An Important Note About this Document: This document represents an initial evaluation of vulnerability for food and fiber on Kaua‘i based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by habitat experts, 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 cultivated agriculture, hunted/gathered natural resources, biomass (e.g., for green energy), and medicinal/cultural materials (e.g., noni [Morinda citrifolia], māmaki [Pipturus albidus], kukui [candlenut tree; Aleurites moluccana], and cinnamon [Cinnamomum zeylanicum]; Vuln. Assessment Workshop, pers. comm., 2017).

Kaua‘i supports conventional, organic, permaculture, and traditional Hawaiian agriculture (Vuln. Assessment Workshop, pers. comm., 2017), and agriculture is one of the primary economic drivers on the island (Hawai‘i Department of Land and Natural Resources 2015). Commercial food production was dominated by ko (sugarcane; Saccharum officinarum) for most of the twentieth century (Izuka et al. 2004; Hawai‘i Department of Land and Natural Resources 2015). However, the sugarcane industry declined starting in the 1970s, and all five sugarcane plantations closed by November 2009 (Izuka et al. 2004; Hawai‘i Department of Land and Natural Resources 2015; Perroy et al. 2016; Vuln. Assessment Reviewers, pers. comm., 2017). Since 1980, macadamia nuts (Macadamia integrifolia), coffee (Coffea arabica), and diversified agriculture (e.g., fruits and vegetables) have increased dramatically (Izuka et al. 2004; Perroy et al. 2016). Cultivated crops currently grown on Kaua‘i include tree fruits, berries, hala kahiki (pineapple; Ananas comosus), vegetables, macadamia nut, coffee, cacao (Theobroma cacao), and mahogany (Swietenia macrophylla, S. mahagoni); livestock rearing includes chicken (Gallus gallus domesticus; for household meat and eggs), pigs (Sus scrofa), cattle (Bos taurus), and goats (Capra hircus; for commercial and household use; Vuln. Assessment Workshop, pers. comm., 2017).

On Kaua‘i, agriculture, aquaculture, hunting (feral goat, pig, deer [Odocoileus hemionus columbianus], and cattle), fishing, and the gathering of natural resources are used to obtain

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1 This information was gathered during a vulnerability assessment and scenario planning workshop in January 2017 (http://ecoadapt.org/workshops/kauaivulnerabilityworkshop). Further information and citations can be found in the Hawaiian Islands Climate Vulnerability and Adaptation Synthesis and other products available online at www.bit.ly/HawaiiClimate.
food and fiber resources, and involve many traditional cultural practices such as feral pig 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). Taro cultivation on Kaua‘i is extensive compared to other Hawaiian Islands, and fields in the Hanalei River Valley (including the Hanalei National Wildlife Refuge) represent 60% of the state’s taro production (Pacific Coast Joint Venture Hawai‘i 2006). Natural resources utilized for food, fiber, and medicinal/cultural materials include goat, pig, deer, cattle, guava (*Psidium guajava*), mai’a (banana; *Musa acuminata*), niu (coconut; *Cocos nucifera*), ornamental flowers, private/state timber, high-value wood (koa [*Acacia koa*]), sandalwood (*Santalum pyrularium*), teak (*Tectona grandis*), mahogany, mango (*Mangifera indica*), and cordage (*Vu.* Assessment Workshop, pers. comm., 2017). 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.

### Ecosystem Service Vulnerability

Food and fiber on Kaua‘i were evaluated within three distinct groups: native species utilized for food and fiber (e.g., forest plants), non-native species that are not considered invasive (e.g., cultivated species such as taro), and non-native species that are considered invasive and are utilized for food/fiber. Overall, food and fiber ecosystem services were evaluated as having moderate vulnerability to climate change due to moderate sensitivity to climate and non-climate stressors, moderate exposure to projected future climate changes, and moderate-high adaptive capacity.

