- Murphy MJ, Inman-Narahari F, Ostertag R, Litton CM. 2014. Invasive feral pigs impact native tree ferns and woody seedlings in Hawaiian forest. *Biological Invasions* **16**:63–71.
- Nelson SC. 2004. Banana bunchy top: detailed signs and symptoms. Page 22. Cooperative Extension Service, College of Tropical Agriculture and Human Resources, University of Hawai'i at Mānoa.
- NOAA/National Ocean Service. 2017. NOAA Tides and Currents: Sea Level Trends. Available from <http://tidesandcurrents.noaa.gov/sltrends/sltrends.html> (accessed July 13, 2017).
- Oki DS, Wolff RH, Perreault JA. 2010. Effects of surface-water diversion on streamflow, recharge, physical habitat, and temperature, Nā Wai 'Ehā, Maui, Hawai'i. U.S. Geological Survey Scientific Investigations Report 2010–5011. U.S. Geological Survey.
- Pacific Coast Joint Venture Hawai'i. 2006. Strategic plan for wetland conservation in Hawai'i. Ducks Unlimited. Available from <http://www.pacificbirds.org/wp-content/uploads/2014/12/HWJVStrategicPlan-3.pdf>.
- Pau S, Okin GS, Gillespie TW. 2010. Asynchronous response of tropical forest leaf phenology to seasonal and El Niño-driven drought. *PLOS ONE* **5**:e11325.
- Perkins KS, Nimmo JR, Medeiros AC. 2012. Effects of native forest restoration on soil hydraulic properties, Auwahi, Maui, Hawaiian Islands. *Geophysical Research Letters* **39**:L05405.
- Perkins KS, Nimmo JR, Medeiros AC, Szutu DJ, von Allmen E. 2014. Assessing effects of native forest restoration on soil moisture dynamics and potential aquifer recharge, Auwahi, Maui. *Ecohydrology* **7**:1437–1451.
- Perroy RL, Melrose J, Cares S. 2016. The evolving agricultural landscape of post-plantation Hawai'i. *Applied Geography* **76**:154–162.
- Régnière J, Powell JA, Bentz BJ, Nealis V. 2012. Effects of temperature on development, survival and reproduction of insects: experimental design, data analysis and modeling. *Journal of Insect Physiology* **58**:634–647.

- Richmond BM, Fletcher CH, Grossman EE, Gibbs AE. 2001. Islands at risk: Coastal hazard assessment and mapping in the Hawaiian islands. *Environmental Geosciences* **8**:21–37.
- Romine BM, Fletcher CH. 2012. A summary of historical shoreline changes on beaches of Kauaʻi, Oʻahu, and Maui, Hawaiʻi. *Journal of Coastal Research* **29**:605–614.
- Rooney JJB, Fletcher CH. 2005. Shoreline Change and Pacific Climatic Oscillations in Kihei, Maui, Hawaiʻi. *Journal of Coastal Research*:535–547.
- Rotzoll K, Fletcher CH. 2013. Assessment of groundwater inundation as a consequence of sea-level rise. *Nature Climate Change* **3**:477–481.
- Rotzoll K, Oki DS, El-Kadi AI. 2010. Changes of freshwater-lens thickness in basaltic island aquifers overlain by thick coastal sediments. *Hydrogeology Journal* **18**:1425–1436.
- Rovzar CM. 2016. Conservation of Hawaiʻi's dry forest: An application of habitat suitability modeling, GIS, and field methods. Ph.D, Geography 0396. University of California, Los Angeles. Available from <http://escholarship.org/uc/item/2307z1c7>.
- Rubinoff D, Holland BS, Shibata A, Messing RH, Wright MG. 2010. Rapid invasion despite lack of genetic variation in the *Erythrina* gall wasp (*Quadrastichus erythrinae* Kim). *Pacific Science* **64**:23–31.
- Scholl MA, Giambelluca TW, Gingerich SB, Nullet MA, Loope LL. 2007. Cloud water in windward and leeward mountain forests: The stable isotope signature of orographic cloud water. *Water Resources Research* **43**:W12411.
- Scowcroft PG, Conrad CE. 1992. Alien and native plant response to release from feral sheep browsing on Mauna Kea. Pages 625–665 in C. P. Stone, C. W. Smith, and J. T. Tunison, editors. *Alien plant invasions in native ecosystems of Hawaiʻi: Management and research*. University of Hawaiʻi Cooperative National Park Resources Unit, Honolulu, HI.
- Shiels AB, Medeiros AC, von Allmen EI. 2017. Shifts in an invasive rodent community favoring black rats (*Rattus rattus*) following restoration of native forest. *Restoration Ecology*:n/a-n/a.
- Sproat DK. 2016. An Indigenous People's Right to Environmental Self-Determination: Native Hawaiians and the Struggle against Climate Change Devastation. *Stanford Environmental Law Journal* **35**:157.
- Stone CP. 1988. Hawaiʻi's wetlands, streams, fishponds, and pools. Pages 125–136 in C. P. Stone and D. B. Stone, editors. *Conservation biology in Hawaiʻi*. Cooperative National Park Resources Studies Unit, University of Hawaiʻi, Honolulu, HI. Available from http://manoa.hawaii.edu/hpicesu/book/1988_chap/29.pdf.
- Strauch AM, Bruland GL, MacKenzie RA, Giardina CP. 2016. Soil and hydrological responses to wild pig (*Sus scrofa*) exclusion from native and strawberry guava (*Psidium cattleianum*)-invaded tropical montane wet forests. *Geoderma* **279**:53–60.
- Sturrock RN, Frankel SJ, Brown AV, Hennon PE, Kliejunas JT, Lewis KJ, Worrall JJ, Woods AJ. 2011. Climate change and forest diseases. *Plant Pathology* **60**:133–149.
- Sweet WV, Kopp RE, Weaver CP, Obeysekera J, Horton RM, Thieler ER, Zervas C. 2017. Global and regional sea level rise scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. National Oceanic and Atmospheric Administration, Silver Spring, MD.
- Sylva R. 2010. Kūkulu Hou 'Ia Ka Loko I'a o Kō'ie'ie (Rebuilding Kō'ie'ie Fishpond). *HOHONU: A Journal of Academic Writing* **8**:49–55.
- Takahashi M, Giambelluca TW, Mudd RG, DeLay JK, Nullet MA, Asner GP. 2011. Rainfall partitioning and cloud water interception in native forest and invaded forest in Hawaiʻi Volcanoes National Park. *Hydrological Processes* **25**:448–464.
- Trauernicht C, Pickett E, Giardina CP, Litton CM, Cordell S, Beavers A. 2015. The contemporary scale and context of wildfire in Hawaiʻi. *Pacific Science* **69**:427–444.

