Mesic and Wet Forest Habitats

Climate Change Vulnerability Assessment Synthesis for Kauaʻi

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for mesic and wet forest habitats on Kauaʻi based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by habitat experts,*[1] *relevant references from the literature, and peer-review comments and revisions (see end of document for methods and defining terms). The aim of this document is to expand understanding of habitat vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.*

Habitat Description

Mesic and wet forests occur at mid- and high-elevation sites on Kauaʻi, spanning both the leeward and windward sides of the island between 600–1,500 m (2,000–5,000 ft; The Nature Conservancy 2006; Vuln. Assessment Workshop, pers. comm., 2017). Wet forests cover the high plateau on the summit of Kauaʻi, as well as areas on the windward slopes (The Nature Conservancy 2006). These forests receive at least ~1,900 mm (75 in) of rainfall each year (The Nature Conservancy 2006); they do not have a significant dry period (Juvik & Juvik 1998) and have high recharge rates (Vuln. Assessment Workshop, pers. comm., 2017). Mount Waiʻaleʻale on the summit of Kauaʻi is among the wettest places on Earth, receiving an average of 9,986 mm (393 in) of rain per year (Giambelluca et al. 2013). Mesic forests are found on the leeward slopes of Kauaʻi, immediately below the montane wet forests on the summit of the island (The Nature Conservancy 2006). Mesic forests receive ~1,270–1,900 mm (50–75 in) of precipitation per year (The Nature Conservancy 2006), and experience a seasonal drought period from May to October (Juvik & Juvik 1998).

Forest structure ranges from closed high canopy cloud forests to open bogs and low-stature forests (Vuln. Assessment Workshop, pers. comm., 2017); the most significant bogs are found in the Alakaʻi Wilderness Preserve (Hawaiʻi Department of Land and Natural Resources 2015). Dominant tree species in mesic and wet forest types include ʻōhiʻa lehua (*Metrosideros polymorpha*), koa (*Acacia koa*), lama (*Diospyros sandwicensis*), ʻōlapa (*Cheirodendron trigynum*), lapalapa (*Cheirodendron platyphyllum*), olopua (*Nestegis sandwicensis*), and mānele (*Sapindus saponaria*), with dense understories comprising shrubs, ferns, and sedges (Hawaiʻi Department of Land and Natural Resources 2015; Gon & Olson 2016; Vuln. Assessment Workshop, pers. comm., 2017). Mesic and wet forests also provide habitat for a variety of wildlife, including endangered seabirds, waterbirds, and forest birds (e.g, nēnē [*Branta sandvicensis*], puaiohi [small Kauaʻi thrush; *Myadestes palmeri*]), ʻōpeʻapeʻa (Hawaiian hoary bat; *Lasiurus cinereus semotus*), and other invertebrates (U.S. Fish and Wildlife Service 2006;

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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.

Hawaiʻi Department of Land and Natural Resources 2015; Vuln. Assessment Workshop, pers. comm., 2017).

Habitat Vulnerability

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

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

Overall Mesic & Wet Forest Habitats	Rank	Confidence
Sensitivity	Moderate-High	High
Future Exposure	Moderate-High	Moderate
Adaptive Capacity	Moderate	High
Vulnerability	**Moderate**	**Moderate**

Mesic and wet forest habitats on Kauaʻi were evaluated within two separate groups: mesic forest and wet forest. Overall, mesic and wet forest habitats were evaluated as having moderate vulnerability to climate change due to moderate-high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and moderate adaptive capacity. Mesic forest habitats were evaluated as having moderate vulnerability to climate change due to moderate-high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and moderate adaptive capacity. Wet forest habitats were evaluated to have moderate vulnerability to climate change due to moderate-high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and moderate-high adaptive capacity.

Mesic and wet forest habitat types are primarily sensitive to factors that alter moisture gradients and water availability, including drought, changes in precipitation amount and timing, soil moisture, and air temperature. Reduced water availability can alter species composition and forest distribution, potentially reducing habitat extent. Wildfire and storms can damage large areas of forest, resetting succession and increasing the risk of invasive species establishment. Invasive species (e.g., trees/shrubs, flammable grasses, ungulates, mammalian predators, pathogens/parasites, social insects) are a major non-climate stressor for mesic and wet forest types, altering ecosystem processes and competing directly with native species, contributing to species mortality and reduced recruitment. Direct human presence (e.g., recreational visits) and infrastructure associated with human activity (e.g., water diversions) also facilitate the introduction of invasive plants, increase erosion, and generally exacerbate existing stressors, undermining the ecological integrity and persistence of native forests.

Wet forests in the remote central areas of Kauaʻi remain relatively intact, but lower-elevation forests are more fragmented and degraded due to human activity. Native species diversity and endemism is high, and many species are able to recover rapidly from wildfire and other disturbances; however, habitat fragmentation has limited forest regeneration. Management and restoration efforts are not likely to alleviate the impacts of climate change, in part due to low public value and societal support for mesic and wet forests.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Mesic and wet forests on Kauaʻi are sensitive to drought, changes in precipitation amount and timing, soil moisture, and air temperature; these factors drive species composition and habitat distribution, primarily by altering water availability for native vegetation (Table 1). Disturbances such as wildfire and storms can also damage forest vegetation and potentially allow invasive plant establishment in disturbed areas.

Mesic and wet forests on Kauaʻi are projected to decline by 2100, with very slight declines in wet forests and a loss of almost 250 km^2 of mesic forest, including all but a small area of mesic forest on the windward side of the island (Fortini et al. 2017). This shift in forest cover type corresponds to a projected ~80% decrease in the mesic moisture zone on Kauaʻi by the end of the century, leaving only ~15% of the current mesic zone unchanged. In contrast, only ~5% of the current wet moisture zone will be lost, leaving ~90% of the current area unchanged (Fortini et al. 2017).

In a modeling study by Fortini et al. (2013), single-island endemic plants were one of the most vulnerable species groups to changing climate conditions and increasingly frequent disturbances; these factors may lead to extirpation or extinction where species are unable to either persist in remaining suitable areas or shift upslope. However, spatial climate envelope distributions for these species indicate that many are located within existing conservation priority areas (Fortini et al. 2013). Wet forest species were found to be the one of the least vulnerable vegetative groups to projected future climate change, while mesic forest species were found to be moderately vulnerable (Fortini et al. 2013). Fortini et al. (2015) also found that, in general, forest bird distributions are expected to shift upslope and survive in only the highest-elevation areas near the tree line (Fortini et al. 2015). Many forest bird species are projected to lose most or all of their range; species projected to lose 100% of their range on Kauaʻi by 2100 include the ʻakekeʻe (*Loxops caeruleirostris*), ʻakikiki (Kauaʻi creeper; *Oreomystis bairdi*), and puaiohi (small Kauaʻi thrush; Fortini et al. 2015).

