Mesic & Wet Forest Habitats

Climate Change Vulnerability Assessment Synthesis for Hawaiʻi

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for mesic and wet forest habitats on the island of Hawaiʻi 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 forests on Hawaiʻi occur at mid-elevation sites between 1,000 and 2,000 m (3,280 and 6,560 ft), and span both the windward and leeward sides of the island, including the Kona region and the slopes of Mauna Kea and Mauna Loa (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). Mesic habitats are typically dominated by koa (*Acacia koa*), ʻōhiʻa lehua (*Metrosideros polymorpha*), and lama (*Diospyros sandwicensis*) trees (Hawaiʻi Department of Land and Natural Resources 2015).

Wet forests are found in two bands on Hawaiʻi; lowland forests are found at sites up to 762 m (2,500 ft) in elevation, and montane forests are found at elevations of 762–1,830 m (2,500–6,000 ft). Wet forests are found primarily on the windward side of the island and receive over 1,900 mm (75 in) of rainfall each year (The Nature Conservancy 2006), and do not have a significant dry period (Juvik & Juvik 1998). This forest type, which is typically dominated by ʻōhiʻa trees, also supports bog sub-habitats (Vuln. Assessment Workshop, pers. comm., 2017).

Mesic and wet forest types have dense understories composed of shrubs, ferns, and sedges (Hawaiʻi Department of Land and Natural Resources 2015; Gon & Olson 2016); ʻōhiʻa, maile (*Alyxia oliviformis*), and palapalai ferns (*Microlepia strigosa*) are used for lei making and are among the many culturally significant species found within these habitat types (Vuln. Assessment Workshop, pers. comm., 2017). Mesic and wet forests also provide habitat for a variety of wildlife, including endangered forest birds, endemic tree snails, and the ʻōpeʻapeʻa (Hawaiian hoary bat, *Lasiurus cinereus semotus*; Hawaiʻi Department of Land and Natural Resources 2015; Vuln. Assessment Workshop, pers. comm., 2017).

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[1] This information was gathered during a vulnerability assessment and scenario planning workshop in January 2017 (http://ecoadapt.org/workshops/hawaiivulnerabilityworkshop). Further information and citations can be found in the *Hawaiian Islands Climate Vulnerability and Adaptation Synthesis* and other products available online at www.bit.ly/HawaiiClimate.

Habitat Vulnerability

Mesic and wet habitats on Hawai'i were evaluated within three groups: mesic forests, montane wet forests, and lowland wet forests. 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, although individual rankings varied slightly between the forest types.

Mesic & Montane Wet Forests	Rank	Confidence
Sensitivity	Moderate-High	Moderate
Future Exposure	Moderate-High	Low
Adaptive Capacity	Moderate-High	Moderate
Vulnerability	**Moderate**	**Moderate**

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

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

Mesic and wet forest habitat types are primarily sensitive to factors that impact moisture gradients and water availability, including drought, changes in precipitation amount and timing, soil moisture, air temperature, and changes in wind and circulation patterns. Reduced water availability can alter species composition and forest distribution, potentially reducing habitat extent. Wildfire, tropical storms, disease, and volcanic activity 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, mammals, pathogens/parasites, social insects) are a major non-climate stressor for mesic and wet forest types, and these can alter ecosystem processes and directly compete with native species, contributing to species mortality and reduced recruitment, and undermining the ecological integrity and persistence of native forests. Development, agriculture, and roads/highways reduce habitat extent and fragment and degrade remaining forest area.