Climate-driven changes such as increased soil temperature and changes in the amount and timing of precipitation are likely to impact both cultivated crops and native species used for food and fiber on Kaua‘i. These factors may reduce water availability and quality, stress native ecosystems, and limit plant growth and vigor, especially where they interact with other stressors. Species and habitats may also be impacted by extreme events and disturbances (e.g., storms, wildfire, insects, disease) that can damage habitats and infrastructure and cause direct species injury or mortality. Non-climate stressors reduce habitat extent, introduce pollutants,

<table>
<thead>
<tr>
<th>Overall Food &amp; Fiber</th>
<th>Rank</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Future Exposure</td>
<td>Moderate</td>
<td>Moderate²</td>
</tr>
<tr>
<td>Adaptive Capacity</td>
<td>Moderate-High</td>
<td>High</td>
</tr>
<tr>
<td><strong>Vulnerability</strong></td>
<td>Moderate</td>
<td>High</td>
</tr>
</tbody>
</table>

² 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.*

Kaua‘i Climate Change Vulnerability Assessment for the Hawaiian Islands Climate Synthesis Project
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and diminish surface 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 outcompete native species for resources or lead to the damage or decline of cultivated and/or wild plants and animals.

Although food and fiber 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 limited, but some efforts to restore fishponds and increase traditional taro cultivation have been successful.

<table>
<thead>
<tr>
<th>Native Species</th>
<th>Rank</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Future Exposure</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Adaptive Capacity</td>
<td>Moderate-High</td>
<td>High</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>High</td>
<td>High</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-Native Species</th>
<th>Rank</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>Moderate-High</td>
<td>High</td>
</tr>
<tr>
<td>Future Exposure</td>
<td>Low-Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Adaptive Capacity</td>
<td>Moderate-High</td>
<td>High</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>Low-Moderate</td>
<td>High</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Invasive Species</th>
<th>Rank</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Future Exposure</td>
<td>Low-Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Adaptive Capacity</td>
<td>Moderate-High</td>
<td>High</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

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 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; however, non-native species are less sensitive to disturbance regimes than native species because they typically are highly cultivated and managed, and some invasive species (e.g., strawberry guava [*Psidium cattleianum*]) may thrive following a disturbance (Vuln. Assessment Workshop, pers. comm., 2017). Additional sensitivity factors include volcanic emissions and UV radiation, which impact vegetation growth and can exacerbate the effects of other stressors. Food and fiber ecosystem service are also sensitive to pollinator loss, which reduces the ability of native vegetation to reproduce. Warmer air temperatures may benefit this ecosystem service by enhancing production of some non-native species such as mango, banana, and guava (Vuln. Assessment Workshop, pers. comm., 2017).

Overall, it is likely that large-scale agriculture on Kaua‘i will continue to decline as it has over the last several decades (Perroy et al. 2016). Many native plants utilized for food and fiber may also decline due to changing climate conditions and increasingly frequent disturbances, leading to extirpation or extinction when species are unable to persist in remaining suitable areas or shift upslope (Fortini et al. 2013).
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.

<table>
<thead>
<tr>
<th>Climatic factors and disturbance regimes</th>
<th>Native species: High impact (high confidence)</th>
<th>Non-native species: Moderate-high impact (high confidence)</th>
<th>Invasive species: Low impact (high confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil temperature</td>
<td><strong>Historical and current trends</strong></td>
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</tr>
<tr>
<td></td>
<td>• No current soil temperature trends are available</td>
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<td></td>
</tr>
<tr>
<td></td>
<td><strong>Projected future trends</strong></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>• No regional soil temperature projections are available, but soil temperatures are likely to increase as air temperatures increase (Vuln. Assessment Reviewers, pers. comm., 2017)</td>
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<tr>
<td>Precipitation</td>
<td><strong>Historical and current trends</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(amount and timing)</td>
<td>• 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 &amp; Giambelluca 2017)</td>
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<td></td>
<td>• From 1920 to 2012, dry season (May–Oct.) precipitation on Kaua‘i declined an average of 1.05% per decade across the island, with the largest declines at high elevations (Frazier &amp; Giambelluca 2017)</td>
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<tr>
<td></td>
<td>• From 1920–2012, wet-season (Nov.–April) precipitation on Kaua‘i declined an average of 0.94% per decade across the island, with the largest declines at high elevations and on the windward side (as much as 4%; Frazier &amp; Giambelluca 2017)</td>
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<tr>
<td></td>
<td><strong>Projected future trends</strong></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Precipitation projections are highly uncertain because</td>
<td></td>
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<tr>
<td></td>
<td><strong>Potential impacts on ecosystem service</strong></td>
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</tr>
<tr>
<td></td>
<td>• High soil temperatures may increase disease outbreaks, including <em>Fusarium</em> infections (Elias et al. 2015)</td>
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<tr>
<td></td>
<td>• Dense vegetation, such as that provided by biomass crops (e.g., sugarcane and Napier grass [<em>Pennisetum purpureum</em>]), helps moderate soil temperature increases as air temperatures increase (Pawlowski et al. 2017)</td>
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<tr>
<td></td>
<td><strong>Potential impacts on ecosystem service</strong></td>
<td></td>
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<tr>
<td></td>
<td>• Increasingly dry conditions are likely to stress already-limited water resources over the coming century (Izuka et al. 2004)</td>
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<tr>
<td></td>
<td>• Below-average precipitation in the 1980s and 1990s was correlated with a decline in the water level of wells in the Līhuʻe Basin, reducing water availability for crop irrigation (Izuka et al. 2004)</td>
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<tr>
<td></td>
<td>• 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)</td>
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<tr>
<td></td>
<td>• Reduced precipitation may degrade the health and integrity of native ecosystems and species (Cristini et al. 2013), reducing their availability for food and fiber</td>
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</tbody>
</table>
they vary in projected direction and magnitude, and will be affected by shifts in the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), as well as the amount of future greenhouse gas emissions. Possible future scenarios include:

