# Cultural Knowledge & Heritage Values

## *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 cultural knowledge and heritage values on Maui Nui*[1] *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.*

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## Ecosystem Service Description

Natural resources and Native Hawaiian culture are closely interwoven:

> *"Natural resources comprise the tapestry of [Native Hawaiian] culture;*
> *remove one piece of fabric and the entire tapestry unravels."*
> (Vuln. Assessment Workshop, pers. comm., 2016)

Native Hawaiian value is placed on interactions with the consciousness of all things, including living creatures and animate or inanimate natural objects, which are conferred rights and responsibilities. Hawaiians speak directly to all things, asking permission for their use and giving back where resources are taken (Gon 2003). Native Hawaiian culture places strong importance on the wao akua, upland forests that were uninhabited and considered sacred because they were the "realm of the gods" (Gon 2003; Hawaiʻi Department of Land and Natural Resources 2015). Land management designations, called ahupuaʻa, often encompass ecosystems from mauka to makai (from the mountains to the sea), ensuring access to diverse resources and increasing food security and community self-sufficiency (Gon 2003; Vaughan & Ayers 2016). In pre-colonial times, Hawaiians generally did not recognize land ownership, and ahupuaʻa were overseen by konohiki (administrators of the ahupuaʻa; Gon 2003; Vaughan & Ayers 2016). Traditional practices are closely tied to the seasonal patterns of wind, rain, and other weather conditions, and this knowledge has been passed down in oral and written traditions (Gon 2003). This knowledge still exists, but much of today's society may not have the capacity to

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[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/mauivulnerabilityworkshop). 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.

access the information, although this is changing (Vuln. Assessment Reviewer, pers. comm., 2017). The fabric of cultural knowledge relates to the provisioning of food, clothing, and shelter, crop cultivation, plant propagation, and general stewardship of natural resources and the land (Vuln. Assessment Workshop, pers. comm., 2016). This cultural knowledge is essential to maintain the ecosystems of Maui, Lānaʻi, and Kahoʻolawe (Vuln. Assessment Workshop, pers. comm., 2016).

Cultural heritage incorporates past legacies that relate to ecosystems and a sense of place, and includes many aspects of identity and spirituality (Gould et al. 2014; Bremer et al. 2015). The understanding and importance of cultural values and heritage varies from individual to individual, but is strongly held at the community and societal levels (Gould et al. 2014). Great cultural importance is placed on the land and native species, especially forest plants and terrestrial birds: "*Every time we lose a species it's a loss of our identity*" (Gould et al. 2014 p. 9). Many cultural practices are dependent on natural ecosystems (Bremer et al. 2015), such as the gathering of native plant and animal species for food, medicine, carving, tools, weaving, jewelry, hula or traditional dance, and ceremonial practices (Hawaiʻi Department of Land and Natural Resources 2015).

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## Ecosystem Service Vulnerability

Cultural knowledge and heritage values were evaluated as having high vulnerability to climate change due to high sensitivity to climate and non-climate stressors, high exposure to projected future climate changes, and low adaptive capacity.

| Cultural Knowledge & Heritage | Rank | Confidence |
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| Sensitivity | High | High |
| Future Exposure | High | Moderate[3] |
| Adaptive Capacity | Low | High |
| **Vulnerability** | **High** | **High** |

This ecosystem service is vulnerable to climate changes that impact the health and integrity of ecosystems and/or native species, and changes that damage or destroy valued cultural assets and heritage sites; these include changes in precipitation and drought, air and water temperatures, sea level rise, coastal erosion, and disturbance events such as wildfire, flooding, insects, and disease. Disturbance events can affect large areas and cause extensive damage or loss of living things and landscapes of cultural importance, and they can also limit access to traditional gathering areas or the ability to carry out traditional practices. Many non-climate stressors are linked to increasing human populations and associated impacts of changes in land use and the overuse of

[3] 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*.

natural resources (e.g., residential and commercial development, pollution and poisons, water diversions, recreation, etc.), which have fragmented and degraded natural habitats, exacerbating the negative effects of climate change. The introduction and establishment of invasive species, including plants, wildlife, insects, fish, and pathogens/parasites, have had an especially large impact on cultural knowledge and heritage by altering ecosystem functions and driving the loss of native species and habitats.

Native Hawaiian knowledge and heritage is still affected by colonialism, and these values receive relatively little public and societal recognition and support. However, the importance of cultural knowledge, as well as the benefits it offers to ecosystems and other ecosystem services, is starting to be incorporated into natural resource management and decision-making processes to a greater degree.

## Sensitivity and Exposure

### Climatic Factors and Disturbance Regimes

Cultural knowledge and heritage is vulnerable to climate changes that affect the ecosystems and native species that hold significant cultural value (Table 1). Changes in precipitation, increased drought, and warmer air and water temperatures impact forest, stream, and wetland habitats heavily, while sea level rise and ocean acidification also contribute to damage and degradation in coastal and nearshore ocean habitats. Disturbance events (e.g., wildfire, floods, insect/disease outbreaks) can damage large areas and cause the injury and/or death of living things, putting some highly localized populations of culturally significant species at risk of extinction.

