Mesic and Wet Forest Habitats

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

An Important Note About this Document: *This document represents an initial evaluation of vulnerability for mesic and wet forest habitats on Maui Nui*[1] *based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by habitat experts,*[2] *relevant references from the literature, and peer-review comments and revisions (see end of document for methods and defining terms). The aim of this document is to expand understanding of habitat vulnerability to changing climate conditions, and to provide a foundation for developing appropriate adaptation responses.*

Habitat Description

Mesic and wet forest habitats are typically found on windward lowland areas and montane slopes up to elevations of 2,194 m (7,200 ft; Crausbay et al. 2014; Gon & Olson 2016). These mesic/wet bands are created in areas that lie at or below the mean height of the trade wind inversion (TWI), and receive up to 7,620 mm (300 in) of rainfall per year (Vuln. Assessment Workshop, pers. comm., 2016). Mesic and wet forest habitat types range from mesic forests to tropical montane cloud forests, and are typically dominated by ʻōhiʻa lehua (*Metrosideros polymorpha*) and koa (*Acacia koa*) trees with dense understories composed of shrubs, ferns, and sedges (Hawaiʻi Department of Land and Natural Resources 2015; Gon & Olson 2016). Other species present may include olopua (*Nestegis sandwicensis*), mānele (*Sapindus saponaria*), ʻōlapa (*Cheirodendron trigynum*), and ʻaʻaliʻi (*Dodonaea viscosa*) trees, as well as hāpuʻu (*Cibotium* spp.) and ʻamaʻu (*Sadleria* spp.) ferns, sedges (*Carex* spp.), and *Oreobolus furcatus*, a species of sedge typically found within bogs present on montane plateaus or in depressions throughout the forest (Hawaiʻi Department of Land and Natural Resources 2015; Gon & Olson 2016; Vuln. Assessment Workshop, pers. comm., 2016).

Mesic and wet forest habitats can be found on east Maui from Makawao clockwise to Kipahulu and Kahikinui, and on the upland, windward slopes of west Maui. On Lānaʻi, mesic forest habitats are distributed on the windward slopes and extend down to the ocean (Hawaiʻi Department of Land and Natural Resources 2015; Vuln. Assessment Workshop, pers. comm.,

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

[2] This information was gathered during a vulnerability assessment and scenario planning workshop in August 2016 (http://ecoadapt.org/workshops/mauivulnerabilityworkshop). Further information and citations can be found in the *Hawaiian Islands Climate Vulnerability and Adaptation Synthesis* and other products available online at www.bit.ly/HawaiiClimate.

2016). Kahoʻolawe lies in the rain shadow of Maui and does not contain mesic or wet forest habitat (Hawaiʻi Department of Land and Natural Resources 2015).

Habitat Vulnerability

Mesic and wet forest habitats on Maui 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 & Wet Forest Habitats	Rank	Confidence
Sensitivity	Moderate-High	Moderate
Future Exposure	Moderate-High	Moderate
Adaptive Capacity	Moderate	High
Vulnerability	**Moderate**	**High**

Mesic and wet forests are sensitive to factors that alter moisture gradients, such as drought, precipitation amount and timing, storms, and air temperature. Disturbance events, such as disease, wind, and insect outbreaks can damage large habitat areas, potentially allowing invasive plants to become established. Invasive ungulates, mammalian predators, trees/shrubs, flammable grasses, and pathogens/parasites are the primary non-climate stressors for mesic and wet forest types, and have led to the rapid decline of many native and endemic species over the past several hundred years.

High-elevation wet forests remain relatively intact, but lowland areas and mesic forests experience development pressure and conversion to agriculture, ranching, or other uses. Forest species diversity and endemism is very high, and many species are able to recover rapidly from wildfire and other disturbances. Management and restoration efforts are likely to be relatively successful at alleviating the impacts of climate change, though public value and societal support for mesic and wet forest habitats is low.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Habitat distribution and species composition in mesic and wet forests are driven primarily by the strong rainfall and moisture gradients created by the TWI (Table 1). Disease, wind, and insect outbreaks may damage forest vegetation and potentially allow invasive plant establishment in disturbed areas.

