Dry 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 dry forest habitat 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

Dry forests and mesic lowland shrublands are typically found in low-elevation areas and on leeward slopes (up to 2,000 m [6,560 ft]). These areas receive the majority of their moisture from cloud/fog drip and intermittent rain from Kona storms and convection weather (Vuln. Assessment Workshop, pers. comm., 2016). These habitat types are often associated with younger, shallow substrates composed of cinder, ash, and lava flows (Hawaiʻi Department of Land and Natural Resources 2015), and plant succession corresponds to substrate age (Stemmermann & Ihsle 1993); dry forests also feature ephemeral streams and wetlands (Vuln. Assessment Workshop, pers. comm., 2016).

Dry forest habitats are dominated by a variety of species, including lama (*Diospyros sandwicensis*), ʻōhiʻa lehua (on young soils; *Metrosideros polymorpha*), koa (often found on more mesic sites; *Acacia koa*), wiliwili (*Erythrina sandwicensis*; major dry forest type found in lowland areas), ʻaʻaliʻi (*Dodonaea viscosa*), olopua (*Nestegis sandwicensis*), ʻālaʻa (*Pouteria sandwicensis*), alaheʻe (*Canthium odoratum*), ʻōlapa (*Cheirodendron trigynum*), lovegrass (*Eragrostis atropioides*), and pili grass (*Panicum tenuifolium*), among others (Cuddihy 1988; Juvik & Juvik 1998; Medeiros et al. 1998; Hawaiʻi Department of Land and Natural Resources 2015; Vuln. Assessment Reviewer, pers. comm., 2017).

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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.

Habitat Vulnerability

Dry Forest Habitats	Rank	Confidence
Sensitivity	Moderate-High	High
Future Exposure	Moderate-High	Low
Adaptive Capacity	Low-Moderate	High
Vulnerability	**Moderate-High**	**High**

Dry forest habitats on Maui Nui were evaluated as having moderate-high vulnerability to climate change due to moderate-high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and low-moderate adaptive capacity.

Because dry forests are already limited by moisture, they are most sensitive to climatic factors that increase water stress, such as increased drought, warmer air and soil temperatures, reduced soil moisture, and changes in the timing of precipitation; these changes are likely to impact species recruitment, community composition, and forest distribution. Disturbance events (e.g., wildfire, floods, wind, insects, disease) may also damage forest areas, reducing forest cover and canopy integrity and increasing vulnerability to invasion, while non-climate stressors, such as residential and commercial development, agriculture, and pollution, further reduce habitat extent, integrity, and continuity, limiting species dispersal and recruitment. Invasive species (e.g., ungulates, mammalian predators, trees/shrubs, flammable grasses, social insects, and pathogens/parasites) also impair dry forest recruitment and recovery by competing with and displacing vegetation, altering ecosystem processes (e.g., water infiltration, pollination), and/or causing direct plant damage or mortality.

Over 90% of historical dry forest area in Hawaiʻi has already been lost, and the remaining area is highly fragmented and vulnerable to conversion to agriculture or other uses. Although dry forests are diverse and have high numbers of endemic species, many native species are endangered. Although intensive restoration efforts have led to the successful reestablishment of native species in some areas, degraded dry forests are largely unable to recover without active management.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Native dry forest species are vulnerable to climate impacts that further reduce available moisture, including changes in precipitation patterns and drought (Table 1). Drier conditions are likely to affect plant photosynthesis, recruitment, and survival, impacting dry forest distribution, composition, and vulnerability to fire. Dry forests are also sensitive to climatic factors that increase vulnerability to erosion and invasion by flammable grasses, including fires, floods, and storm damage. Disease and insects further degrade dry forests by contributing to canopy damage and dieback, and resultant altered light regimes can elevate vulnerability to grass invasion.