Table 1. Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on mesic and wet forest habitats. This habitat is sensitive to the climatic factors and disturbance regimes listed below, and will likely be exposed to projected future changes in them. All factors were ranked as having a moderate or higher impact on these habitats.

Climatic factors and disturbance regimes	**Mesic and wet forest:** Moderate-high impact (moderate confidence)	
Tropical storms/ hurricanes	***Historical and current trends*** • Tropical storm frequency was particularly high from 1982–1995, but then decreased slightly from 1995–2000 (Chu 2002) • Overall, tropical storm frequency increased slightly since 1966–1981 (Chu 2002) ***Projected future trends*** Tropical storm projections are highly uncertain because they are influenced by large-scale patterns within the ocean and atmosphere (Murakami et al. 2013). Possible future scenarios include: • Increased frequency and strength of tropical storm activity around the Hawaiian Islands due to a northwest shift in storm track and increased strength because of large-scale changes in environmental conditions (Murakami et al. 2013)	***Potential impacts on habitat*** • Kaua'i has been struck twice by hurricanes in the last 40 years (Iwa in 1982 and Iniki in 1992); these events resulted in major forest damage (Loope & Giambelluca 1998) • Canopy openings caused by storm damage may reset succession in affected areas; this can also increase colonization and growth rates for invasive plants (Loope & Giambelluca 1998); invasive vegetation was introduced into many native-dominated forest areas after Hurricanes Iwa and Iniki (Hawai'i Department of Land and Natural Resources 2015) • Given the small, highly localized populations of many endemic species, a single large disturbance event such as a hurricane can have severe impacts (Johnson & Winker 2010); for instance, several forest bird species endemic to Kaua'i experienced population declines following Hurricanes Iwa and Iniki, and extinction of some species may have occurred (Conant et al. 1998; Foster et al. 2004)
Drought	***Historical and current trends*** • Drought length increased in 1980–2011 compared to 1950–1979 (Chu et al. 2010) • Drought conditions are usually less prevalent during La Niña years, and more prevalent during El Niño years (Dolling et al. 2009; Chu et al. 2010) ***Projected future trends*** Drought projections are highly uncertain because they are primarily dependent on precipitation projections,	***Potential impacts on habitat*** • Some native species exhibit traits that promote survival during short-term and seasonal droughts (Michaud et al. 2015); for instance, 'ōhi'a trees are able to regulate opening/closing their stomata, as well as adjust water transport and gas exchange processes in response to drought conditions, reducing water loss (Cornwell et al. 2007), and koa seedlings can excise leaflets and change leaf physiological characteristics (Craven et al. 2010) • Severe drought may cause high shrub mortality, potentially shifting species composition towards herbaceous species,

	which are variable and have high uncertainty. Possible future scenarios include: • By 2100, drought risk is likely to increase for low-elevation leeward areas, decrease at high elevations, and remain static elsewhere (Keener et al. 2012)	although some shrub species can reduce water stress through mechanisms such as shedding leaves or angling them towards a vertical position (Lohse et al. 1995) • Prolonged drought periods may allow the establishment of invasive vegetation more tolerant of water stress (Weller et al. 2011; Michaud et al. 2015); however, some invasive understory grass and shrub species declined in mesic forest areas during drought years (Weller et al. 2011) • Longer and/or more severe droughts are associated with an increase in the likelihood of wildfires (Loope & Giambelluca 1998; Dolling et al. 2005)
Precipitation (amount & timing) & soil moisture	***Historical and current trends*** • Since 1920, precipitation has decreased across the Hawaiian Islands, with the strongest drying trends occurring over the last 30 years (Frazier et al. 2016; Frazier & Giambelluca 2017) • From 1920 to 2012, dry season (May–Oct.) precipitation on Kauaʻi declined an average of 1.05% per decade across the island, with the largest declines at high elevations (Frazier & Giambelluca 2017) • From 1920–2012, wet-season (Nov.–April) precipitation on Kauaʻi 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 & Giambelluca 2017) • No information is available about soil moisture trends over time ***Projected future trends*** Precipitation projections are highly uncertain because they vary in projected direction and magnitude, and will be affected by shifts in the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), as well as	***Potential impacts on habitat*** • Precipitation and soil moisture gradients influence mesic and wet forest distribution and vegetative composition (Juvik & Juvik 1998; Crausbay et al. 2014; Hawaiʻi Department of Land and Natural Resources 2015) • Evaporative demand at or near the trade wind inversion (TWI) is very high due to a sharp decrease in rainfall and relative humidity; thus, vegetation near the experiences high rates of transpiration and greater sensitivity to moisture availability (Gotsch et al. 2014) • Reduced precipitation and lower moisture availability may limit native tree and shrub recruitment (Denslow et al. 2006) and decrease mature tree survival (Michaud et al. 2015) ○ ʻŌhiʻa trees can alter their leaf structure and composition (Cornwell et al. 2007), along with water transport and gas exchange processes, on drier sites or during periods of low rainfall (Cornwell et al. 2007; Gotsch et al. 2014). But they are vulnerable to more significant changes in moisture availability, especially changes in the length of dry periods (Gotsch et al. 2014), because they have relatively low tolerance for cell water loss before their leaves wilt (Cornwell et al. 2007; Gotsch et al. 2014), and are vulnerable to carbon starvation during closed