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

| **Climatic factors and disturbance regimes** High impact (high confidence) | | |
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| *Precipitation (amount and timing)* | ***Historical and current trends***<br>• 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)<br>• From 1920 to 2012, dry season (May–Oct.) precipitation declined 1% to 5% per decade for most areas on Maui and Lānaʻi, particularly in leeward areas; Kahoʻolawe experienced more modest drying of up to 1.2% per decade (Frazier & Giambelluca 2017)<br>• 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)<br>• 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)<br><br>***Projected future trends***<br>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: | ***Potential impacts on ecosystem service***<br>• More frequent occurrence of the TWI and a lower mean base height of the TWI has reduced precipitation in high-elevation areas over the past several decades, contributing to water stress in montane and subalpine forests (Longman et al. 2015) that harbor valued native plants and wildlife such as ʻōhiʻa (*Metrosideros polymorpha*) and koa (*Acacia koa*) trees, Hawaiian honeycreepers, and the pueo (Hawaiian short-eared owl; *Asio flammeus sandwichensis*), among others (Hawaiʻi Department of Land and Natural Resources 2015)<br>• Drier high-elevation conditions may prevent montane and subalpine forests from expanding upslope in response to warming temperatures, resulting in reduced habitat area for native species with cultural value (Atkinson & LaPointe 2009; Crausbay et al. 2014a); in fact, the forest upper limit may shift downslope in response to increasing moisture stress (Crausbay & Hotchkiss 2015)<br>• ʻŌhiʻa trees, which provide leaves and blossoms for making lei (adornments) and other traditional purposes, can alter their leaf structure/composition and control water transport and gas exchange processes during periods of low rainfall or on drier sites (Cornwell et al. 2007; Gotsch et al. 2014)<br>• Lower streamflows/baseflows as a result of decreased precipitation reduce habitat availability (Bassiouni & Oki 2013) and ridge-to-reef connectivity for unique aquatic fauna, such as amphidromous fish (Benbow et al. 2004; |

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| | • Little to no change in average precipitation by 2100 (Keener et al. 2012)<br>• 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)<br>• By 2100, increased rainfall on windward slopes of Maui (up to 30% in the dry season), and decreased rainfall on Lānaʻi and leeward slopes of Maui in both seasons (Zhang et al. 2016) | Walter et al. 2012)<br>• Increased precipitation could benefit this ecosystem service by increasing streamflow and reducing vegetation water stress, contributing to overall ecosystem health and integrity (Vuln. Assessment Workshop, pers. comm., 2016) |
| *Air temperature* | ***Historical and current trends***<br>• 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)<br>• The annual number of freezing days on Haleakalā has declined since 1958 (Hamilton 2013)<br><br>***Projected future trends***<br>Projections that air temperature will increase are highly certain, although the magnitude of change is less certain. Possible future scenarios include:<br>• Air temperature increases by 2.0°C (3.6°F) to 3.5°C (6.3°F) across the Hawaiian Islands by 2100, with more significant increases at higher elevations (Zhang et al. 2016)<br>• More frequent and more intense extreme heat days (Keener et al. 2012) | ***Potential impacts on ecosystem service***<br>• Warmer air temperatures increase evaporative demand and leaf transpiration rates in native vegetation, resulting in greater water loss and contributing to the decline of culturally important species such as ʻōhiʻa (Gotsch et al. 2014)<br>• Increasing temperatures may cause native species to shift upslope, altering the location of vegetation changes that served as traditional horizontal land divisions (Sproat 2016)<br>• Forest bird distributions are expected to shift upslope and survive in only the highest-elevation areas near the tree line in response to warming conditions, with many species losing all or almost all of their range (Fortini et al. 2015)<br>• Increasing temperatures are also allowing the upslope expansion of mosquitos that carry avian malaria (*Plasmodium* spp.), which threatens endemic forest birds (Atkinson & LaPointe 2009; Fortini et al. 2015) |

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| *Stream temperature* | ***Historical and current trends***<br>• No regional stream temperature trends are available; however, the following patterns typically occur:<br>  ○ Stream temperatures are lower in forested areas compared to urban areas (Brasher 2003)<br>  ○ Stream temperatures are lower in the wet season than during the dry season (MacKenzie et al. 2013)<br><br>***Projected future trends***<br>• No regional stream temperature projections are available, but they are likely to increase over the coming century (Gehrke et al. 2011) | ***Potential impacts on ecosystem service***<br>• Higher water temperatures may alter native aquatic species growth, assemblages, distribution, and abundance (Brasher 2003; Gingerich & Wolff 2005; Oki et al. 2010b)<br>• Higher water temperatures (>27–29°C [81–84°F]) may increase the likelihood of *Pythium* rot or undermine new plant root growth in kalo (taro; *Colocasia esculenta*), a staple crop that has been cultivated by Native Hawaiians for hundreds of years (Oki et al. 2010b) |
| *Ocean acidification* | ***Historical and current trends***<br>• Globally, ocean surface pH has decreased by 30% (0.1 unit) since the pre-industrial era, creating more acidic conditions (IPCC 2013)<br>• In the Central North Pacific, ocean surface pH decreased by 0.0019 to 0.0002 per year (Dore et al. 2009)<br><br>***Projected future trends***<br>There is high certainty that ocean pH will decline because changes in pH correspond very closely to the amount of atmospheric $CO_2$ absorbed by oceans (e.g., a ~30% increase in $CO_2$ absorbed by oceans has been associated with a ~30% drop in pH since pre-industrial times; IPCC 2013; Bopp et al. 2013; Gattuso et al. 2015).<br>• By 2090–2099, ocean surface pH may decline by an additional 0.07–0.33 units compared to 1990–1999 (Bopp et al. 2013) | ***Potential impacts on ecosystem service***<br>• Ocean acidification impacts corals, shellfish, and other marine organisms with calcium carbonate shells or skeletons by interfering with calcification processes (Eversole & Andrews 2014); many of these species are culturally important, and are harvested directly or support harvested species at higher levels of the food chain (Fletcher 2010) |