Exposure to changes in precipitation amount, wildfire, drought, and storms are likely higher on mesic sites compared to wet sites (Vuln. Assessment Workshop, pers. comm., 2016). Mesic and wet forests are unlikely to be able to migrate upslope in response to warmer conditions because the upper limit is determined primarily by rainfall gradients, and changes in the frequency and/or mean height of the trade wind inversion would drastically reduce rainfall and

relative humidity at higher elevations (Crausbay et al. 2014). In fact, the upper limit of cloud forests may shift downslope in response to increasing moisture stress (Crausbay & Hotchkiss 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. These habitats are sensitive to the climatic factors and disturbance regimes listed below, and will likely be exposed to projected future changes in them. 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 extreme precipitation events.

Climatic factors and disturbance regimes Moderate-high 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: • Maui drought risk is likely to increase by 2100 for low- and mid-elevation leeward slopes, decrease on mid-elevation windward Haleakalā slopes and the summit of Mauna Kahālāwai, and remain static elsewhere (Keener et al. 2012) • Drought risk is likely to increase by 2100 for Lānaʻi and Kahoʻolawe, except for the summit of Lānaʻi, which may not experience a change in drought risk (Keener et al. 2012)	***Potential impacts on habitat*** • The upper limit of cloud forests is largely determined by moisture availability, which is regulated by periods of reduced rainfall and droughts that characterize El Niño events; this suggests that forest vegetation existing near the edge of suitable habitat is more vulnerable to short-term drought events (Crausbay et al. 2014) • Paleoecological records indicate that the location of high-elevation cloud forest tree lines on Maui were altered by periods of drought, wildfire, and dieback (Crausbay & Hotchkiss 2015) • 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) • A severe drought in Hawaiʻi from Jan.–May 1992 caused high shrub mortality, suggesting that drought may cause shifts in plant dominance towards herbaceous species (Lohse et al. 1995) • 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	***Potential impacts on habitat*** • Evaporative demand at and above the TWI is very high due to a sharp decrease in rainfall and relative humidity (Longman et al. 2015); thus, vegetation near the tree line

	& Giambelluca 2017) • From 1920 to 2012, dry season (May–Oct.) precipitation declined 1% to 5% per decade for most areas on Maui and Lānaʻi, particularly in leeward areas; Kahoʻolawe experienced more modest drying of up to 1.2% per decade (Frazier & Giambelluca 2017) • From 1920–2012, Maui experienced the most significant wet-season (Nov.–April) precipitation declines of any island in the state, decreasing 27.6 mm per decade, which ranged from declines of 2% to 5% per decade in East Maui (Frazier & Giambelluca 2017) • The frequency of trade wind inversion (TWI) occurrence increased an average of 20% since 1990, resulting in a 31% reduction in wet-season rainfall and a 16% reduction in dry-season rainfall at nine high-elevation sites on Maui (over 1,900 m [6,234 ft]; Longman et al. 2015) • 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: • Little to no change in average precipitation by 2100 (Keener et al. 2012) • Significant decreases in precipitation across all seasons by 2100, particularly in leeward areas (30% to 80% decrease in wet-season leeward precipitation and -20% to +20% change in wet-season windward precipitation; 10% to 90% decrease in dry-season precipitation) (Elison Timm et al. 2015)	experiences high rates of transpiration and greater sensitivity to moisture availability (Gotsch et al. 2014) • 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). However, they have a relatively low tolerance for cell water loss before their leaves wilt, making them vulnerable to changes in moisture availability, especially changes in the length of dry periods (Gotsch et al. 2014). • 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 study of forest sites on the windward slope of Haleakalā projected that 30% of sites would shift downslope under drier conditions (10% less rainfall); response to precipitation increases were smaller, with only 15% of plots increasing in area under a 20% increase in precipitation (Crausbay & Hotchkiss 2015) • Mesic forests are more sensitive to changes in precipitation patterns than wet forests (Vuln. Assessment Workshop, pers. comm., 2016) • Bog habitats on Maui typically receive the highest amount of annual precipitation in the Hawaiian Islands, meaning they are more resilient to precipitation shifts than bogs elsewhere in the archipelago (Polhemus 2015) • Shifts in TWI elevation and associated shifts in moisture availability are likely to cause contraction of upland swamp (i.e. forested wetland) area occurring on windward Haleakalā due to limited migration opportunities