- No change to moderate decrease in precipitation by 2100 (Keener et al. 2013)
- Moderate decrease in precipitation across all seasons by 2100 (26% to 41% decrease in wet-season precipitation; 3% to 6% decrease in dry-season precipitation) (Elison Timm et al. 2015)
- By 2100, increased precipitation at high elevations (up to 20%) and slightly decreased precipitation at low elevations in the dry season; slight increases at high elevations and slight decreases at low elevations in the wet season (Zhang et al. 2016)

| Tropical storms/hurricanes, surface winds, & riverine flooding | **Historical and current trends**

- **Tropical storms/hurricanes**
  - Tropical storm frequency was particularly high from 1982–1995, but then decreased slightly from 1995–2000 (Chu 2002)
  - Overall, tropical storm frequency increased slightly since 1966–1981 (Chu 2002)

- **Riverine flooding**
  - No consistent trends were found in stream peak discharge statewide (Oki et al. 2010a)

| **Projected future trends**

- **Tropical storms/hurricanes**
  - Tropical storm projections are highly uncertain because they are influenced by large-scale patterns within the ocean and atmosphere (Murakami et al. 2013). Possible future scenarios include:

| Potential impacts on ecosystem service | **Crops** are vulnerable to damage from hurricanes and other large storms; Hurricane Iniki, which occurred in September of 1992, was associated with a large drop in agricultural production due to the loss and damage of crops (Coffman & Noy 2009)

- 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
  - 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 (Anthony et al. 2004; Mead & Wiegner 2010)
- 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)

**Surface winds**
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 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)

**Riverine flooding**
- No regional stream/river flooding projections are available, but flows may become more variable/flashy if mean annual precipitation declines (Strauch et al. 2015)

- 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); these effects can in turn 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 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

**Potential refugia**
- Gulches (Vuln. Assessment Workshop, pers. comm., 2017)

<table>
<thead>
<tr>
<th>Wildfire</th>
<th><strong>Historical and current trends</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>- 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)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Projected future trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>- No regional wildfire projections are available, but increased wildfire is likely if drier conditions and more drought occur (Trauernicht et al. 2015)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potential impacts on ecosystem service</th>
</tr>
</thead>
<tbody>
<tr>
<td>- 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 reduce fuel biomass (Blackmore &amp; Vitousek 2000)</td>
</tr>
<tr>
<td>- Severe wildfires have the potential to convert forest area to non-native grasslands (Blackmore &amp; 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</td>
</tr>
</tbody>
</table>
### 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)
  - 12,000 acres across the Hawaiian Islands are at risk due to Erythrina gall wasp (*Quadrastichus erythrinae*); on Kaua‘i, 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 (*Klambothrips myopori*; 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 ‘ōhi‘a (*Metrosideros polymorpha*) 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 the species, which is used for fiber and other materials
- 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 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 trends are available for diseases that impact food and fiber ecosystem services