	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) • No regional soil moisture projections are available, but soil moisture is likely to decline in the future, especially if precipitation decreases (Longman 2015) as air temperatures increase	stomatal periods (Michaud et al. 2015) • A study comparing leaf phenology in rainforests and dry forests across the main Hawaiian Islands found that rainforests exhibit a period of increased productivity at the beginning of seasonal dry periods when clouds clear; this suggests that rainforest photosynthesis is primarily limited by light rather than precipitation (Pau et al. 2010) • A decrease in the frequency and intensity of heavy rainfall that produces flooding events is likely to increase availability of mosquito breeding habitat and thus transmission of deadly avian malaria (*Plasmodium* spp.) to forest birds (Atkinson et al. 2014)
Air temperature	***Historical and current trends*** • From 1975–2006, the rate of air temperature increases has accelerated to 0.2°C (0.36°F) per decade, compared to overall increases of 0.04°C (0.07°F) per decade for all records from 1919–1975; the strongest warming is found at high elevations and in winter minimum temperatures (Giambelluca et al. 2008) ***Projected future trends*** Projections that air temperature will increase are highly certain, although the magnitude of change is less certain. Possible future scenarios include: • Air temperature increases by 2°C (3.6°F) to 3.5°C (6.3°F) across the Hawaiian Islands by 2100 (Zhang et al. 2016)	***Potential impacts on habitat*** • Temperature gradients are not associated with species composition or habitat distribution in mesic and wet forests on Maui, suggesting that moisture is a more important driver in determining cloud forest distribution (Crausbay et al. 2014; Gotsch et al. 2014) • Mesic and wet forests are sensitive to increased temperatures, which increase evaporative demand and leaf transpiration rates, resulting in greater water loss (Gotsch et al. 2014); impacts will be greatest if air temperature increases co-occur with decreased rainfall (Conry & Cannarella 2010) • The average daily range of soil temperature is lower than the range of air temperature where soils are moist and shaded; where soils are exposed to wind and higher solar radiation (e.g., shrubby forest areas), the range of soil temperature exceeds that of air temperature (Juvik & Nullet 1994)

	• More frequent and more intense extreme heat days (Keener et al. 2012)	• Warming temperatures, as well as changes in precipitation, may alter the distribution and severity of fungal diseases and other pathogens that can affect mesic and wet forest trees (e.g., koa wilt [*Fusarium oxysporum* f. sp. *koae*]; Conry & Cannarella 2010; Hawaiʻi Department of Land and Natural Resources 2015) • Warming temperatures are allowing the upslope expansion of mosquitos that carry avian malaria and avian pox (*Avipoxvirus* spp.), which threatens endemic forest birds (Atkinson & LaPointe 2009; Fortini et al. 2015); bird populations on Kauaʻi are at greater risk because it lacks high-elevation forest area where malaria transmission would remain low (Benning et al. 2002; Hawaiʻi Department of Land and Natural Resources 2015) ○ Malarial infections on the Alakaʻi Plateau have increased significantly over the last several decades, especially at lower elevations (Atkinson et al. 2014)
Wildfire	***Historical and current trends*** • From 1904–2011, the overall trend has been towards increases in area burned across all of the Hawaiian Islands, but with high interannual variability (Trauernicht et al. 2015) ***Projected future trends*** • No regional wildfire projections are available, but increased wildfire is likely if drier conditions and more drought occur (Trauernicht et al. 2015)	***Potential impacts on habitat*** • Although native wet and mesic forest exhibit some ability to recover from fire, more frequent fires inhibit forest recovery, resulting in reduced structural complexity and the increased establishment of non-native species (Ainsworth & Kauffman 2008) • More frequent fires may promote the dominance and continued expansion of invasive grasses, which can perpetuate fire regime alterations (D'Antonio et al. 2011) • Wildfire increases erosion by removing vegetation and exposing bare soil (Ice et al. 2004) • Mesic forests are more vulnerable to wildfire than wet forests, and impacts are greater in late-successional forests and with increasing fragmentation and loss of wet forests (Vuln. Assessment Reviewer, pers. comm., 2017)

Non-Climate Stressors

Sensitivity of the habitat to climate change impacts may be highly influenced by the existence and extent of, and current exposure to, non-climate stressors (Table 2). Many invasive species, including trees/shrubs, flammable grasses, ungulates, mammalian predators, parasites/pathogens, and insects degrade native forests by damaging or killing native species, inhibiting native species recruitment, competing with native species for resources, and altering ecosystem processes (e.g., wildfire regimes, water infiltration, erosion). In addition, recreation and water diversions can contribute to the degradation of forest vegetation, either directly (e.g., through trampling) or indirectly (e.g., by increasing erosion or reducing water availability.

Table 2. Key non-climate stressors that affect the overall sensitivity of mesic and wet forest habitats to climate change. Factors presented are those ranked as having a moderate or higher impact on these habitats; additional factors that may influence these habitats to a lesser degree include invasive/problematic fish.

Non-climate stressors	**Mesic and wet forest:** Moderate-high overall impact (high confidence)
Invasive/ problematic trees & shrubs	***Potential impacts on habitat*** • Invasive trees and shrubs (e.g., strawberry guava [*Psidium cattleianum*], Himalayan ginger [*Hedychium gardnerianum*]) alter the composition and structure of mesic and wet forests, replacing native species in both the canopy and the understory (Asner et al. 2008) • Canopy water storage was reduced by half in forests invaded by strawberry guava compared to forests dominated by native ʻōhiʻa on the island of Hawaiʻi; in addition, less rainfall reached the forest floor and cloud water interception was lower, suggesting that native species may have a greater ability to harvest cloud droplets (Takahashi et al. 2011) • Modeling results based on a study conducted on the windward side of Hawaiʻi (MacKenzie et al. 2014) indicated that full restoration of wet forests invaded by strawberry guava would increase mean annual water yield by 2.8% • Endangered forest birds may be less likely to use areas dominated by non-native plants (Behnke et al. 2015; Crampton et al. 2017)
Invasive/ problematic flammable grasses	***Potential impacts on habitat*** • Flammable invasive grasses increase fuel loads and fuel continuity, contributing to increased wildfire severity and area burned (Ellsworth et al. 2013, 2014; Trauernicht et al. 2015) • Invasive grasses may impede native species' regeneration of native species (e.g., koa; Denslow et al. 2006) • The growth of invasive grasses on Hawaiʻi was reduced under low-light conditions that mimicked a mesic and wet forest understory, providing conditions in which native species may become established (McDaniel & Ostertag 2010); however, some flammable grasses (e.g., guinea grass [*Megathyrsus maximus*]) are tolerant of shady, mesic conditions and colonize rapidly following disturbance, increasing their potential to affect mesic and wet forest habitat (Ellsworth et al. 2013)