	• By 2100, increased rainfall on windward slopes of Maui (up to 30% in the dry season), and decreased rainfall on Lānaʻi and leeward slopes of Maui in both seasons (Zhang et al. 2016) • 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)	(Polhemus 2015) ***Geographic variation*** • Puʻu Kukui has recently showed a multi-year shift in precipitation timing (Vuln. Assessment Workshop, pers. comm., 2016)
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) • The annual number of freezing days on Haleakalā has declined since 1958 (Hamilton 2013) ***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 (Keener et al. 2012)	***Potential impacts on habitat*** • 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); mesic forests and areas near the tree line are impacted to a greater degree due to lower moisture availability (Gotsch et al. 2014; Vuln. Assessment Workshop, pers. comm., 2016) • Temperature gradients are not associated with species composition or habitat distribution in mesic and wet forests, suggesting that moisture is a more important driver in determining cloud forest distribution (Crausbay et al. 2014; Gotsch et al. 2014) • Increased temperatures could also allow existing invasive species to expand their range and/or new species to become established (Vorsino et al. 2014) • 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)
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)	***Potential impacts on habitat*** • No recent hurricanes have struck Maui directly; however, Kauaʻi has been struck twice (Iwa in 1982 and Iniki in 1992), which resulted in major forest damage (Loope &

	• 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 of tropical storm activity around the Hawaiian Islands due to a northwest shift in storm track and increased strength due to large-scale changes in environmental conditions (Murakami et al. 2013)	Giambelluca 1998) • 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) • Severe weather may cause Maui parrotbills (*Pseudonestor xanthophrys*) to abandon their nests, especially during cold weather (Becker et al. 2010) • 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) • Heavy rainfall associated with storms can benefit vegetation experiencing water stress (Vuln. Assessment Workshop, pers. comm., 2016)
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 Hanawi Natural Area Reserve on Maui, areas of montane forest where birds are at low risk of contracting malaria may be reduced by up to 47% by 2100 (Lānaʻi and Kahoʻolawe do not receive enough precipitation to support mosquito habitat; Benning et al. 2002) • 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)	***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*) has caused extensive tree mortality in ʻōhiʻa stands on Hawaiʻi and is spreading to other islands; this disease has the potential to significantly alter forest species composition (Keith et al. 2015) • ʻŌhiʻa rust was introduced to the Hawaiian Islands in 2005 and can damage seedlings and reduce regeneration,

	○ On Maui, the greatest threat from ʻōhiʻa rust (*Austropuccinia psidii*) is on mid-elevation windward slopes (Krist et al. 2014) ○ 53,000 acres across the Hawaiian Islands are at risk due to koa wilt (*Fusarium oxysporum* f. sp. *koae*); on Maui, the greatest threat is on mid-elevation windward slopes Krist et al. 2014) • Little change is expected in the suitable climatic space for ʻōhiʻa rust (Hanna et al. 2012)	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 diseases have drastically reduced native honeycreeper populations over the last century (Atkinson & LaPointe 2009)
Insects	***Historical and current trends*** • No information is available about trends in insect outbreaks ***Projected future trends*** • 0.4 million forested acres across the Hawaiian Islands are at risk of experiencing a 25% decrease in standing live basal area by 2027 due to the combined threat of insects and disease (not taking climatic changes into account; Krist et al. 2014)	***Potential impacts on habitat*** • Insects may impact large areas of forest, causing defoliation, dieback, and/or mortality in native vegetation (Conant et al. 2010; Krist et al. 2014); for instance, a 2003 outbreak of koa moths (*Scotorythra paludicola*) defoliated 16 km^2 of forest in East Maui (Haines et al. 2009) • Warmer temperatures may alter insect development, reproduction, survival, and distribution (Régnière et al. 2012) • Large areas of insect-killed vegetation within a watershed can increase erosion and allow the establishment of invasive plants (Jones et al. 2006) • Many mesic and wet forest species, including ʻōhiʻa trees and the uluhe fern (*Dicranopteris linearis*), are vulnerable to damage from the two-spotted leafhopper (*Sophonia rufofascia*); plants stressed by drought or other causes may be more vulnerable to damage and mortality (Lenz & Taylor 2001; Jones et al. 2006; Conant et al. 2010) • The black twig borer (*Xylosandrus compactus*) is a serious pest of several native shrubs and trees, especially those stressed by transplanting or drought (Hara et al. 1976) • *Scotorythra* moths (multiple species) can defoliate and damage koa trees (Conant et al. 2010)

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). Invasive and problematic vegetation (e.g., trees, shrubs, and grasses), ungulates, mammalian predators, and pathogens/parasites cause severe impacts to mesic and wet forests, altering vegetation and wildlife species composition, distribution, survival, and reproduction/recruitment.