**Potential impacts on ecosystem service**
- 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)
### 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)
  - On Kaua‘i, the greatest threat from ʻōhiʻa rust (*Austropuccinia psidii*) is on mid- and high-elevation slopes (Krist et al. 2014)
  - 53,000 acres across the Hawaiian Islands are at risk due to koa wilt (*Fusarium oxysporum* f. sp. *koae*); on Kaua‘i, the greatest threat is on mid- and high-elevation slopes, especially on the windward side of the island (Krist et al. 2014)
- Little change is expected in the suitable climatic space for ʻōhiʻa rust (Hanna et al. 2012)

- Diseases such as koa wilt, caused by a soil-borne disease organism, and banana bunchy top disease, caused by a virus carried by aphids (*Pentalonia nigronervosa*), can impact 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; Hawai‘i 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 (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 such as residential and commercial development, roads/highways, and recreation, also introduce nutrients and pollutants into agricultural areas and lowland, coastal, and nearshore habitats, where many species are sensitive to contaminants. Many of 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, 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. Native species are also sensitive to overuse, while invasive species, including pigs, feral goats, and strawberry guava, are extremely resilient and often thrive in areas with high levels of human disturbance (Vuln. Assessment Workshop, pers. comm., 2017).

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

<table>
<thead>
<tr>
<th>Non-climate stressors</th>
<th>Native species: High impact (high confidence)</th>
<th>Non-native species: Moderate impact (high confidence)</th>
<th>Invasive species: Low impact (high confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential &amp; commercial</td>
<td><em>Prime agricultural land is vulnerable to residential development (Vuln. Assessment Workshop, pers. comm., 2017)</em></td>
<td><em>Extensive land-use conversion from agriculture (e.g., sugarcane, pineapple) to urban development has occurred over the past decade, especially on the Hāmākua Coast (Hawaiʻi Department of Land and Natural Resources 2015)</em></td>
<td><em>Development has also caused many anchialine ponds to be filled (Hawaiʻi Department of Land and Natural Resources 2015), reducing sources of shrimp used for ‘ōpelu (Decapterus macarellus) and akule (Selar crumenophthalmus) fishing (Conservation Council for Hawaiʻi 2011)</em></td>
</tr>
<tr>
<td>commercial development</td>
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<td></td>
<td><em>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)</em></td>
<td><em>Development has replaced many taro fields, contributing to the loss of the majority of the historically cultivated area (Stone 1988)</em></td>
<td><em>Development is strongly associated with the introduction of invasive plants, wildlife, pests, and disease (Conry &amp; Cannarella 2010)</em></td>
</tr>
<tr>
<td>Pollutions &amp; poisons</td>
<td><em>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</em></td>
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<tr>
<td><strong>Roads, highways, &amp; trails</strong></td>
<td><strong>Potential impacts on ecosystem service</strong></td>
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<td>-------------------------------</td>
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<tr>
<td></td>
<td>Runoff from roads, highways, and trails increases erosion and can contain contaminants, affecting water quality (Conry &amp; Cannarella 2010; Hawai`i Department of Land and Natural Resources 2015) and the health and survival of aquatic species utilized for food (Keala et al. 2007)</td>
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<tr>
<td></td>
<td>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)</td>
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<table>
<thead>
<tr>
<th><strong>Groundwater development</strong></th>
<th><strong>Potential impacts on ecosystem service</strong></th>
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<tbody>
<tr>
<td></td>
<td>Groundwater withdrawals in the Līhuʻe basin increased dramatically in the 1960s, as evidenced by an increase in the number of wells in use; this increase corresponds to a decline in the well water levels, but reduced recharge due to below-average precipitation in the 1980s and 1990s. More efficient agricultural irrigation also contributed to changes in the regional groundwater levels (Izuka et al. 2004)</td>
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<tr>
<td></td>
<td>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)</td>
</tr>
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<thead>
<tr>
<th><strong>Water diversions</strong></th>
<th><strong>Potential impacts on ecosystem service</strong></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Twenty-five of the 61 perennial streams on Kaua<code>i have been diverted, primarily to provide water for agricultural and urban use (Hawai</code>i Department of Land and Natural Resources 2015)</td>
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<tr>
<td></td>
<td>Beginning in the 19th century, sugarcane plantations on Kaua`i built many water diversions and reservoirs to support their plantations; these both redistributed water within the watershed and transported water in and out of neighboring watersheds (Izuka et al. 2004)</td>
</tr>
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<td>Surface water diversions decrease water delivery to downstream areas, and during the dry season, diversions can cause some stream sections to dry up completely (Brasher 2003); reduced streamflow negatively affects traditional taro cultivation (Sproat 2016) and reduces habitat availability and suitability for aquatic wildlife harvested for food (Brasher 2003)</td>
</tr>
<tr>
<td></td>
<td>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, 2010b)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Recreation</strong></th>
<th><strong>Potential impacts on ecosystem service</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>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 &amp; Cannarella 2010)</td>
</tr>
</tbody>
</table>
### 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 freshwater fish (‘o’opu) 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 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)