Invasive/ problematic ungulates	***Potential impacts on habitat*** • Invasive ungulates, including deer (*Odocoileus hemionus columbianus*) and feral pigs (*Sus scrofa*) and goats (*Capra hircus*), are a major cause of degradation in mesic and wet forest habitats; ungulate browsing and rooting may reduce species richness, native abundance, stem density and cover, ground litter and epiphyte cover, and increase the area of bare ground (Weller et al. 2011; Cole & Litton 2014; Murphy et al. 2014; Hawaiʻi Department of Land and Natural Resources 2015) • Invasive ungulates also introduce invasive species, including strawberry guava and Himalayan ginger (Hawaiʻi Department of Land and Natural Resources 2015) • When comparing the effects of wild pig activity and strawberry guava on runoff amount, soil erosion, and fecal indicator bacteria (FIB), Strauch et al. (2016) found that impacts were higher in native forests than those invaded by strawberry guava due to reduced canopy cover and more pig activity, suggesting that the removal of invasive trees without ungulate fencing may lead to an increase in disturbance and negatively impact forests and aquatic systems. • Bog communities are especially sensitive to damage from rooting pigs (Hawaiʻi Department of Land and Natural Resources 2015) • Wallowing by feral pigs may increase mosquito breeding habitat (Atkinson & LaPointe 2009) • Feral pigs prey on seabird burrows (A. Raine, pers. comm., 2017) • *Pattern of exposure:* Consistent across habitat
Invasive/ problematic mammalian predators	***Potential impacts on habitat*** • Mammalian predators, including rats (*Rattus* spp.), mongooses (*Herpestes* spp.), and feral cats (*Felis catus*) are the primary predators of forest bird eggs, nestlings, and incubating adults, as well as seabird and water bird eggs and nestlings (U.S. Fish and Wildlife Service 2006; Becker et al. 2010; Hawaiʻi Department of Land and Natural Resources 2015) • Rodents consume the seeds of native plant species, reducing seedling recruitment (Juvik & Juvik 1998; Hawaiʻi Department of Land and Natural Resources 2015); they have also been shown to damage the bark of adult koa trees (Scowcroft & Conrad 1992) and *Clermontia* shrubs (L. Crampton, pers. comm., 2017) • *Pattern of exposure:* Consistent across habitat
Invasive/ problematic parasites & pathogens	***Potential impacts on habitat*** • Introduced pathogens and parasites are a major cause of decline for endemic species, especially forest birds vulnerable to avian malaria and pox (Benning et al. 2002; Atkinson & LaPointe 2009) • A strain of rust introduced from Brazil (*Austropuccinia psidii*) can affect ʻōhiʻa, a keystone species within forests (Loope & Giambelluca 1998) • Two new species of *Ceratocystis* have infected over 50,000 acres of ʻōhiʻa forest on Hawaiʻi Island and are a significant threat to trees on the other Hawaiian Islands (Keith et al. 2015) • *Pattern of exposure:* Localized

Recreation	***Potential impacts on habitat*** • Recreation can degrade vegetation and increase erosion around heavily used areas (Conry & Cannarella 2010) • Recreation can also contribute to the spread of invasive vegetation (Conry & Cannarella 2010) • Recreation can cause puddles in roads and trails, creating breeding habitat for mosquitoes that transmit diseases to native birds (L. Crampton, pers. comm., 2017) • *Pattern of exposure:* Localized
Water diversions	***Potential impacts on habitat*** • Twenty-five of the 61 perennial streams on Kauaʻi have been diverted, primarily to provide water for agricultural and urban use (Hawaiʻi Department of Land and Natural Resources 2015) • Water diversions contribute to watershed/ahupuaʻa degradation; for instance, loss or changes in headwaters can contribute to channelization, which alters flow rates and causes siltation, mosquito production, and changes in vegetation composition along stream courses (Hawaiʻi Department of Land and Natural Resources 2015; Vuln. Assessment Reviewer, pers. comm., 2017) • *Pattern of exposure:* Localized
Invasive/ problematic social insects	***Potential impacts on habitat*** • Social insects were not historically present in Hawaiian ecosystems (Wilson 1996), and their introduction has changed habitats by impacting populations of native insects (e.g., pollinators) through predation, parasitism, and/or competition for food (Wilson & Holway 2010) • Introduced ants (e.g., yellow crazy ants [*Anoplolepis gracilipes*], little fire ants [*Wasmannia auropunctata*]) compete with native invertebrates (Hawaiʻi Department of Land and Natural Resources 2015) and contribute to the loss of native vegetation by allowing aphids and other piercing/sucking insects to thrive (Conry & Cannarella 2010) • Some introduced insects may reduce food availability for forest birds by preying on or parasitizing native insects (Banko et al. 2002)

Adaptive Capacity

The remote central region of Kauaʻi retains areas of pristine wet forest, but lower-elevation wet and mesic forests are significantly more degraded, and many areas have been fragmented and/or lost due to human activity (Table 3). Habitat fragmentation impacts seed dispersal and animal movement, reducing mesic and wet forest recovery; however, some native species can resist disease and disturbances such as wildfire, increasing their resilience to climate-related changes. Species diversity and endemism is relatively high, and mesic and wet forests are home to many rare and endangered species. Habitat protection and restoration may be unable to alleviate the impacts of climate change, and public value and societal support for these habitat types are low; biosecurity measures could limit further introduction and spread of invasive species, decreasing some additional threats to native species.

Table 3. Adaptive capacity factors that influence the ability of mesic and wet forest habitats to adapt to projected future climate changes. Factors that receive a ranking of "High" enhance adaptive capacity for this habitat (+), while factors that receive a ranking of "Low" undermine adaptive capacity (-).