Although mesic and wet forests are relatively extensive on Hawai'i, lower-elevation forests are more fragmented and degraded due to human activity. Native species diversity and endemism is high; however, habitat fragmentation and invasive species invasion have limited native mesic and wet forest regeneration following wildfire and other disturbances. Management and restoration efforts are not likely to significantly alleviate the impacts of climate change, but mesic and wet forests have relatively high public value and societal support.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

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

Mesic forests on Hawaiʻi are projected to decline by the end of the century, with a loss of about 250 km^2 of mesic forest area, including many low-elevation mesic forests on the windward side of the island (Fortini et al. 2017). In contrast, wet forests are projected to increase overall by an area of about 100 km^2, primarily by expanding into higher elevations on the windward side of the island. This shift in forest cover type corresponds to a projected ~15% decrease in the mesic moisture zone and a ~15% increase in the wet moisture zone on Hawaiʻi by the end of the century (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 vegetation was found to be the one of the least vulnerable vegetative groups to projected future climate change, while mesic forest vegetation was found to moderately vulnerable (Fortini et al. 2013). Fortini et al. (2015) also found that, in general, forest bird distributions are expected to shift upslope and persist in only the highest-elevation areas near the tree line. Many forest bird species are projected to lose most or all of their range, including the Hawaiʻi ʻākepa (*Loxops coccineus coccineus*) and the endemic ʻakiapōlāʻau (*Hemignathus wilsoni*; 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	**All mesic and wet forest types:** Moderate-high overall impact (moderate confidence)	
Drought	***Historical and current trends*** • Drought length increased in 1980–2011 compared to 1950–1979 (Chu et al. 2010) • Drought conditions are usually less prevalent during La Niña years, and more prevalent during El Niño years (Dolling et al. 2009; Chu et al. 2010) ***Projected future trends*** Drought projections are highly uncertain because they are primarily dependent on precipitation projections, which are variable and have high uncertainty. Possible future scenarios include: • By 2100, drought risk is likely to increase for low- and mid-elevation leeward areas, decrease for mid-elevation windward slopes, and remain static elsewhere (Keener et al. 2012)	***Potential impacts on habitat*** • Some native species exhibit traits that promote survival during short-term and seasonal droughts (Michaud et al. 2015); for instance, ʻōhiʻa 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, although some shrub species can reduce water stress through mechanisms such as shedding leaves or angling leaves 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 wildfire frequency and size (Loope & Giambelluca 1998; Dolling et al. 2005), as well as severity (Vuln. Assessment Reviewer, pers. comm., 2017) ***Geographic variation*** • Windward/leeward aspect, proximity to roads (Vuln. Assessment Workshop, pers. comm., 2017)

Precipitation (amount & timing) and soil moisture	***Historical and current trends*** • Since 1920, precipitation has decreased across the Hawaiian Islands, with the strongest drying trends occurring over the last 30 years (Frazier et al. 2016; Frazier & Giambelluca 2017) • From 1920 to 2012, dry season (May–Oct.) precipitation on Hawaiʻi declined an average of 3.19% per decade across the island; declines were greatest leeward side, and declines were at least 6% per decade for most of the Kona region (Frazier & Giambelluca 2017) • From 1920–2012, wet season (Nov.–April) precipitation on Hawaiʻi declined an average of 1.64% per decade across the island, with the largest declines on the leeward side, especially in the Kona region (Frazier & Giambelluca 2017) • Since 1997, dry years were twice as common as wet years on Mauna Kea, and monthly rainfall was lower than normal for 65% of months at Puʻu Lāʻau and 71% of months at Halepōhaku (Banko et al. 2013) • 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 the amount of future greenhouse gas emissions. Possible future scenarios include: • Slight increase or no change by 2100 (Keener et al. 2013) • Decrease in precipitation across all seasons by 2100	***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 tree line 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 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) • Increased precipitation and soil moisture could benefit both montane wet and mesic forests (Vuln. Assessment Workshop, pers. comm., 2017)