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| *Sea level rise, coastal flooding, & shoreline change* | ***Historical and current trends***<br>• 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)<br>• Rising sea levels over the past century have accelerated beach erosion; Maui beaches are the most erosive in Hawaiʻi (Fletcher et al. 2012)<br>• Maui beaches eroded by an average of 0.17 m/year (0.56 ft) across all beaches, with 85% of beaches eroding and 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)<br>• No historical/current trends are available for Lānaʻi and Kahoʻolawe<br><br>***Projected future trends***<br>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:<br>• 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<br>• 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)<br>• No projected future trends are available for Lānaʻi and Kahoʻolawe<br><br>Coastal flooding projections are relatively uncertain because | ***Potential impacts on ecosystem service***<br>• Beach erosion has reduced nesting habitat for green sea turtles (*Chelonia mydas agassizi*; Hawaiʻi Department of Land and Natural Resources 2015), a species of great cultural significance in the Hawaiian Islands (NOAA 2016)<br>• Sea level rise may inundate, enlarge, or create new anchialine pools (Marrack & O'Grady 2014), historically used for irrigating trees such as niu (*Cocos nucifera*) and hala (*Pandanus tectorius*), and as sources of ʻōpaeʻula (*Halocaridina rubra*) utilized as fish bait for ʻōpelu (*Decapterus macarellus*) and akule (*Selar crumenophthalmus*) fishing (Conservation Council for Hawaiʻi 2011)<br>• Sea level rise may also cause fishpond inundation, potentially altering fishpond size, abundance, and distribution (Marrack & O'Grady 2014)<br>• Sea level rise and associated coastal flooding is likely to threaten vulnerable coastal heritage sites, inundating archeological remains and eroding sand deposits from iwi kūpuna (ancestral burials), structures and still-covered artifacts, and features related to the historical collection and processing of fish and other marine resources (Kane et al. 2012; Johnson et al. 2015)<br>• Saltwater intrusion is likely to increase groundwater salinity (Keener et al. 2012), affecting freshwater supply (Keener et al. 2012) and native species dispersal (Marrack 2014)<br>• Sea level rise may contribute to a transition from freshwater to brackish conditions in coastal wetlands due to increased tidal flooding (Hawaiʻi Department of Land and Natural Resources 2015; Kane et al. 2015), impacting kalo cultivation in lowland areas (Keener et al. 2012; Sproat 2016) |

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| | there are no downscaled sea level rise projections for this region. Possible future scenarios include:<br>• At 0.74 m (2.4 ft) of SLR (estimated to occur around 2100), 25.3% of the total area of Kanaha Pond State Wildlife Sanctuary in north Maui and 28.2% of the area of Keālia Pond National Wildlife Refuge in south Maui would be inundated (Kane et al. 2015)<br>• At 0.75 m (2.5 ft) of SLR, 0.55 $km^2$ (135 acres) would flood in Kahului with saltwater intrusion significantly impacting the Kanaha Pond State Wildlife Sanctuary, and 0.04 $km^2$ (~10 acres) would flood in Lahaina (Cooper et al. 2013)<br>• At 1.9 m (6 ft) of SLR, 2.13 $km^2$ (526 acres) would flood in Kahului and 0.37 $km^2$ (91 acres) would flood in Lahaina (Cooper et al. 2013)<br>• No projected future trends are available for Lānaʻi and Kahoʻolawe | |
| *Drought* | ***Historical and current trends***<br>• Drought length increased in 1980–2011 compared to 1950–1979 (Chu et al. 2010)<br>• 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)<br><br>***Projected future trends***<br>Drought projections are highly uncertain because they are primarily dependent on precipitation projections, which are variable and have high uncertainty. Possible future scenarios include:<br>• 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. | ***Potential impacts on ecosystem service***<br>• Drought affects the health and integrity of native ecosystems and associated species, particularly tree/shrub growth and mortality (Lohse et al. 1995; Pau et al. 2010; Crausbay et al. 2014b; Gotsch et al. 2014)<br>• ʻŌhiʻa trees are able to regulate opening/closing their stomata, as well as adjust water transport and gas exchange responses in response to drought conditions, reducing water loss and increasing the survival of this culturally significant species (Cornwell et al. 2007)<br>• Longer and/or more severe droughts are associated with an increase in the likelihood of wildfires (Loope & Giambelluca 1998; Dolling et al. 2005), which can destroy large areas of intact forest (Blackmore & Vitousek 2000) valued as part of Native Hawaiian heritage<br>• Drought can reduce or eliminate streamflow and stream connectivity to the ocean, affecting aquatic species |