Adaptive capacity factors	**Mesic forest**: Moderate adaptive capacity (high confidence) **Wet forest:** Moderate-high adaptive capacity (high confidence)
Extent & integrity **Mesic forest:** Low-moderate (high confidence) **Wet forest:** Moderate-high (high confidence)	+ The Alakaʻi Plateau contains areas of pristine wet forest, due in part to its remote nature, and forest bird populations remained intact until the 1960s (Conant et al. 1998; Atkinson et al. 2014) - Lowland wet and mesic forest types are under increased pressure from anthropogenic uses (Hawaiʻi Department of Land and Natural Resources 2015) - Logging, commercial tree planting, conversion to agriculture and pasture, and development have contributed to habitat loss and degradation (Hawaiʻi Department of Land and Natural Resources 2015) - Reduced range size generally increases species vulnerability to climate change and disturbances (Fortini et al. 2013)
Habitat isolation **Mesic forest:** High (high confidence) **Wet forest:** Low-moderate (high confidence)	+/- Barriers to mesic and wet forest dispersal include alien vegetation, water diversions, geologic/water/atmospheric features (e.g., topographical features; Vuln. Assessment Workshop, pers. comm., 2017) - Population declines and/or extinction in seed-dispersing species contributes to the decline of mesic and wet forest vegetation; this include the kāmaʻo (large Kauaʻi thrush; *Myadestes myadestinus*), which went extinct in 1992, and the puaiohi, which now numbers only ~500 birds and has a very restricted range (Vuln. Assessment Reviewer, pers. comm., 2017)
Resistance & recovery **Mesic forest:** Low-moderate (high confidence) **Wet forest:** Moderate-high (high confidence)	+ Several native woody species such as ʻōhiʻa are adapted to wildfire, and are able to resprout or quickly colonize following fire (Ainsworth & Kauffman 2008) + Some endemic forest birds may be able to develop resistance to avian malaria, and modeling results suggest that rodent control at middle elevations may support this evolution (Kilpatrick 2006); however, populations of all native honeycreepers on Kauaʻi are declining (Paxton et al. 2016) - The highest point of the Alakaʻi Plateau is still slightly below the elevation at which avian malaria transmission may continue to be limited by cooler temperatures; thus, island-endemic forest birds on Kauaʻi may be unable to persist under changing climate conditions (Benning et al. 2002; Atkinson & LaPointe 2009) - Reduced mesic native vegetation abundance can limit seed production and forest recovery from disturbance (Denslow et al. 2006) - Reduction and loss of pollinator and dispersal species may impede the ability of native forest species to reproduce, disperse, and colonize disturbed areas, potentially elevating their risk of extirpation (Sakai et al. 2002)
Habitat diversity **Mesic & wet forest:** Moderate-high (moderate confidence)	+ Because Kauaʻi is one of the older and more isolated islands, more island-endemic species occur on Kauaʻi than on any of the other islands (Hawaiʻi Department of Land and Natural Resources 2015) + Mesic forests host a high density of endemic and endangered plant species, and have the highest rates of plant endemism in the state (Vuln. Assessment

	Workshop, pers. comm., 2017) + Endangered wildlife species found in Kauaʻi mesic and wet forests include the endemic ʻōpeʻapeʻa (Hawaiian hoary bat), pueo (Hawaiian short-eared owl; *Asio flammeus sandwichensis*), puaiohi, ʻakekeʻe, ʻakikiki, Newell's shearwater (*Puffinus newelli*), and ʻuaʻu (Hawaiian petrel; *Pterodroma sandwichensis*; Hawaiʻi Department of Land and Natural Resources 2015) +/- The keystone species in wet forests is ʻōhiʻa, and ʻōhiʻa and koa are the keystone species in mesic forests; the loss or removal of these species would likely result in a shift towards invasive species dominance (Vuln. Assessment Workshop, pers. comm., 2017) +/- Epiphytes (ferns) and bryophytes (mosses, hornworts) are more common in wetter forest areas, while tree ferns and graminoids are more commonly found in mesic areas (Crausbay et al. 2014) - Native species are intrinsically vulnerable to climate change; factors such as small population sizes and changes in soil chemistry, as well as the loss of pollinators and increasingly limited dispersal, are likely to impact species diversity in mesic and wet forests (Vuln. Assessment Workshop, pers. comm., 2017) - Threatened/endangered species and obligate montane bog plants likely are particularly sensitive to climate change (Vuln. Assessment Workshop, pers. comm., 2017) - Many forest bird species endemic to Kauaʻi have already been lost and/or have not been seen in many years, and others have experienced significant declines over the last several decades (Paxton et al. 2016); forest bird species richness is expected to decline by 2100, if not sooner (Fortini et al. 2015; Paxton et al. 2016)
Management potential **Mesic & wet forest:** Low-moderate (high confidence)	+ Biosecurity measures increase adaptive capacity by preventing the introduction and/or limiting the spread of invasive species, such as the mongoose; Kauaʻi and Lānaʻi are the only islands where the mongoose has not yet been established (Hawaiʻi Department of Land and Natural Resources 2015) ○ A predator-proof fence has been installed at Kīlauea Point National Wildlife Refuge to protect bird communities from the invasive mongoose, in case any were to appear on the island; additional biosecurity measures include screening and search protocols at airports (Hawaiʻi Department of Land and Natural Resources 2015) ○ Rapid response by agencies such as the Kauaʻi Invasive Species Committee (KISC) helps curtail the spread of incipient pathogens, plants, and animals (Vuln. Assessment Reviewer, pers. comm., 2017) +/- Moderate public value: In addition to their intrinsic value, mesic and wet forests are valued by the public for hiking, fishing, hunting, tourism, bird watching, and scientific research (Vuln. Assessment Workshop, pers. comm., 2017) - Low-moderate societal support for habitat management and conservation: Less than 1% of the state budget is allocated for the Department of Land and Natural Resources, although the state manages 25% of the land mass (Vuln. Assessment Workshop, pers. comm., 2017) - Regulatory requirements associated with seabird recovery efforts have caused some conflict in communities that have had to reduce certain activities (e.g.,

	high school football games held at night) due to their impacts on seabird colonies; these are slowly being addressed through outreach programs (Vuln. Assessment Reviewer, pers. comm., 2017) - Low manager capacity and ability to cope with impacts: Bureaucracy, logistics, cost, and lack of resources (e.g., institutional knowledge, funding, staff) limit habitat protection and restoration efforts, while social and cultural development impact the ability to implement management actions; in addition, targeted research is needed to answer critical questions (Vuln. Assessment Workshop, pers. comm., 2017) - Extreme events (e.g., hurricanes) would likely have a low-moderate impact on societal support for the management and conservation of this habitat: Large-scale events may drastically alter the landscape, allowing invasive species to become established in disturbed habitats; similarly, diversion of funds to address extreme events could reduce money available for ongoing invasive species programs (Vuln. Assessment Reviewer, pers. comm., 2017) - Low-moderate likelihood of alleviating climate impacts: The likelihood of alleviating climate impacts depends largely on the specific concern; for example, endangered plants can be moved/out planted in different locations (Vuln. Assessment Workshop, pers. comm., 2017), but little can be done to alleviate climate-related spread of disease (Vuln. Assessment Reviewer, pers. comm., 2017) - Mesic forests are the primary hunting areas on Kauaʻi; this use may conflict with forest management and conservation (Vuln. Assessment Workshop, pers. comm., 2017)

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Literature Cited

Ainsworth A, Kauffman JB. 2008. Response of native Hawaiian woody species to lava-ignited wildfires in tropical forests and shrublands. Plant Ecology **201**:197–209.