	(4% to 6% decrease in wet-season precipitation; 16% to 28% decrease in dry-season precipitation; Elison Timm et al. 2015) • By 2100, large increase in windward precipitation in the dry season (up to 40%) and moderate increases in wet-season windward precipitation (up to 20%); decreased leeward precipitation in both seasons (up to 40%; Zhang et al. 2016) • No regional soil moisture projections are available, but soil moisture is likely to decline in the future, especially if precipitation decreases as air temperatures increase (Longman et al. 2015)	
Air temperature	***Historical and current trends*** • From 1975–2006, the rate of air temperature increases has accelerated to 0.2°C (0.36°F) per decade, compared to overall increases of 0.04°C (0.07°F) per decade for all records from 1919–1975; the strongest warming is found at high elevations and in winter minimum temperatures (Giambelluca et al. 2008) • From 1958–2009, the number of freezing days declined from ~4–5 days per year to ~1 day per year (Diaz et al. 2011) ***Projected future trends*** Projections that air temperature will increase are highly certain, although the magnitude of change is less certain. Possible future scenarios include: • Air temperature increases by 2°C (3.6°F) to 3.5°C (6.3°F) across the Hawaiian Islands by 2100, with more significant increases at higher elevations (Zhang et al. 2016) • More frequent and more intense extreme heat days	***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) • Warming temperatures are allowing the upslope expansion of mosquitos that carry avian malaria (*Plasmodium* spp.), which threatens endemic forest birds (Atkinson & LaPointe 2009; Fortini et al. 2015)

	(Keener et al. 2012)	***Geographic variation*** • Some forest pests and diseases have elevational limits, which are thought to be temperature related, similar to mosquitos (Vuln. Assessment Reviewer, pers. comm., 2017) ***Potential refugia*** • Higher elevations (Vuln. Assessment Workshop, pers. comm., 2017)
Wind & circulation	***Historical and current trends*** • Since the 1990s, the Pacific trade winds (both the Walker and Hadley cells) have increased, corresponding with a negative PDO phase (England et al. 2014) • Trade wind direction has shifted from predominantly northeast to east from 1973–2009 (Garza et al. 2012), which represents a cyclical shift that is known to complete its cycle approximately every 45 years (Wentworth 1949) • The frequency of TWI occurrence increased an average of 16% starting in 1990 (Longman et al. 2015) ***Projected future trends*** Projections for the TWI are moderately uncertain due to the influence of large-scale atmospheric patterns (e.g., El Niño-Southern Oscillation [ENSO] and Pacific Decadal Oscillation [PDO]). Possible future scenarios include: • An 8-9% increase in TWI frequency of occurrence, corresponding to an almost 50% decrease in days without a well-defined TWI (decrease from 17% of days currently to 9% of days by 2100; Zhang et al. 2016, 2017) • Possible decrease in TWI base height, ranging from	***Potential impacts on habitat*** • Trade wind changes could alter rainfall, relative humidity, and soil moisture at high-elevation sites (Longman et al. 2015), affecting atmospheric demand and increasing water stress for wet and mesic forest species (Gotsch et al. 2014) • More frequent occurrence and/or lowering of the TWI could alter cloud forest distribution and potentially prevent upslope movement of forest vegetation in response to warming temperatures, likely resulting in an overall loss of habitat area (Crausbay & Hotchkiss 2015; Harter et al. 2015) • Wind is a major driver of wildfire spread from areas dominated by non-native grasslands to forest (Freifelder et al. 1998; Blackmore & Vitousek 2000), and is a component of calculating “red flag warnings” by the National Weather Service (Vuln. Assessment Reviewer, pers. comm., 2017)

	small (Zhang et al. 2016, 2017) to more significant (Lauer et al. 2013) Surface wind speed and direction may change, but studies have reached varying conclusions: • Nov.–Dec. surface wind speeds across the Hawaiian Islands may decrease strongly by 2100, with small changes in surface wind speed possible in other seasons (Storlazzi et al. 2015) • Surface winds in the Hawaiian Islands may increase modestly, with a very modest increase in frequency of strong wind days (Zhang et al. 2016)	
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*** • Hurricanes and tropical storms can result in major forest damage (Loope & Giambelluca 1998); although no recent hurricanes have struck Hawaiʻi directly, damage occurred in lowland wet forests after Iselle in 2014 and Darby in 2016 (Vuln. Assessment Reviewer, pers. comm., 2017) • Canopy openings caused by storm damage may reset succession in affected areas, and can also increase colonization and growth rates for invasive plants (Loope & Giambelluca 1998) • 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)
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	***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

	variability (Trauernicht et al. 2015) ***Projected future trends*** • The probability of fire occurrence in grassland, shrubland, and forest areas on the leeward side of the island is expected to roughly double; wildfire risk is highest at mid-elevation sites and in grasslands (Wada et al. 2017) • Increased wildfire is likely if drier conditions and more drought occur (Trauernicht et al. 2015)	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 forest erosion by removing vegetation and exposing bare soil (Ice et al. 2004)