- Underwood JG, Silbernagle M, Nishimoto M, Uyehara K. 2013. Managing conservation reliant species: Hawai'i's endangered endemic waterbirds. *PLOS ONE* **8**:e67872.
- Vitousek PM, Walker LR. 1989. Biological Invasion by *Myrica faya* in Hawai'i: Plant Demography, Nitrogen Fixation, Ecosystem Effects. *Ecological Monographs* **59**:247–265.
- Vitousek S, Barbee MM, Fletcher CH, Richmond BM, Genz AS. 2009. Pu'ukoholā Heiau National Historic Site and Kaloko-Honokōhau Historical Park, Big Island of Hawai'i: Coastal hazards analysis report. National Park Service. Available from http://www.soest.hawaii.edu/coasts/nps/nps_report.pdf.
- Vose J, Clark JS, Luce C, Patel-Weynand T eds. 2016. Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis. Available from <http://www.treeseearch.fs.fed.us/pubs/50261> (accessed July 13, 2016).
- Weller SG, Cabin RJ, Lorence DH, Perlman S, Wood K, Flynn T, Sakai AK. 2011. Alien plant invasions, introduced ungulates, and alternative states in a mesic forest in Hawai'i. *Restoration Ecology* **19**:671–680.
- White LD. 1994. Canoe Plants of Ancient Hawai'i. *Ka Imi Naauao o Hawai'i Nei*. Available from <http://www.canoepplants.com>.
- Wilson EE, Holway DA. 2010. Multiple mechanisms underlie displacement of solitary Hawaiian Hymenoptera by an invasive social wasp. *Ecology* **91**:3294–3302.
- Wilson EO. 1996. Hawai'i: a world without social insects. *Bishop Museum Occasional Papers* **45**:4–8.
- Witmer GW, Sanders RB, Taft AC. 2003. Feral swine - are they a disease threat to livestock in the United States? Page in G. W. Witmer and K. A. Fagerstone, editors. *Proceedings of the 10th Wildlife Damage Management Conference*. Available from <http://digitalcommons.unl.edu/michbovinetb/113>.
- Wolanski E, Martinez JA, Richmond RH. 2009. Quantifying the impact of watershed urbanization on a coral reef: Maunaloa Bay, Hawai'i. *Estuarine, Coastal and Shelf Science* **84**:259–268.
- Zhang C, Wang Y, Hamilton K, Lauer A. 2016. Dynamical downscaling of the climate for the Hawaiian Islands. Part II: Projection for the late twenty-first century. *Journal of Climate* **29**:8333–8354.
-

Hawaiian Islands Climate Synthesis Project: Vulnerability Assessment Methods and Application

Defining Terms

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

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

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

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

Vulnerability Assessment Model

The vulnerability assessment model applied in this process was developed by EcoAdapt⁵ (Hutto et al. 2015, EcoAdapt 2014a, EcoAdapt 2014b, Kershner 2014), and includes evaluations of relative vulnerability by local stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats and ecosystem services. Stakeholders evaluated vulnerability of each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Habitat exposure was evaluated by EcoAdapt using future climate projections from the scientific literature; ecosystem service exposure was evaluated by workshop participants using the climate impacts table provided by EcoAdapt. Each vulnerability component (i.e. sensitivity, adaptive capacity, and exposure) was divided into specific elements. For example, habitats included three elements for assessing sensitivity and five elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

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

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

⁵ Sensitivity and adaptive capacity elements were informed by Glick et al. 2011, Manomet Center for Conservation Sciences 2013, and Lawler 2010.

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

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

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

Habitat & Ecosystem Service Elements

Sensitivity & Exposure (Applies to Habitats and Ecosystem Services)

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

Adaptive Capacity (Habitats)

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

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

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

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

Adaptive Capacity (Ecosystem Services)

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

Literature Cited

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