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| | 2012)<br>• 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) | habitat availability, migration, recruitment, and survival (Benbow et al. 2004; Hau 2007; McIntosh et al. 2008; Bassiouni & Oki 2013)<br>• Drought reduces groundwater recharge (Engott & Vana 2007), which can temporarily shrink the aquifer freshwater lens (Keener et al. 2012) and/or increase groundwater salinity (Gingerich & Engott 2012) |
| *Wind & circulation* | ***Historical and current trends***<br>• Since the 1990s, the Pacific trade winds (both the Walker and Hadley cells) have increased, corresponding with a negative Pacific Decadal Oscillation (PDO) phase (England et al. 2014)<br>• Trade wind direction has shifted from predominantly northeast to east from 1973–2009 (Garza et al. 2012), which represents a cyclical shift that is known to complete its cycle approximately every 45 years (Wentworth 1949)<br>• The frequency of trade wind inversion (TWI) occurrence increased an average of 16% starting in 1990 (Longman et al. 2015)<br><br>***Projected future trends***<br>Projections for the TWI are moderately uncertain due to the influence of large-scale atmospheric patterns (e.g., El Niño-Southern Oscillation [ENSO] and Pacific Decadal Oscillation [PDO]). Possible future scenarios include:<br>• 8% increase in TWI frequency of occurrence, corresponding to an almost 50% decrease in days without a well-defined TWI (decrease from 17% of days currently to 9% of days by 2100; Zhang et al. 2016)<br>• Possible decrease in TWI base height, ranging from small (Zhang et al. 2016) to more significant (Lauer et al. 2013)<br><br>Surface wind speed and direction may change, but studies | ***Potential impacts on ecosystem service***<br>• Changes in the frequency and/or mean height of the TWI drastically reduces rainfall and relative humidity at higher elevations (Longman et al. 2015), which may drive plant mortality and alter species distribution in montane forests, limiting future upslope migration (Crausbay et al. 2014b)<br>• Changes in the trade winds could impact traditional navigation practices by fisherman on the open ocean (Sproat 2016)<br>• Windy conditions are one of the primary determinants for wildfire spread from areas dominated by non-native grasses to forest, which can destroy large areas of habitat and associated wildlife species important to Hawaiian culture and heritage (Freifelder et al. 1998; Blackmore & Vitousek 2000) |

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| | have reached varying conclusions:<br>• 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)<br>• Surface winds in the Hawaiian Islands may increase modestly, with a very modest increase in frequency of strong wind days (Zhang et al. 2016) | |
| *Tropical storms/ hurricanes* | ***Historical and current trends***<br>• Tropical storm frequency was particularly high from 1982–1995, but then decreased slightly from 1995–2000 (Chu 2002)<br>• Overall, tropical storm frequency increased slightly since 1966–1981 (Chu 2002)<br><br>***Projected future trends***<br>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:<br>• 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) | ***Potential impacts on ecosystem service***<br>• The Hawaiian Islands are vulnerable to tsunamis, since they are located on active fault lines; tsunamis can be several meters in height and cause flooding that can extend damage far inland (Johnson et al. 2015)<br>• Hurricanes infrequently strike the islands directly (the last was Hurricane Iniki, which struck Kauaʻi in 1992), but even hurricanes passing near the islands can create extremely heavy surf, high winds, and torrential rainfall, causing extensive damage to coastal areas, forests, and other valued landscapes and heritage sites (Johnson et al. 2015)<br>• Given the small, highly localized populations of many endemic species, a single large disturbance event such as a hurricane could extirpate an entire population, or even a species (Johnson & Winker 2010)<br>• Hurricanes can damage native forest vegetation, resetting succession in damaged areas and potentially allowing the colonization and growth of invasive species (Loope & Giambelluca 1998) |
| *Wildfire* | ***Historical and current trends***<br>• 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) | ***Potential impacts on ecosystem service***<br>• Larger and more severe wildfires have become increasingly common over the past 200 years, a shift driven largely by the introduction of flammable non-native grasses that provide ample fuel; severe wildfires |

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| | • 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)<br>• No wildfire data is available for Lānaʻi and Kahoʻolawe<br><br>***Projected future trends***<br>• No regional wildfire projections are available, but increased wildfire is likely if drier conditions and more drought occur (Trauernicht et al. 2015) | have the potential to convert intact native forest area to non-native grasslands (Blackmore & Vitousek 2000)<br>• Wildfires can cause road closures and burned areas can be inaccessible for days to months due to hazardous conditions (Trauernicht et al. 2015), reducing access to the forest for the gathering of traditional materials<br>• Wildfire may benefit the ecosystem service by killing forest pests (Vuln. Assessment Workshop, pers. comm., 2016) |
| *Riverine flooding* | ***Historical and current trends***<br>• No consistent trends were found in stream peak discharge statewide (Oki et al. 2010a)<br><br>***Projected future trends***<br>• No regional stream/river flooding projections are available, but flows may become more variable/flashy if mean annual precipitation declines (Strauch et al. 2015) | ***Potential impacts on ecosystem service***<br>• Flash flooding events caused by heavy rainfall are common in the small, steep watersheds typical of Maui, and can cause significant damage to native plant and wildlife species, as well as heritage sites and infrastructure; flooding is generally less severe on Lānaʻi (Richmond et al. 2001)<br>• Flood damage is more severe where native forest cover has been lost due to invasive plant establishment, ungulate grazing, and soil disturbances (Conry & Cannarella 2010)<br>• Native fauna are adapted to flashy streamflow regimes; flooding may help prevent aquatic invasive species establishment and dominance (Brasher 2003) and mitigate parasitism (Gagne & Blum 2016) |
| *Insects* | ***Historical and current trends***<br>• No information is available about trends in insect outbreaks<br><br>***Projected future trends***<br>• 0.4 million forested acres across the Hawaiian Islands are at risk of experiencing a 25% decrease in standing live | ***Potential impacts on ecosystem service***<br>• Insects may impact large areas of forest, causing reduced recruitment, defoliation, dieback, and/or mortality in native vegetation (Conant et al. 2010; Krist et al. 2014); for instance, a 2003 outbreak of koa moths (*Scotorythra paludicola*) defoliated 16 $km^2$ of forest in East Maui (Haines et al. 2009) |