Asner GP, Hughes RF, Vitousek PM, Knapp DE, Kennedy-Bowdoin T, Boardman J, Martin RE, Eastwood M, Green RO. 2008. Invasive plants transform the three-dimensional structure of rain forests. Proceedings of the National Academy of Sciences **105**:4519–4523.

Atkinson CT, LaPointe DA. 2009. Introduced avian diseases, climate change, and the future of Hawaiian honeycreepers. Journal of Avian Medicine and Surgery **23**:53–63.

Atkinson CT, Utzurrum RB, Lapointe DA, Camp RJ, Crampton LH, Foster JT, Giambelluca TW. 2014. Changing climate and the altitudinal range of avian malaria in the Hawaiian Islands – an ongoing conservation crisis on the island of Kauaʻi. Global Change Biology **20**:2426–2436.

Banko PC, Oboyski PT, Slotterback JW, Dougill SJ, Goltz DM, Johnson L, Laut ME, Murray TC. 2002. Availability of food resources, distribution of invasive species, and conservation of a Hawaiian bird along a gradient of elevation. Journal of Biogeography **29**:789–808.

Becker CD, Mounce HL, Rassmussen TA, Rauch-Sasseen A, Swinnerton KJ, Leonard DL. 2010. Nest success and parental investment in the critically endangered Maui parrotbill Pseudonestor xanthophrys with implications for recovery. Endangered Species Research **11**:189–194.

Behnke LAH, Pejchar L, Crampton LH. 2015. Occupancy and habitat use of the endangered Akikiki and Akekee on Kauaʻi Island, Hawaiʻi. The Condor **118**:148–158.

Benning TL, LaPointe D, Atkinson CT, Vitousek PM. 2002. Interactions of climate change with biological invasions and land use in the Hawaiian Islands: Modeling the fate of endemic birds using a geographic information system. Proceedings of the National Academy of Sciences **99**:14246–14249.

Chu P-S. 2002. Large-scale circulation features associated with decadal variations of tropical cyclone activity over the Central North Pacific. Journal of Climate **15**:2678–2689.

Chu P-S, Chen YR, Schroeder TA. 2010. Changes in precipitation extremes in the Hawaiian Islands in a warming climate. Journal of Climate **23**:4881–4900.

Cole RJ, Litton CM. 2014. Vegetation response to removal of non-native feral pigs from Hawaiian tropical montane wet forest. Biological Invasions **16**:125–140.

Conant S, Pratt HD, Shallenberger RJ. 1998. Reflections on a 1975 expedition to the lost world of the Alakaʻi and other notes on the natural history, systematics, and conservation of Kauaʻi birds. Wilson Bulletin **110**:1–22.

Conry PJ, Cannarella RJ. 2010. Hawaiʻi statewide assessment of forest conditions and resource strategy. Hawaiʻi Department of Land and Natural Resources - Division of Foresty and Wildlife, Honolulu, HI. Available from http://dlnr.hawaii.gov/forestry/files/2013/09/SWARS-Entire-Assessment-and-Strategy.pdf.

Cornwell WK, Bhaskar R, Sack L, Cordell S, Lunch CK. 2007. Adjustment of structure and function of Hawaiian *Metrosideros polymorpha* at high vs. low precipitation. Functional Ecology **21**:1063–1071.

Crampton LH, Brinck KW, Pias KE, Heindl BAP, Savre T, Diegmann JS, Paxton EH. 2017. Linking occupancy surveys with habitat characteristics to estimate abundance and distribution in an endangered cryptic bird. Biodiversity and Conservation **26**:1525–1539.

Crausbay SD, Frazier AG, Giambelluca TW, Longman RJ, Hotchkiss SC. 2014. Moisture status during a strong El Niño explains a tropical montane cloud forest's upper limit. Oecologia **175**:273–284.

Craven D, Gulamhussein S, Berlyn GP. 2010. Physiological and anatomical responses of *Acacia koa* (Gray) seedlings to varying light and drought conditions. Environmental and Experimental Botany **69**:205–213.

D'Antonio CM, Hughes RF, Tunison JT. 2011. Long-term impacts of invasive grasses and subsequent fire in seasonally dry Hawaiian woodlands. Ecological Applications **21**:1617–1628.

Denslow JS, Uowolo AL, Hughes RF. 2006. Limitations to seedling establishment in a mesic Hawaiian forest. Oecologia **148**:118–128.

Dolling K, Chu P-S, Fujioka F. 2005. A climatological study of the Keetch/Byram drought index and fire activity in the Hawaiian Islands. Agricultural and Forest Meteorology **133**:17–27.

Dolling K, Chu P-S, Fujioka F. 2009. Natural variability of the Keetch–Byram Drought Index in the Hawaiian Islands. International Journal of Wildland Fire **18**:459–475.

Elison Timm O, Giambelluca TW, Diaz HF. 2015. Statistical downscaling of rainfall changes in Hawaiʻi based on the CMIP5 global model projections. Journal of Geophysical Research: Atmospheres **120**:2014JD022059.

Ellsworth LM, Litton CM, Dale AP, Miura T. 2014. Invasive grasses change landscape structure and fire behaviour in Hawaiʻi. Applied Vegetation Science **17**:680–689.

Ellsworth LM, Litton CM, Taylor AD, Kauffman JB. 2013. Spatial and temporal variability of guinea grass (*Megathyrsus maximus*) fuel loads and moisture on Oʻahu, Hawaiʻi. International Journal of Wildland Fire **22**:1083–1092.

Fortini L, Price J, Jacobi J, Vorsino A, Burgett J, Brinck KW, Amidon F, Miller S, Gon III S, Koob G, Paxton E. 2013. A landscape-based assessment of climate change vulnerability for all native Hawaiian plants. Technical Report HCSU-044. Hawaiʻi Cooperative Studies Unit, University of Hawaiʻi at Hilo. Available from https://dspace.lib.hawaii.edu/bitstream/10790/2620/1/TR44_Fortini_plant_vulnerability_assessment.pdf.