Disease	***Historical and current trends***
	• No information is available for plant disease
	
	Projected future trends
	• Warming temperatures are expected to increase the distribution of avian diseases spread by mosquitos, such as avian malaria (Fortini et al. 2015)
	    ○ Within the Hakalau National Wildlife Refuge, areas of montane forest where birds are at low risk of contracting malaria will be nearly eliminated by 2100 (Benning et al. 2002)
	• 0.4 million forested acres across the Hawaiian Islands are at risk of experiencing a 25% decrease in standing live basal area by 2027 due to the combined threat of insects and disease (not taking climatic changes into account; Krist et al. 2014)
	    ○ Koa wilt (*Fusarium oxysporum* f. sp. *koae*) and ʻōhiʻa rust (*Austropuccinia psidii*) are the greatest disease threats on Hawaiʻi, primarily on mid-elevation windward slopes (Krist et al. 2014)
	    ○ 53,000 acres across the Hawaiian Islands are at risk due to koa wilt (Krist et al. 2014)
		Potential impacts on habitat
		• Warming air and water temperatures and changes in precipitation may alter the distribution and severity of root rot, fungal diseases, and other pathogens that can affect mesic and wet forest species (Conry & Cannarella 2010; Sturrock et al. 2011; Hawaiʻi Department of Land and Natural Resources 2015)
		• Fungal diseases such as koa wilt can cause extensive damage to native species, resulting in widespread damage and high mortality in young trees (Conry & Cannarella 2010; Krist et al. 2014)
		• Rapid ʻōhiʻa death (caused by the fungal pathogen *Ceratocystis fimbriata*) has caused extensive tree mortality in ʻōhiʻa stands on Hawaiʻi and is spreading to other islands (Keith et al. 2015; Loope 2016); this disease causes high tree mortality and has the potential to significantly alter forest species composition (Mortenson et al. 2016)
		• ʻŌhiʻa rust was introduced to the Hawaiian Islands in 2005 and can damage seedlings and reduce regeneration, though it does not typically affect adult trees (Krist et al. 2014)
		• 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

	• Little change is expected in the suitable climatic space for ʻōhiʻa rust (Hanna et al. 2012)	diseases have drastically reduced native honeycreeper populations over the last century (Atkinson & LaPointe 2009)

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, land-use conversion to development and agriculture fragments forests and reduces habitat extent, while impacts associated with development, agriculture, and roads/highways degrade habitats by introducing pollutants and invasive species, increasing erosion, and 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 recreation and invasive/problematic reptiles.