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| | basal area by 2027 due to the combined threat of insects and disease (not taking climatic changes into account; Krist et al. 2014)<br>◦ 61,000 acres across the Hawaiian Islands are at risk due to myoporum thrips (*Klambothrips myopori*); on Maui, the greatest threat is in low-elevation forests on the leeward side (Krist et al. 2014)<br>◦ 12,000 acres across the Hawaiian Islands are at risk due to Erythrina gall wasp (*Quadrastichus erythrinae*); on Maui, the greatest threat is in low-elevation forests on the leeward side (Krist et al. 2014) | • Insects target many culturally significant species such as ʻōhiʻa (Jones et al. 2006), koa (Haines et al. 2009) and wiliwili (*Erythrina sandwicensis*) trees (Rubinoff et al. 2010); these include the black twig borer (*Xylosandrus compactus*), myoporum thrips, and Erythrina gall wasp, among others (Conant et al. 2010; Krist et al. 2014)<br>• Large areas of insect-killed vegetation within a watershed can increase erosion and allow the establishment of invasive plants (Jones et al. 2006)<br>• Warmer temperatures may alter insect development, reproduction, survival, and distribution (Régnière et al. 2012), exacerbating the impact on species of cultural importance<br>• Plants stressed by drought or other causes may be more vulnerable to insect-related damage and mortality (Hara et al. 1976; Lenz & Taylor 2001; Jones et al. 2006) |
| *Disease* | ***Historical and current trends***<br>• No information is available for plant disease<br><br>***Projected future trends***<br>• Within the Hanawi Natural Area Reserve on Maui, areas of montane forest where birds are at low risk of contracting malaria may be reduced by up to 47% by 2100 (Lānaʻi and Kahoʻolawe do not receive enough precipitation to support mosquito habitat; Benning et al. 2002)<br>• 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)<br>◦ On Maui, the greatest threat from ʻōhiʻa rust (*Austropuccinia psidii*) is on mid-elevation windward slopes (Krist et al. 2014) | ***Potential impacts on ecosystem service***<br>• 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; Hawaiʻi Department of Land and Natural Resources 2015)<br>• Koa wilt, ʻōhiʻa rust, and rapid ʻōhiʻa death (caused by the fungal pathogen *Ceratocystis*) can cause widespread damage, reduced regeneration, and high mortality in native trees, significantly altering forest species composition (Conry & Cannarella 2010; Krist et al. 2014; Keith et al. 2015)<br>• Diseases can impact forest products gathered for cultural purposes, and in some cases gathering activities may inadvertently spread disease as well; in 2016, many |

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| | ○ 53,000 acres across the Hawaiian Islands are at risk due to koa wilt (*Fusarium oxysporum* f. sp. *koae*); on Maui, the greatest threat is on mid-elevation windward slopes Krist et al. 2014)<br>• Little change is expected in the suitable climatic space for ʻōhiʻa rust (Hanna et al. 2012) | people raised concerns about the collection of lehua (ʻōhiʻa blossoms) and liko (young leaf shoots from ʻōhiʻa) for lei during the annual Merrie Monarch Festival in Hilo, the largest hula festival in the world, due to the potential risk of a fungal disease attacking ʻōhiʻa trees across large portions of the island of Hawaiʻi and spreading to healthy forest on Hawaiʻi Island and to other islands (Solomon 2016)<br>• Mosquito distributions are expected to continue expanding upslope, increasing the threat of avian malaria and avian pox (*Avipoxvirus* spp.) to endemic forest birds (Benning et al. 2002; Atkinson & LaPointe 2009; Kolivras 2010); these introduced diseases have drastically reduced native honeycreeper populations over the last century (Atkinson & LaPointe 2009)<br>• Parasite infections in native freshwater fish may increase if climate and human-driven changes reduce streamflows (Gagne & Blum 2016) |

## 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). Land-use change and invasive species can degrade, fragment, and destroy many aspects of Native Hawaiian cultural heritage, and large-scale habitat alterations caused by conversion to agriculture and development have also increased pollution and the overuse of natural resources.