Table 1. Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on dry 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. 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 (high 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*** • Across the main Hawaiian Islands, dry forest growth and photosynthesis is closely correlated to precipitation patterns; a study comparing leaf phenology in mesic and dry forests found that a significant browning-down of the forest canopy occurs during the dry season and during severe El Niño-related droughts, suggesting that dry forests are limited by moisture rather than light (Pau et al. 2010) • Increases in drought frequency, duration, or intensity could impact dry forest plant germination and recruit survival to maturity (Rovzar 2016) • Longer or more severe droughts will likely increase the likelihood of wildfires (Loope & Giambelluca 1998; Dolling et al. 2005), affecting overall forest area and promoting a positive feedback cycle of invasive grass establishment and more frequent fires (D'Antonio et al. 2011; Rovzar 2016); invasive grasses also thrive under dry conditions (Ammondt et al. 2013)
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	***Potential impacts on habitat*** • Canopy openings caused by storm damage may increase colonization and growth rates for invasive plants (Loope & Giambelluca 1998), increasing vulnerability to wildfire (D'Antonio et al. 2011) • 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

	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)	even a species (Johnson & Winker 2010)
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*** • Air temperatures are higher on the leeward slopes of Haleakalā compared to windward slopes, primarily due to decreased cloud cover; this further increases evaporative demand, potentially enhancing plant water stress (Longman et al. 2015) • Warming temperatures are allowing the upslope expansion of mosquitos that carry avian malaria (*Plasmodium* spp.), which threatens endemic forest birds (Atkinson & LaPointe 2009); however, lowland dry forests can potentially be utilized as malaria refugia due to low abundance of naturally occurring mosquito breeding habitat (Tucker-Mohl et al. 2010) • Increased temperatures could also allow existing invasive species to expand their range and/or new species to become established (Vorsino et al. 2014) • Increased vegetative cover reduces air and soil temperatures within the forest, reducing water loss and potentially providing refugia for native species (Vuln. Assessment Workshop, pers. comm., 2016) ***Potential refugia*** • North-facing slopes, gulches, and shaded areas (Vuln. Assessment Workshop, pers. comm., 2016)

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 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 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	***Potential impacts on habitat*** • Areas with higher precipitation and soil moisture are correlated with higher growth rates and survival in native species (Rovzar 2016) • A study comparing leaf phenology in mesic and dry forests found that dry forests exhibit an immediate browning-down response to seasonal dry periods, suggesting that they are sensitive to the timing of precipitation (Pau et al. 2010) • Precipitation infiltrates soil faster and more deeply within a restored dry forest compared to adjacent degraded areas invaded by non-native grasses, increasing soil moisture available for native plant growth and reproduction; however, a greater percentage of water was also lost in restored forests, either to rapid movement into the aquifer or through higher levels of plant transpiration (Perkins et al. 2014) • Reduced precipitation could create suitable habitat for dry forest species in previously mesic areas and/or at higher elevations, as the area within the dry zone is projected to increase (Fortini et al. 2017) • Changes in the timing of precipitation could impact seed production and growth rates in native and non-native species (Vuln. Assessment Workshop, pers. comm., 2016)

	dry season precipitation) (Elison Timm et al. 2015) • 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)	
Extreme precipitation events	***Historical and current trends*** • Since 1950, overall trend towards decreased intensity and frequency of extreme precipitation events (Chu et al. 2010) • However, in recent years this trend appears to be reversing direction, with more frequent extreme events occurring except on Lānaʻi, where the frequency of extreme events has continued to decline (Chu et al. 2010) • From 1960–2000, the annual maximum one-day precipitation volume has decreased (Chen & Chu 2014) ***Projected future trends*** Extreme precipitation projections are highly uncertain because of the variability associated with precipitation projections. Possible future scenarios include: • Reduced frequency of extreme precipitation events by 2100, particularly in dry areas (Elison Timm et al. 2011, 2013) • Little to no change in the frequency of extreme precipitation events by 2100 (Takahashi et al. 2011) • Significant increase in extreme precipitation events by 2100 (Zhang et al. 2016)	***Potential impacts on habitat*** • Heavy precipitation may increase cover of fire-adapted invasive grasses, providing more fine fuel for wildfire (Adkins et al. 2011) • Extreme precipitation events help increase soil moisture (Stratton et al. 2000) • Extreme precipitation could have a positive impact on the habitat by increasing water availability and boosting growth rates, seed production, and seedling recruitment; however, flooding and severe erosion may also occur, potentially damaging native vegetation (Vuln. Assessment Workshop, pers. comm., 2016)
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)	***Potential impacts on habitat*** • Native dry forest species are generally not adapted to wildfire, which was historically infrequent (Burney et al. 1995); however, ʻaʻaliʻi can sometimes regenerate