Non-climate stressors	**All mesic and wet forest types:** 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*]) limit native plant growth and recruitment (Daehler 2005) and alter the structure of mesic and wet forests by 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 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% • *Pattern of exposure:* Consistent across habitat
Invasive/ problematic ungulates	***Potential impacts on habitat*** • Invasive ungulates, including 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 facilitate the invasion of introduced non-native species, including strawberry guava (*Psidium cattleianum*) and Himalayan ginger (*Hedychium gardnerianum*; 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) • *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) • ʻŌhiʻa rust was introduced to the Hawaiian Islands in 2005 and causes damage to seedlings, reducing regeneration (Krist et al. 2014) • Rapid ʻōhiʻa death has infected over 50,000 acres of ʻōhiʻa forest on Hawaiʻi Island and is a significant threat to ʻōhiʻa trees on the other Hawaiian Islands (Keith et al. 2015); this disease can cause high rates of tree mortality, potentially shifting forest species composition (Mortenson et al. 2016) • *Pattern of exposure:* Consistent across habitat
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, other arthropods) through predation and/or competition for food (Nishida & Evenhuis 2000; Banko & Banko 2009; Wilson & Holway 2010; Medeiros et al. 2013) • Highly invasive western yellowjackets (*Vespula pensylvanica*) prey on and displace pollinators (both introduced and endemic) and rob nectar (Wilson & Holway 2010; Hanna et al. 2013), significantly decreasing pollination and seed set of ʻōhiʻa (Hanna et al. 2013) • The majority of parasitoid wasp species found in windward forests on Hawaiʻi Island are non-native species (44 of 58 collected), including nine species introduced to control pests; endemic species were primarily found at mid- and high-elevation sites (Peck et al. 2008) • Introduced ants contribute to the loss of native vegetation by allowing aphids and other piercing/sucking insects to thrive (Conry & Cannarella 2010) • *Pattern of exposure:* Variable across habitat
Residential & commercial development	***Potential impacts on habitat*** • Development pressure is highest in lowland areas, and development has resulted in the loss of forest area over the last century (Conry & Cannarella 2010) • Development may alter soil composition and destroy seed banks, as well as introduce pollutants/contaminants and increase erosion (Conry & Cannarella 2010) • Development is also associated with the introduction of invasive plants, wildlife, pests, and disease (Conry & Cannarella 2010) • Increased human activity associated with developed areas can lead to more wildfire ignitions (Trauernicht et al. 2015) • *Pattern of exposure:* Localized in multiple areas — moderate high exposure for lowland wet forests, low for mesic and montane wet forests

Roads, highways, & trails	***Potential impacts on habitat*** • Roads contribute to the spread of invasive plants into forest areas (Daehler 2005) • Roads also increase impervious surface area, increasing polluted runoff and erosion and reducing water infiltration (Conry & Cannarella 2010) • *Pattern of exposure:* Variable across habitat
Agriculture	***Potential impacts on habitat*** • Montane forest area has been cleared for cattle ranching, including in the Kona region where the extent of koa/ʻōhiʻa forests have been reduced (Cuddihy 1988; Goldstein et al. 2008); these areas are now typically dominated by non-native grasses, which limits seedling establishment and subsequent forest recovery (Denslow et al. 2006; McDaniel & Ostertag 2010) • The use of high-elevation sites as pasture may prevent montane forests from migrating upslope under changing climate conditions, reducing potential refugia from avian malaria (Benning et al. 2002) • Lowland wet forest has been heavily impacted by conversion to agricultural uses; few remaining patches remain (Price et al. 2012) • *Pattern of exposure:* Variable 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 (Lindsey et al. 2009; Becker et al. 2010; Vanderwerf 2012; Hawaiʻi Department of Land and Natural Resources 2015); feral and domestic dogs (*Canis* spp.) also prey on nesting seabird colonies (Hawaiʻi Department of Land and Natural Resources 2015; F. Duval and Vuln. Assessment Reviewer, pers. comm., 2017) • Rats are also major predators of endemic tree snails, and have contributed to the decline of several rare and endangered species (Hadfield et al. 1993; Hadfield & Saufler 2009) • Rats and mice consume the seeds of native plant species, reducing seedling recruitment (Juvik & Juvik 1998; Hawaiʻi Department of Land and Natural Resources 2015; Shiels & Drake 2015); impacts are especially large for native palms in lowland wet forests, which may take several months to germinate (Shiels & Drake 2015) • Rats have also been shown to damage the bark of adult koa trees (Scowcroft & Conrad 1992), and consume threatened and endangered tree snails and lobeliods (e.g., *Clermontia*, *Cyanea*; Patrick Hart, pers. comm., 2017) • *Pattern of exposure:* Consistent across habitat
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) • Mesic forests are more vulnerable to flammable grasses than wet forests (Vuln. Assessment Workshop, pers. comm., 2017) • *Pattern of exposure:* Variable across habitat

Other Sensitivities

Mesic and wet forest habitats are also sensitive to volcanic activity, which may damage forest vegetation (Table 3).

Table 3. Other sensitivities that may affect the vulnerability of mesic and wet forest habitats to climate change.