**Table 2.** Key non-climate stressors that affect the overall sensitivity of cultural knowledge and heritage to climate change.

| **Non-climate stressors** | High overall impact (high confidence) |
| --- | --- |
| *Residential & commercial development* | ***Potential impacts on ecosystem service***<br>• Development limits access to customary gathering areas for Native Hawaiians, even where these rights have been legally protected (Jarman & Verchick 2002; Vaughan & Ayers 2016)<br>• Development and deforestation is a major threat to forest areas, especially within the wildland-urban interface, and contribute to habitat loss, fragmentation, and degradation (Conry & Cannarella 2010; Rovzar 2016) of native species and ecosystems that hold cultural significance<br>• Development increases runoff, sedimentation, and pollutants, affecting coastal and nearshore water quality that supports many species of cultural value (Conry & Cannarella 2010; Hawaiʻi Department of Land and Natural Resources 2015)<br>• Development is strongly associated with the introduction of invasive plants, wildlife, pests, and disease (Conry & Cannarella 2010)<br>• Development has caused many anchialine ponds on Maui to be filled (Hawaiʻi Department of Land and Natural Resources 2015), reducing ʻōpaeʻula (endemic shrimp) that are traditionally used as chum for ʻōpelu and akule fishing (Conservation Council for Hawaiʻi 2011) |
| *Agriculture & aquaculture* | ***Potential impacts on ecosystem service***<br>• Land-use conversion to large-scale commercial agriculture has been a major driver of forest loss (Pau et al. 2009), as well as the rapid decline or extirpation of many native species with cultural value, including endemic honeycreepers and other forest birds (Hawaiʻi Department of Land and Natural Resources 2015)<br>• Lowland areas in the Nā Wai ʻEhā area (below 183 m [600 ft]) were converted to large-scale sugarcane plantations beginning in the $19^{th}$ century (Oki et al. 2010b), reducing wetland habitat that supports species such as the ʻio (*Buteo solitarius*), which is considered one of the ʻaumākua (family or ancestral gods) in Hawaiian culture (Hawaiʻi Department of Land and Natural Resources 2015)<br>• Areas cleared for commercial agriculture are vulnerable to invasion by flammable grasses and other invasive species (Rovzar 2016)<br>• Water diversions for the irrigation of commercial crops reduce instream flows necessary for the protection of important native aquatic species and cultivation of kalo (Oki et al. 2010b) |

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| | • Aquaculture has contributed to invasive fish, such as tilapia (*Oreochromis mossambicus*), that escape and prey on native aquatic species (Brasher 2003; Hawaiʻi Department of Land and Natural Resources 2015) |
| *Pollution & poisons* | ***Potential impacts on ecosystem service***<br>• Common sources of pollution and/or poisons include fertilizer, pesticides/herbicides, animal waste, oils, and chemicals that run off from developed areas, agricultural and rangeland areas, and golf courses (Conry & Cannarella 2010)<br>• Point-source discharge from wastewater plants and industrial facilities can degrade coastal water quality (Conry & Cannarella 2010), reducing habitat suitability for valued wildlife including seabirds and shorebirds (Hawaiʻi Department of Land and Natural Resources 2015)<br>• Several non-point source pollutants (nutrients, sedimentation, chemicals) pose a threat to native freshwater fishes, but impacts are largely unknown (Mitchell et al. 2005)<br>• Native shrimps are sensitive to pollution from human pool use (e.g., soaps, shampoos, litter) and human and pet refuse (Mitchell et al. 2005; Conservation Council for Hawaiʻi 2011) |
| *Energy production* | ***Potential impacts on ecosystem service***<br>• The development of energy sources, such as wind turbines, impacts the endemic ʻōpeʻapeʻa (Hawaiian hoary bat; *Lasiurus cinereus*), as well as seabirds and waterbirds (Hawaiʻi Department of Land and Natural Resources 2015) |
| *Roads, highways, & trails* | ***Potential impacts on ecosystem service***<br>• Runoff from roads, highways, and trails increases erosion and can contain contaminants, affecting fresh and nearshore water quality (Conry & Cannarella 2010; Hawaiʻi Department of Land and Natural Resources 2015) |
| *Groundwater development* | ***Potential impacts on ecosystem service***<br>• Groundwater withdrawals can reduce or eliminate streamflow by reducing base flow, affecting native aquatic communities (Brasher 2003; Mair & Fares 2010; Safeeq & Fares 2012), including those of cultural value<br>• Continued population growth and increased tourism will increase water demand, likely leading to development of new groundwater sources (e.g., Launiupoko aquifer; Grubert 2010; Gingerich & Engott 2012) |
| *Water diversions* | ***Potential impacts on ecosystem service***<br>• Water diversions in Maui exist in all Nā Wai ʻEhā streams (Oki et al. 2010b); Maui has the highest streamflow diversions statewide (Hawaiʻi Department of Land and Natural Resources 2015), and water is used for irrigation of crops, pastures, golf courses, and other anthropogenic landscapes (Oki et al. 2010b)<br>• Surface water diversions decrease water delivery to downstream areas, and during the dry season these diversions impact the instream flows necessary for kalo cultivation, a protected cultural practice (Oki et al. 2010b; Gingerich & Engott 2012)<br>• Reduced instream flows caused by water diversions also impact native fish and other aquatic species that hold cultural significance, reducing macroinvertebrate biomass (McIntosh et al. 2002), increasing species mortality (Hau 2007), reducing recruitment (Benbow et al. 2004), and isolating upstream populations (McIntosh et al. 2002; |