### Invasive/problematic mammalian predators

**Potential impacts on ecosystem service**
- Non-native rats 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 forests 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., *Leptospira, Toxoplasma*; Dubey & Jones 2008; Buchholz et al. 2016)

### Invasive/problematic ungulates

**Potential impacts on ecosystem service**
- Ungulate browsing and rooting impacts 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
### Invasive/Problematic Trees

**Potential impacts on ecosystem service**

- Invasive trees (e.g., *Morella faya*, *Falcataura moluccana*, *Prosopis pallida*) displace native species and can alter soil biochemical processes, favoring further invasion by non-natives and potentially altering stream food webs, aquifers, and nearshore coastal waters (Vitousek & Walker 1989; Atwood et al. 2010; Miyazawa et al. 2016)
- In native forests, strawberry guava 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); for example, the walls of Alekoko Fishpond have been damaged by mangrove roots (El-Kadi et al. 2008)

### 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
Other Sensitivities

Food and fiber ecosystem services are also sensitive to volcanic activity and ultraviolet radiation, which can impact vegetation growth (Table 3).

**Table 3.** Other sensitivities that may affect the vulnerability of food and fiber ecosystem services to climate change.

<table>
<thead>
<tr>
<th>Other sensitivities</th>
<th>Sensitivity unknown (low confidence)</th>
</tr>
</thead>
</table>
| **Volcanic activity**                | **Potential impacts on ecosystem service**
|                                      | • Volcanic emissions (VOG, or volcanic smog) contain high levels of sulfur dioxide (SO₂), a harmful gas that can be absorbed into plants through their stomata where it is converted to sulfurous acid and burns plant tissue; forest vegetation downwind of active vents is most affected, although some species are SO₂-resistant (e.g., ‘ōhi‘a; Nelson & Sewake 2008)
|                                      | • SO₂ can also combine with water in the atmosphere to create acidic precipitation or fog, which can injure plants, reduce growth and productivity, impact soil acidity and fertility, and mobilize heavy metals found within soil (Nelson & Sewake 2008)
|                                      | • VOG can be increased with changing wind patterns, which increases CO₂ fertilization; however, studies on these impacts have not been done in the Pacific (Vuln. Assessment Workshop, pers. comm. 2017)
|                                      | • Volcanic pollutants can interact with other stressors (e.g., insect outbreaks) to cause greater damage to forest vegetation (Conry & Cannarella 2010)
| **Ultraviolet (UV) radiation**       | **Potential impacts on ecosystem service**
|                                      | • The impacts of UV radiation on plants can include reduced height and increased biomass (Sullivan et al. 1992); however, plant responses range widely depending on species considered, elevation, and additional environmental stressors (Sullivan et al. 1992; Funk 2008; Ballaré et al. 2011; Barnes et al. 2016)
|                                      | • Plants native to high elevations (where plant exposure to UV radiation is naturally higher) are less sensitive to increased UV radiation than plants from lower elevations (Sullivan et al. 1992)

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 4). 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.

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3 VOG is extremely rare on Kaua‘i, and described ecosystem impacts from VOG have only been observed on the island of Hawai‘i (Vuln. Assessment Reviewers, pers. comm., 2017).
Table 4. 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 (-).