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 social insects and roads/highways/trails.

Non-climate stressors	**Mesic forest:** High overall impact (high confidence) **Wet forest:** Moderate-high overall impact (high confidence)
Invasive/ problematic ungulates	***Potential impacts on habitat*** • Invasive ungulates, including axis deer (*Axis axis*), feral pigs (*Sus scrofa*), and goats (*Capra hircus*), are a major cause of degradation in mesic and wet forest habitats, and 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 (Cole & Litton 2014; Murphy et al. 2014; Hawai‘i Department of Land and Natural Resources 2015) • Invasive ungulates also introduce invasive species, including strawberry guava (*Psidium cattleianum*) and Himalayan ginger (*Hedychium gardnerianum*; Hawai‘i 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 (Hawai‘i Department of Land and Natural Resources 2015)
Invasive/ problematic trees & shrubs	***Potential impacts on habitat*** • Invasive trees and shrubs alter the structure of mesic and wet forests, replacing native species within 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 ‘ōhi‘a on Hawai‘i; 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 Hawai‘i (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:* Localized, but will likely spread across the landscape under changing climate conditions (Vuln. Assessment Workshop, pers. comm., 2016)

Invasive/ problematic pathogens & parasites	***Potential impacts on habitat*** • Introduced pathogens and parasites are a major cause of endemic plant and wildlife decline; for instance, avian malaria and avian pox have drastically reduced native honeycreeper populations over the last century (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) • 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 Maui and the other Hawaiian Islands (Keith et al. 2015) • *Pattern of exposure:* Pathogens/parasites will not be highly localized; by their nature they spread even if local now (Vuln. Assessment Workshop, pers. comm., 2016)
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, preventing successful recruitment (Becker et al. 2010; Hawaiʻi Department of Land and Natural Resources 2015) • Rats also 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) • *Pattern of exposure:* Mammalian predators are widespread/consistent on Maui and are at close to carrying capacity across this habitat type (Vuln. Assessment Workshop, pers. comm., 2016)
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 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 much more sensitive to invasion by flammable grasses than wet forest types (Vuln. Assessment Workshop, pers. comm., 2016) • *Pattern of exposure:* Localized based on forest type; will likely spread across the landscape under changing climate conditions (Vuln. Assessment Workshop, pers. comm., 2016)

Adaptive Capacity

Mesic and wet forest types are found on Maui and Lānaʻi, and East Maui supports the largest intact area of cloud forest within the Hawaiian Islands (Table 3). Lowland forest areas in particular are threatened by development pressure and land-use conversion (e.g., agriculture or pasture), and fragmentation impacts seed dispersal and animal movement. In general, mesic and wet forest resistance to climate and non-climate stressors is not high, but they are able to recover relatively well, especially in wetter areas. Species diversity and endemism is very high, and mesic and wet forests are home to many rare and endangered species. Management actions, such as habitat protection and restoration, are likely to alleviate at least some impacts of climate change, although public value and societal support for these habitat types are low.

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	**East Maui:** Moderate adaptive capacity (high confidence) **West Maui:** Moderate adaptive capacity (high confidence) **Lānaʻi:** Low-moderate adaptive capacity (high confidence)
Extent, integrity, & continuity **East Maui:** Moderate-high (high confidence) **West Maui:** Low-moderate (high confidence) **Lānaʻi:** Low (high confidence)	**+** The windward slopes of Haleakalā in East Maui contain one of the largest areas of intact tropical cloud forest on the Hawaiian Islands (150 km^2), covering portions of Haleakala National Park, the Hanawi Natural Area Reserve, and Waikamoi Preserve (Loope & Giambelluca 1998) **+/-** In general, wetter areas are less degraded than more mesic areas (Vuln. Assessment Workshop, pers. comm., 2016) **-** 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)
Habitat isolation **East Maui:** Moderate (high confidence) **West Maui:** Low-moderate (high confidence) **Lānaʻi:** Low (high confidence)	**-** Agriculture and invasive vegetation have contributed to habitat loss and fragmentation, and can negatively impact seed dispersal and wildlife movement between isolated forest areas (Vuln. Assessment Workshop, pers. comm., 2016) **-** Roads and residential and commercial development are additional barriers to migration and dispersal, although they are relatively localized to areas with high levels of human activity (Vuln. Assessment Workshop, pers. comm., 2016)