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| | Brasher 2003)<br>• During the dry season, diversions can cause intermittent flows or cause downstream reaches to dry up completely (Oki et al. 2010b)<br>• Native Hawaiians historically used ʻauwai (water diversions) to temporarily reroute water from streams for kalo irrigation and to transport water to dryland agricultural areas (Conry & Cannarella 2010; Oki et al. 2010b); these are typically designed to minimize sedimentation and have relatively few negative impacts on this ecosystem service (Vuln. Assessment Reviewer, pers. comm., 2017) |
| *Recreation* | ***Potential impacts on ecosystem service***<br>• Recreation can degrade native habitats by increasing erosion, introducing invasive species, and increasing trash and pollution, and other impacts associated with overuse (Sutherland et al. 2001; Conry & Cannarella 2010)<br>• Although cultural tourism can help revive cultural lifestyles and practices, recreation and tourism can also displace local communities and/or reinforce stereotypes (Bhattacharya et al. 2005) |
| *Invasive/ problematic parasites & pathogens* | ***Potential impacts on ecosystem service***<br>• Introduced diseases, such as avian malaria and pox, have drastically reduced or extirpated native honeycreeper species and other culturally valued endemic birds over the last century; warmer temperatures are expanding the range of mosquito vectors that carry these diseases (Benning et al. 2002; Atkinson & LaPointe 2009)<br>• Warming temperatures and changes in precipitation may alter the distribution and severity of fungal diseases and other introduced pathogens that affect native plant species traditionally harvested for food, fiber, canoe-making, and lei-making (e.g., koa, ʻōhiʻa; Hawaiʻi Department of Land and Natural Resources 2015) |
| *Invasive/ problematic flammable grasses* | ***Potential impacts on ecosystem service***<br>• Invasive grasses increase wildfire severity and area burned, impacting many culturally significant natural resources (Trauernicht et al. 2015)<br>• Fountain grass (*Pennisetum setaceum*) and other invasive grasses have degraded native forests, preventing native species recruitment (Cabin et al. 2000) and converting some areas to non-native grasslands (Leopold & Hess 2016)<br>• Fountain grass may alter soil moisture availability for native dry forest vegetation; in dry forests on the island of Hawaiʻi, lama trees (*Diospyros sandwicensis*) took up less water from shallow soils in areas invaded by fountain grass compared to forest areas without invasive grasses (Cordell & Sandquist 2008) |
| *Invasive/ problematic reptiles & amphibians* | ***Potential impacts on ecosystem service***<br>• Coqui frogs (*Eleutherodactylus coqui*) and veiled chameleons (*Chamaeleo calyptratus*) compete for food with Maui's endemic forest birds (Hawaiʻi Department of Land and Natural Resources 2015), potentially contributing to the decline of this culturally significant species group |
| *Invasive/ problematic mammalian predators* | ***Potential impacts on ecosystem service***<br>• Introduced rodents have contributed to the decline of valued native forest species by consuming seeds, stripping bark, and preying on bird eggs, nestlings, and incubating adults (Cabin et al. 2000; Becker et al. 2010; Hawaiʻi Department of Land and Natural Resources 2015) |

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| | • Feral cats (*Felis catus*) are predators of wild birds, particularly ground-nesting and burrowing species (Hess 2016)<br>• Feral cats also carry toxoplasmosis (*Toxoplasma gondii*), a parasitic protozoan that is shed in feces and passed to other birds and mammals (including humans; Wallace et al. 1972); on Maui, toxoplasmosis has been a documented cause of mortality for nēnē (*Branta sandvicensis*; Work et al. 2002)<br>  ○ On other islands, toxoplasmosis has also caused mortality in Hawaiian monk seals (*Neomonachus schauinslandi*), red-footed boobies (*Sula sula*), and ʻalala (Hawaiian crow; *Corvus hawaiiensis*; Work et al. 2000, 2002; Honnold et al. 2005) |
| *Invasive/ problematic ungulates* | ***Potential impacts on ecosystem service***<br>• Feral sheep (*Ovis* spp.), goats (*Capra hircus*), axis deer (*Axis axis*), and pigs (*Sus scrofa*) degrade natural areas removing native vegetation, preventing forest regeneration, disturbing soil and increasing erosion, and creating conditions suitable for invasive grasses (Cabin et al. 2000; Bruland et al. 2010; Cole & Litton 2014; Murphy et al. 2014; Hawaiʻi Department of Land and Natural Resources 2015)<br>• Intensive grazing by non-native ungulates is a major factor in the decline of forest and other coastal and upland Hawaiian habitats (Cabin et al. 2000; Hawaiʻi Department of Land and Natural Resources 2015) that are closely linked to traditional Hawaiian values and heritage<br>• Many non-native ungulates are also game species in Hawaiʻi, and hunting, often done for subsistence, is an important aspect of cultural identity (Hawaiʻi Department of Land and Natural Resources 2015) |
| *Invasive/ problematic trees & shrubs* | ***Potential impacts on ecosystem service***<br>• Invasive trees and shrubs simplify the physical structure of forests, replacing native species within both the canopy and the understory (Asner et al. 2008)<br>• Invasive trees and shrubs reduce canopy water harvest (e.g., cloud water interception) and storage and decrease the amount of rainfall that reaches the forest floor (Takahashi et al. 2011) |
| *Invasive/ problematic fish* | ***Potential impacts on ecosystem service***<br>• Invasive fish, including mosquitofish (*Gambusia affinis*), guppies (*Poecilia reticulata*), and tilapia can displace native aquatic species, degrading sites that hold cultural value (e.g., elimination of shrimp in Waiʻanapanapa Cave anchialine pond; Brasher 2003; Havird et al. 2013; Hawaiʻi Department of Land and Natural Resources 2015) |
| *Invasive/ problematic social insects* | ***Potential impacts on ecosystem service***<br>• Social insects were not historically present in Hawaiian ecosystems (Wilson 1996), and their introduction has changed habitats by damaging native vegetation (Conry & Cannarella 2010) and impacting populations of native insects through predation and/or competition for food (Wilson & Holway 2010)<br>• Invasive social insects include ants, bees, mosquitos, borers, and little fire ants (Vuln. Assessment Workshop, pers. comm., 2016) |