<table>
<thead>
<tr>
<th>Adaptive capacity factors</th>
<th>Native, non-native, and invasive species: Moderate-high adaptive capacity (high confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intrinsic value &amp; management potential</strong></td>
<td>+ High public value: Native agricultural commodities have cultural value, but are not utilized for traditional purposes (Vuln. Assessment Workshop, pers. comm., 2017)</td>
</tr>
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<td></td>
<td>+ Moderate-high human willingness to change behavior to continue accessing ecosystem service: Local agriculture is very important for Kaua‘i; local water availability, food security, and reductions in food miles and carbon footprint of food are critical to prevent climate change (Vuln. Assessment Workshop, pers. comm., 2017)</td>
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<td>+ Taro cultivation in the Hanalei River Valley (including the Hanalei National Wildlife Refuge) represents 60% of Hawai‘i’s taro production (Pacific Coast Joint Venture Hawai‘i 2006)</td>
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<td></td>
<td>+ The Hanalei Watershed Management Plan and Hanalei to Ha‘ena: Community Disaster Resilience Plan address ecosystem conditions in the region and provide guidance on minimizing potential climate change threats (Sustainable Resources Group International Inc.. 2012; Henly-Shepard 2014)</td>
</tr>
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<td></td>
<td>+/- Agriculture is an integral component to other aspects of Hawaiian culture (Vuln. Assessment Workshop, pers. comm., 2017)</td>
</tr>
<tr>
<td></td>
<td>+/- All cultivated agriculture on Kaua‘i is affected by water rights (Vuln. Assessment Workshop, pers. comm., 2017)</td>
</tr>
<tr>
<td></td>
<td>+/- 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)</td>
</tr>
<tr>
<td></td>
<td>+/- Some taro fields and fishponds have protected status (e.g., Hanalei National Wildlife Refuge), which may help buffer climate impacts; other areas are not currently protected or highly managed (e.g., Wainiha Valley; Pacific Coast Joint Venture Hawai‘i 2006)</td>
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<tr>
<td></td>
<td>+/- 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)</td>
</tr>
<tr>
<td></td>
<td>- Low-moderate societal support: There is very little financial and educational support for food and fiber ecosystem services, as well as a lack of biosecurity for Hawai‘i (Vuln. Assessment Workshop, pers. comm., 2017)</td>
</tr>
<tr>
<td></td>
<td>- Low-moderate likelihood of alleviating climate change impacts on ecosystem service: Potential actions could include forest management (e.g., thinning, fire prevention, tree planting), managing fallow and unused land, making subsidies available for biosecurity and climate-smart agriculture (e.g., choosing crops appropriate for current and future climates), improving county planning and...</td>
</tr>
</tbody>
</table>
politically driven decision-making, allowing zoning for homesteading, increasing funding, recognizing cultural values, and carrying out innovative and original research that may bolster the adaptive capacity of this ecosystem service (Vuln. Assessment Workshop, pers. comm., 2017)
- The Hawaiian Islands have relatively low food security, due to their dependence on imported products (Perroy et al. 2016)
- Only 500 acres of taro are cultivated today, a 97.5% decline from a peak of over 20,000 acres (Sproat 2016)
- Many historical fishponds have been degraded or eliminated over time (Honua Consulting 2013)
- Many taro fields and fishponds have become degraded by invasive species without active human management (e.g., Lāwa‘i Kai Fishpond, Waimea River and Wailua River taro fields; Pacific Coast Joint Venture Hawai‘i 2006)
- 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)

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**Recommended Citation**

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

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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.


Shiels AB, Medeiros AC, von Allmen EL. 2017. Shifts in an invasive rodent community favoring black rats (Rattus rattus) following restoration of native forest. Restoration Ecology:n/a–n/a.


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® (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:

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

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4 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 both the confidence associated with individual element rankings, and also 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 evaluated 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 was 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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**Literature Cited**

EcoAdapt. 2014a. A climate change vulnerability assessment for aquatic resources in the Tongass National Forest. EcoAdapt, Bainbridge Island, WA.


Kershner JM, editor. 2014. A climate change vulnerability assessment for focal resources of the Sierra Nevada. Version 1.0. EcoAdapt, Bainbridge Island, WA.