Resistance & recovery **East Maui:** Low-moderate (moderate confidence) **West Maui:** Low-moderate (moderate confidence) **Lānaʻi:** Low (moderate 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, and modeling results suggest that rodent control at middle elevations may support this evolution (Kilpatrick 2006) +/- Although wet forest has low resistance to stressors and disturbances, it is able to recover relatively well (Vuln. Assessment Workshop, pers. comm., 2016) - Bogs and mesic forests on the drier end of the continuum are much more sensitive to climate change, and may be unable to recover if disturbed or degraded (Vuln. Assessment Workshop, pers. comm., 2016)
Habitat diversity **All regions:** Moderate (moderate confidence)	+ Mesic and wet forests are still dominated by native species in most areas (Vuln. Assessment Workshop, pers. comm., 2016), and harbor very high species richness, diversity, and endemism (Loope & Giambelluca 1998) + Endangered wildlife species found in Maui mesic and wet forests include the endemic ʻōpeʻapeʻa (Hawaiian hoary bat; *Lasiurus cinereus semotus*), ʻio (Hawaiian hawk; *Buteo solitarius*), and at least nine endemic Hawaiian honeycreepers (family Fringillidae, subfamily Drepanidinae) including the Maui parrotbill (Loope & Giambelluca 1998; Hawaiʻi Department of Land and Natural Resources 2015) +/- Cloud forests typically have higher species diversity than their mesic counterparts (Hawaiʻi Department of Land and Natural Resources 2015) +/- Epiphytes (ferns) and bryophytes (mosses, hornworts) are more common in wetter forest areas, while tree ferns and sedges are more commonly found in mesic areas (Crausbay et al. 2014) - Hawaiian ecosystems have a high proportion of specialist and endemic species and are often unable to compete with generalist invaders (Harter et al. 2015) - A modeling study found that single-island endemics we were one of the most vulnerable plant species groups to changing climate conditions and increasingly frequent disturbances; these changes may cause extirpation or extinction where species are unable to persist in remaining suitable areas or shift upslope (Fortini et al. 2013) - In general, forest bird distributions are expected to shift upslope and survive in only the highest-elevation areas near the tree line, and species richness is expected to decline by 2100; the Maui Parrotbill is projected to lose 90% of its range (Fortini et al. 2015)
Management potential **All regions:** Low-moderate (moderate confidence)	+ Moderate-high likelihood of alleviating climate impacts: Despite setbacks, management actions have produced generally positive outcomes (Vuln. Assessment Workshop, pers. comm., 2016); possible actions 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., removing ungulates and mammalian predators, controlling invasive plants, and preventing further habitat fragmentation; Hawaiʻi Department of Land and Natural Resources 2015)

	+ Constituency groups that influence support for mesic and wet forests include environmentalists, bird-lovers, and cultural groups; these groups have a strong interest in this habitat and can have a large impact (Vuln. Assessment Workshop, pers. comm., 2016) - Extreme events (e.g., hurricanes) would likely have a low impact on societal support for the management and conservation of this habitat (Vuln. Assessment Workshop, pers. comm., 2016) - Low-moderate societal support for conserving habitat: Low funding prevents more extensive habitat protection and restoration efforts; however, Maui County dedicates some money for forest management (Vuln. Assessment Workshop, pers. comm., 2016) - Low public value (Vuln. Assessment Workshop, pers. comm., 2016) - Conflicting/competing interests for this habitat type primarily include land-use conversion for agriculture, ranching, and residential and commercial development, especially in lowland areas (Hawaiʻi Department of Land and Natural Resources 2015)

Recommended Citation

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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[3] (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

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

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

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

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

Habitat & Ecosystem Service Elements

Sensitivity & Exposure (Applies to Habitats and Ecosystem Services)

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

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

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

4. Non-Climate Stressors: e.g., land-use conversion (e.g., residential or commercial development), agriculture and/or aquaculture, transportation corridors (e.g., roads, railroads, trails), water diversions, invasive and other problematic species, pollution and poisons, etc. For non-climate stressors, experts were asked to 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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