Fortini LB, Vorsino AE, Amidon FA, Paxton EH, Jacobi JD. 2015. Large-scale range collapse of Hawaiian forest birds under climate change and the need for 21st century conservation options. PLoS ONE **10**:e0140389.

Fortini LB, Jacobi JD, Price JP. 2017. Chapter 3. Projecting end-of-century shifts in the spatial pattern of plant-available water across Hawaiʻi to assess implications to vegetation shifts. Page in P. C. Selmants, C. P. Giardina, J. D. Jacobi, and Z. Zhu, editors. Baseline and projected future carbon storage and carbon fluxes in ecosystems of Hawaiʻi. U.S. Geological Survey, Reston, VA. Available from https://doi.org/10.3133/pp1834.Foster JT, Tweed EJ, Camp RJ, Woodworth BL, Adler CD, Telfer T. 2004. Long-term population changes of native and introduced birds in the Alakaʻi Swamp, Kauaʻi. Conservation Biology **18**:716–725.

Frazier AG, Giambelluca TW. 2017. Spatial trend analysis of Hawaiian rainfall from 1920 to 2012. International Journal of Climatology **37**:2522–2531.

Frazier AG, Giambelluca TW, Diaz HF, Needham HL. 2016. Comparison of geostatistical approaches to spatially interpolate month-year rainfall for the Hawaiian Islands. International Journal of Climatology **36**:1459–1470.

Giambelluca TW, Chen Q, Frazier AG, Price JP, Chen Y-L, Chu P-S, Eischeid JK, Delparte DM. 2013. Online rainfall atlas of Hawaiʻi. Bulletin of the American Meteorological Society **94**:313–316.

Giambelluca TW, Diaz HF, Luke MSA. 2008. Secular temperature changes in Hawaiʻi. Geophysical Research Letters **35**:L12702.

Gon S, Olson D. 2016. Hawaiʻi tropical moist forests. Available from http://www.worldwildlife.org/ecoregions/oc0106 (accessed November 25, 2016).

Gotsch SG, Crausbay SD, Giambelluca TW, Weintraub AE, Longman RJ, Asbjornsen H, Hotchkiss SC, Dawson TE. 2014. Water relations and microclimate around the upper limit of a cloud forest in Maui, Hawaiʻi. Tree Physiology:tpu050.

Hawaiʻi Department of Land and Natural Resources. 2015. Hawaiʻi's State Wildlife Action Plan (SWAP). Prepared by H. T. Harvey and Associates, Honolulu, HI. Available from http://www.state.hi.us/dlnr/dofaw/swap/ (accessed November 2, 2016).

Ice GG, Neary DG, Adams PW. 2004. Effects of wildfire on soils and watershed processes. Journal of Forestry **102**:16–20.

Johnson AB, Winker K. 2010. Short-term hurricane impacts on a neotropical community of marked birds and implications for early-stage community resilience. PLOS ONE **5**:e15109.

Juvik JO, Nullet D. 1994. A climate transect through tropical montane rain forest in Hawaiʻi. Journal of Applied Meteorology **33**:1304–1312.

Juvik SP, Juvik JO. 1998. Atlas of Hawaiʻi. University of Hawaiʻi Press, Honolulu, HI. Available from http://www.ulukau.org/elib/cgi-bin/library?e=d-0atlas-000Sec--11en-50-20-frameset-book--1-010escapewin&a=d&p2=book.

Keener VW, Hamilton K, Izuka SK, Kunkel KE, Stevens LE, Sun L. 2013. Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 8. Climate of the Pacific Islands. NOAA Technical Report NESDIS 142-8. National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C.

Keener VW, Marra JJ, Finucane ML, Spooner D, Smith MH. 2012. Climate change and Pacific Islands: Indicators and impacts. Report for the 2012 Pacific Islands Regional Climate Assessment (PIRCA). Island Press, Washington, D.C. Available from www.EastWestCenter.org/PIRCA.

Keith LM, Hughes RF, Sugiyama LS, Heller WP, Bushe BC, Friday JB. 2015. First report of *Ceratocystis* Wilt on ʻōhiʻa (*Metrosideros polymorpha*). Plant Disease **99**:1276.

Kilpatrick AM. 2006. Facilitating the evolution of resistance to avian malaria in Hawaiian birds. Biological Conservation **128**:475–485.

Lohse K, Nullet D, Vitousek P. 1995. The effects of an extreme drought on the vegetation of a single lava flow on Mauna Loa, Hawaiʻi. Pacific Science **49**:212–220.

Longman RJ. 2015. The effects of trade wind inversion variability on high elevation climates in Hawaiʻi. University of Hawaiʻi at Mānoa. Available from http://gradworks.umi.com/37/17/3717196.html.

Loope LL, Giambelluca TW. 1998. Vulnerability of island tropical montane cloud forests to climate change, with special reference to East Maui, Hawaiʻi. Climatic Change **39**:503–517.

MacKenzie R, Giardina CP, Povak N, Hessburg P, Reynolds KM, Heider C, Salminen E, Kimball H. 2014. Development of a decision support tool for watershed management in the tropics. Institute of Pacific Islands Forestry, USDA Forest Service.

McDaniel S, Ostertag R. 2010. Strategic light manipulation as a restoration strategy to reduce alien grasses and encourage native regeneration in Hawaiian mesic forests. Applied Vegetation Science **13**:280–290.

Michaud J, Cordell S, Cole TC, Ostertag R. 2015. Drought in an invaded Hawaiian lowland wet forest. Pacific Science **69**:367–383.

Murakami H, Wang B, Li T, Kitoh A. 2013. Projected increase in tropical cyclones near Hawaiʻi. Nature Climate Change **3**:749–754.

Murphy MJ, Inman-Narahari F, Ostertag R, Litton CM. 2014. Invasive feral pigs impact native tree ferns and woody seedlings in Hawaiian forest. Biological Invasions **16**:63–71.

Pau S, Okin GS, Gillespie TW. 2010. Asynchronous response of tropical forest leaf phenology to seasonal and El Niño-driven drought. PLOS ONE **5**:e11325.

Paxton EH, Camp RJ, Gorresen PM, Crampton LH, Leonard DL, VanderWerf EA. 2016. Collapsing avian community on a Hawaiian island. Science Advances **2**:e1600029.