Other sensitivities	**All mesic and wet forest types:** Moderate-high sensitivity (moderate confidence)
Volcanic activity	***Potential impacts on habitat*** • Lava flows are a natural source of wildfire ignitions in mesic and wet forests, resetting plant succession in burned areas (Ainsworth & Kauffman 2008) • Seismic activity can cause earthquakes, resulting in cracks and settling of the ground, landslides, mudflows, and tsunamis (Richmond et al. 2001); these could cause significant damage to forest areas • Volcanic emissions (VOG, or volcanic smog) contain high levels of sulfur dioxide (SO_2), a harmful gas that can be absorbed by plants through their stomata, where it is then converted to sulfuric acid that burns plant tissue; forest vegetation downwind of active vents is most affected, although some species are SO_2-resistant (e.g., ʻōhiʻa; Nelson & Sewake 2008) • SO_2 can also combine with water in the atmosphere to create acidic precipitation or fog, which can injure plants, reduce growth and productivity, impact soil acidity and fertility, and mobilize heavy metals found within soil (Nelson & Sewake 2008) • Pollutants can interact with other stressors (e.g., insect outbreaks) to cause greater damage to forest vegetation (Conry & Cannarella 2010) • Volcanic activity can impact forest wildlife by destroying habitat; for instance, eruptions from Mauna Loa in 1984 caused a decline in the extent of quality habitat for endemic forest birds (Hawaiʻi Department of Land and Natural Resources 2015) • Emissions from active volcanoes can cause loss of habitat and deterioration of forests because of bad air quality, and VOG may exacerbate changes in local climate (Vuln. Assessment Workshop, pers. comm., 2017)

Adaptive Capacity

Mesic and wet forests are extensive on Hawaiʻi, but large areas of forest have been fragmented and/or lost due to human activity, especially in low-elevation areas (Table 4). Habitat fragmentation impacts seed dispersal and animal movement, impacting 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 some of the impacts of climate change, but public value and societal support for these habitat types is relatively good; biosecurity measures could limit further introduction and spread of invasive species, decreasing some additional threats to native species.

Table 4. 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 and montane wet forest:** Moderate-high adaptive capacity (moderate confidence) **Lowland wet forest:** Moderate adaptive capacity (moderate confidence)
Extent & integrity **Mesic & montane wet forest:** Moderate-high (high confidence) **Lowland wet forest:** Low-moderate (high confidence)	+ These habitats contain culturally rare sub-habitats (Vuln. Assessment Workshop, pers. comm., 2017) +/- Mesic and wet forests (e.g., those dominated by ʻōhiʻa and/or mixed ʻōhiʻa/koa) account for 38% of Hawaiʻi's forest area (126,240 ha; Asner et al. 2011) - Lowland wet and mesic forest types are under increased pressure from anthropogenic uses (Hawaiʻi Department of Land and Natural Resources 2015) - Logging, non-native 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 & montane wet forest:** Moderate (moderate confidence) **Lowland wet forest:** High (moderate confidence)	+/- Barriers to mesic and wet forest dispersal include agriculture, alien vegetation and animals, residential and commercial development, and geologic/water/atmospheric features (Vuln. Assessment Workshop, pers. comm., 2017)