## Adaptive Capacity

Although Native Hawaiian cultural knowledge and heritage is valued by natural resource managers, this ecosystem service remains largely unsupported by society, and is often appropriated by the public (Table 3). Native Hawaiians continue to be impacted by the political and psychological effects of colonialism, and their connection with and access to forests and other natural areas of cultural value can conflict with Western ideas of land ownership and resource use.

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

| **Adaptive capacity factors** | Low adaptive capacity (high confidence) |
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| *Intrinsic value & management potential* | + Access to land for the purposes of gathering cultural materials and engaging in traditional practices is protected within the Hawaiʻi state constitution, which attempts to safeguard the right of Native Hawaiians to continue traditional practices related to subsistence, cultural, and religious purposes; however, these protections are not always well-implemented (Sproat 2016)<br>○ In 2000, the Hawaiʻi Supreme Court halted development on the Kona coast of Hawaiʻi, ruling that state agencies must consider the effect of proposed actions on customary and traditional Hawaiian rights and practices, as well as cultural, historical, and natural resources in affected areas (*Ka Paʻakai O Ka ʻāina v. Land Use Commission* 2000; Sproat 2008)<br>○ Aha Moku Advisory Committee and Aha Moku Councils provide an additional framework to support the protection and perpetuation of customary and traditional practices of Native Hawaiians (Vuln. Assessment Reviewer, pers. comm., 2017)<br>+ The island of Kahoʻolawe has been protected and placed into a trust for a future Native Hawaiian sovereign entity (Hawaiʻi Department of Land and Natural Resources 2015)<br>+ Most natural resource managers across the main Hawaiian islands believe that Native Hawaiian cultural values are an important management consideration (Bremer et al. 2015)<br>○ Cultural knowledge and heritage values are being incorporated into natural resource management and decision-making processes to a greater degree (Hawaiʻi Department of Land and Natural Resources 2015); for instance, ahupua'a land management principles are being incorporated into land use and resource planning in Maui Nui (Vuln. Assessment Reviewer, pers. comm., 2017)<br>○ Habitat restoration efforts, such as those taking place on Kahoʻolawe, are increasingly being guided by traditional knowledge and practices (Gon 2003)<br>+ Cultural knowledge and heritage values benefit most other ecosystem services, including biodiversity, recreation and tourism, and aesthetic values (Bhattacharya |

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| | et al. 2005)<br>- Low-moderate likelihood of alleviating climate change impacts: Protecting core habitat areas and expanding mesic forests through planting may help maintain and/or create climate refugia for native species valued in Hawaiian culture (Vuln. Assessment Workshop, pers. comm., 2016); however, increasing human populations and extensive ecosystem degradation by invasive species is likely to make management of climate impacts challenging, and existing prioritization processes may not be adequate for addressing all of these issues (Bremer et al. 2015)<br>- Low public value: The general public seeks to appropriate Hawaiian culture and traditional knowledge (Kauanui 2007)<br>- Low societal support for managing and conserving this ecosystem service: Social support for cultural knowledge and heritage only comes from a small group (Vuln. Assessment Workshop, pers. comm., 2016)<br>    o Lack of funding, access, and collaborative partners can prevent effective management of this service (Bremer et al. 2015), and buy-in from the agencies/organizations responsible for land management is also required (Vuln. Assessment Reviewer, pers. comm., 2017)<br>- Native Hawaiians and traditional/customary practices continue to be impacted by the political and psychological effects of colonialism, and their connection with and access to forests and other natural areas of cultural value can conflict with European ideas of land ownership and resource use (Gould et al. 2014)<br>- Low human willingness to change behavior to continue accessing this ecosystem service: This service is place-specific and cannot be provided elsewhere (Vuln. Assessment Workshop, pers. comm., 2016)<br>- As an ecosystem service, cultural knowledge and heritage is not well-studied, in part because it is more difficult to understand and quantify than services such as flood control, water supply, and recreation (Gould et al. 2014; Bremer et al. 2015) |

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## Hawaiian Islands Climate Synthesis Project: Vulnerability Assessment Methods and Application

### Defining Terms

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

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

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

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

### Vulnerability Assessment Model

The vulnerability assessment model applied in this process was developed by EcoAdapt[4] (Hutto et al. 2015, EcoAdapt 2014a, EcoAdapt 2014b, Kershner 2014), and includes evaluations of relative vulnerability by local stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats and ecosystem services. Stakeholders evaluated vulnerability of each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Habitat exposure was evaluated by EcoAdapt using future climate projections from the scientific literature; ecosystem service exposure was evaluated by workshop participants using the climate impacts table provided by EcoAdapt. Each vulnerability component (i.e. sensitivity, adaptive capacity, and exposure) was divided into specific elements. For example, habitats included three elements for assessing sensitivity and five elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

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

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

[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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