Sakai AK, Wagner WL, Mehrhoff LA. 2002. Patterns of endangerment in the Hawaiian flora. Systematic Biology **51**:276–302.

Scowcroft PG, Conrad CE. 1992. Alien and native plant response to release from feral sheep browsing on Mauna Kea. Pages 625–665 in C. P. Stone, C. W. Smith, and J. T. Tunison, editors. Alien plant invasions in native ecosystems of Hawaiʻi: Management and research. University of Hawaiʻi Cooperative National Park Resources Unit, Honolulu, HI.

Strauch AM, Bruland GL, MacKenzie RA, Giardina CP. 2016. Soil and hydrological responses to wild pig (*Sus scofa*) exclusion from native and strawberry guava (*Psidium cattleianum*)-invaded tropical montane wet forests. Geoderma **279**:53–60.

Takahashi M, Giambelluca TW, Mudd RG, DeLay JK, Nullet MA, Asner GP. 2011. Rainfall partitioning and cloud water interception in native forest and invaded forest in Hawaiʻi Volcanoes National Park. Hydrological Processes **25**:448–464.

The Nature Conservancy. 2006. An ecoregional assessment of biodiversity conservation for the Hawaiian High Islands. The Nature Conservancy. Available from http://www.hawaiiecoregionplan.info/.

Trauernicht C, Pickett E, Giardina CP, Litton CM, Cordell S, Beavers A. 2015. The contemporary scale and context of wildfire in Hawaiʻi. Pacific Science **69**:427–444.

U.S. Fish and Wildlife Service. 2006. Revised recovery plan for Hawaiian forest birds. U.S. Fish & Wildlife Service, Portland, OR.

Weller SG, Cabin RJ, Lorence DH, Perlman S, Wood K, Flynn T, Sakai AK. 2011. Alien plant invasions, introduced ungulates, and alternative states in a mesic forest in Hawaiʻi. Restoration Ecology **19**:671–680.

Wilson EE, Holway DA. 2010. Multiple mechanisms underlie displacement of solitary Hawaiian Hymenoptera by an invasive social wasp. Ecology **91**:3294–3302.

Wilson EO. 1996. Hawaiʻi: a world without social insects. Bishop Museum Occasional Papers **45**:4–8.

Zhang C, Wang Y, Hamilton K, Lauer A. 2016. Dynamical downscaling of the climate for the Hawaiian Islands. Part II: Projection for the late twenty-first century. Journal of Climate **29**:8333–8354.

Hawaiian Islands Climate Synthesis Project: Vulnerability Assessment Methods and Application

Defining Terms

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

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

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

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

Vulnerability Assessment Model

The vulnerability assessment model applied in this process was developed by EcoAdapt[2] (Hutto et al. 2015, EcoAdapt 2014a, EcoAdapt 2014b, Kershner 2014), and includes evaluations of relative vulnerability by local stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats and ecosystem services. Stakeholders evaluated vulnerability of each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Habitat exposure was evaluated by EcoAdapt using future climate projections from the scientific literature; ecosystem service exposure was evaluated by workshop participants using the climate impacts table provided by EcoAdapt. Each vulnerability component (i.e. sensitivity, adaptive capacity, and exposure) was divided into specific elements. For example, habitats included three elements for assessing sensitivity and five elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

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

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

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

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

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

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

Habitat & Ecosystem Service Elements

Sensitivity & Exposure (Applies to Habitats and Ecosystem Services)

1. Climate and Climate-Driven Factors: e.g., air temperature, precipitation, freshwater temperature, sea surface temperature, sea level rise, soil moisture, altered streamflows, etc.

2. Disturbance Regimes: e.g., wildfire, flooding, drought, insect and disease outbreaks, wind, etc.

3. Future Climate Exposure: e.g., consideration of projected future climate changes (e.g., temperature and precipitation) as well as climate-driven changes (e.g., altered fire regimes, altered flow regimes, shifts in vegetation types). Experts were provided with a summary of historical, current, and projected future climate changes for the main Hawaiian Islands.

4. Non-Climate Stressors: e.g., land-use conversion (e.g., residential or commercial development), agriculture and/or aquaculture, transportation corridors (e.g., roads, railroads, trails), water diversions, invasive and other problematic species, pollution and poisons, etc. For non-climate stressors, experts were asked to evaluate sensitivity, whether the habitat or ecosystem service is currently exposed to that stressor, and whether the pattern of exposure is widespread and/or consistent across the study area or is highly localized (e.g., exposure to aquaculture is highly localized but exposure to invasive grasses is often widespread).

Adaptive Capacity (Habitats)

1. Extent and Integrity: e.g., habitats that occur in multiple locations vs. single, small areas; high integrity vs. degraded habitats

2. Habitat Isolation: e.g., adjacent to other native habitat types vs. isolated habitats, barriers to dispersal (e.g., development, energy productions, roads, water diversions, etc.)

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

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

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

Adaptive Capacity (Ecosystem Services)

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

Literature Cited

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

EcoAdapt. 2014b. A climate change vulnerability assessment for resources of Nez Perce-Clearwater National Forests. Version 3.0. EcoAdapt, Bainbridge Island, WA.

Glick P, Stein BA, Edelson NA. 2011. Scanning the conservation horizon: A guide to climate change vulnerability assessment. National Wildlife Federation, Washington, D.C.

Hutto SV, Higgason KD, Kershner JM, Reynier WA, Gregg DS. 2015. Climate change vulnerability assessment for the north-central California coast and ocean. Page 473. ONMS-15-02, Marine Sanctuaries Conservation Series. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD.

Intergovernmental Panel on Climate Change (IPCC). 2014. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

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

Lawler J. 2010. Pacific Northwest Climate Change Vulnerability Assessment. Available from http://climatechangesensitivity.org/.

Manomet Center for Conservation Science, National Wildlife Federation. 2013. The vulnerabilities of fish and wildlife habitats in the Northeast to climate change. A report to the Northeastern Association of Fish and Wildlife Agencies and the North Atlantic Landscape Conservation Cooperative. Manomet Center for Conservation Sciences, Plymouth, MA.

Moss R, Schneider S. 2000. Towards consistent assessment and reporting of uncertainties in the IPCC TAR. In R. Pachauri and T. Taniguchi, editors. Cross-cutting issues in the IPCC Third Assessment Report. Global Industrial and Social Progress Research Institute (for IPCC), Tokyo.