Resistance & recovery **All mesic & wet forest types:** Variable (low confidence)	+ Some native woody species, including ʻōhiʻa, can regenerate after fires through basal sprouting, at least under certain conditions (Ainsworth & Kauffman 2008) + Some endemic forest birds may be able to develop resistance to avian malaria (Woodworth et al. 2005; Kilpatrick 2006); for instance, Hawaiʻi ʻamakihi (*Hemignathus virens*) populations have increased in low-elevation forests on the southeastern side of Hawaiʻi Island despite high year-round transmission of the disease, suggesting the possible evolution of genetic resistance (Woodworth et al. 2005) +/- Resistance/recovery is heavily dependent on the type and combination of stressors involved; as a result, resistance and recovery can be highly variable and site-specific (Vuln. Assessment Workshop, pers. comm., 2017) - 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 (e.g., frugivorous birds) 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; Culliney et al. 2012; Pejchar 2015)
Habitat diversity **All mesic & wet forest types:** Moderate-high (moderate confidence)	+/- Component species diversity depends on functional group diversity (Vuln. Assessment Workshop, pers. comm., 2017) +/- Species diversity is typically low in the forest canopy; however, mesic forests have higher tree diversity than wet forests and undisturbed mesic forest areas may have the highest tree diversity in Hawaiʻi (Vuln. Assessment Reviewer, pers. comm., 2017) +/- Endangered wildlife species found in mesic and wet forests include the endemic ākepa, ʻalawī (Hawaiʻi creeper; *Loxops mana*), ʻakiapolaʻau (*Hemignathus munroi*), nēnē (Hawaiian goose; *Branta sandvicensis*), ʻio (Hawaiian hawk; *Buteo solitarius*), and the ʻōpeʻapeʻa (Hawaiian hoary bat; *Lasiurus cinereus semotus*; Loope & Giambelluca 1998; Hawaiʻi Department of Land and Natural Resources 2015; Vuln. Assessment Reviewer, pers. comm., 2017) - Forest bird species richness is expected to decline by 2100 (Fortini et al. 2015) - Pollinators are particularly sensitive to climate change (Vuln. Assessment Workshop, pers. comm., 2017)

Management potential **All mesic & wet forest types:** Moderate (high confidence)	+ Moderate-high public value (Vuln. Assessment Workshop, pers. comm., 2017) + Extreme events (e.g., hurricanes) would likely have a moderate-high impact on societal support for the management and conservation of this habitat (Vuln. Assessment Workshop, pers. comm., 2017) + Biosecurity measures increase adaptive capacity by preventing the introduction and/or limiting the spread of invasive mammals (e.g., mongooses), insects (e.g., little fire ants), and pathogens/disease (e.g., rapid ʻōhiʻa death; Hawaiʻi Department of Land and Natural Resources 2015; Lee et al. 2015; Loope 2016) ○ For example, the Hawaiʻi Department of Agriculture restricts the movement of ʻōhiʻa material and soil from Hawaiʻi Island to limit further spread of rapid ʻōhiʻa death; the public is also asked to clean boots, clothing, and car undercarriages to avoid transporting fungal spores into new areas (Loope 2016) ○ Additional biosecurity measures include screening and search protocols at airports (Hawaiʻi Department of Land and Natural Resources 2015) + Modeling results suggest that rodent control at middle elevations to limit forest bird predation may support the evolution of resistance to avian malaria by increasing population survival and reproduction (Kilpatrick 2006) +/- Moderate societal support for managing and conserving habitat (Vuln. Assessment Workshop, pers. comm., 2017) - Low-moderate manager capacity/ability to cope with the impacts of climate change on mesic and wet forests (Vuln. Assessment Workshop, pers. comm., 2017) - Low-moderate likelihood of managing or alleviating climate change impacts on habitat: Potential actions could include protecting forest areas that may serve as climate refugia and managing non-climate stressors that may exacerbate the impacts of changing climate conditions (e.g., fencing and removing ungulates and mammalian predators, controlling invasive plants, and preventing further habitat fragmentation; Hawaiʻi Department of Land and Natural Resources 2015) ○ Fencing and ungulate removal are more successful and cost-effective in higher-elevation wet forests where fewer invasive plants have become established; in lower-elevation wet forests and most mesic forests, these activities are still a necessary first step for habitat restoration to prevent invasive plants from outcompeting native forest species (Hess 2016; Vuln. Assessment Reviewer, pers. comm., 2017)

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Hawaiian Islands Climate Synthesis Project:

Vulnerability Assessment Methods and Application

Defining Terms

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

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

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

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

Vulnerability Assessment Model

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

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

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

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

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

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

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

Habitat & Ecosystem Service Elements

Sensitivity & Exposure (Applies to Habitats and Ecosystem Services)

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

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

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

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

Adaptive Capacity (Habitats)

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

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

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

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

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

Adaptive Capacity (Ecosystem Services)

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

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