	• The majority of wildfires on Maui occur during summer (June–Aug.), when conditions are warm and dry, accounting for 57% of the annual area burned (Chu et al. 2002) • No wildfire data is available for Lānaʻi and Kahoʻolawe ***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)	after fires through basal sprouting (Ainsworth & Kauffman 2008; D'Antonio et al. 2011) • Wildfires are larger and more severe in areas dominated by non-native grasses, which provide ample fuel, and severe wildfires have the potential to convert forest area to non-native grasslands (Blackmore & Vitousek 2000; D'Antonio et al. 2011; Ellsworth et al. 2014; Trauernicht et al. 2015) ○ More frequent fires may promote the dominance and continued expansion of invasive grasses, which can perpetuate fire regime alterations (D'Antonio et al. 2011) • Burned dry forests are slow to recover from wildfires; on the island of Hawaiʻi, recruitment of native species was low for 20 years post-fire, and forest areas that had been converted to non-native grasslands did not have an increase in native cover even after 37 years (D'Antonio et al. 2011) ***Potential refugia*** • Rocky outcrops and young, sparsely vegetated lava flows (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	***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 native 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 &

	(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)
	  ○ 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)
		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, 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)
	  ○ 61,000 acres across the Hawaiian Islands are at risk due to myoporum thrips (*Klambothrips myopori*); on Maui, the greatest threat is in low-elevation forests on the leeward side (Krist et al. 2014)
	  ○ 12,000 acres across the Hawaiian Islands are at risk due to Erythrina gall wasp (*Quadrastichus erythrinae*); on Maui, the greatest threat is in low-elevation forests on the leeward side (Krist et al. 2014)
		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 dry forest species, including ʻōhiʻa trees and ʻaʻaliʻi shrubs, 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) • The Erythrina gall wasp defoliates native wiliwili trees and can cause extensive tree mortality (Conant et al. 2010; Rubinoff et al. 2010; Krist et al. 2014) • Myoporum thrips were introduced into Hawaiʻi in 2009, and cause naio (*Myoporum sandwicense*) tree mortality where high levels of infestation occur (Krist et al. 2014) • The dark-butt bruchid (*Specularius impressithorax*) destroys seeds of the wiliwili tree, likely affecting recruitment; in the first three years after their 2001 detection on the main Hawaiian Islands, the beetles were responsible for a 77.4% reduction in the seed crop (Medeiros et al. 2008)
Riverine flooding	***Historical and current trends*** • No consistent trends were found in stream peak discharge statewide (Oki et al. 2010) ***Projected future trends*** • No regional stream/river flooding projections are available, but flows may become more variable/flashy if mean annual precipitation declines (Strauch et al. 2015)	***Potential impacts on habitat*** • Flash flooding events caused by heavy rainfall are common in the small, steep watersheds typical of Maui (Richmond et al. 2001) • Flooding events can damage native dry forest vegetation, which is slow to recover from disturbances (Vuln. Assessment Workshop, pers. comm., 2016) • Flood damage is more severe where native forest cover has been lost due to invasive plant establishment, ungulate grazing, and soil disturbances

		(Conry & Cannarella 2010) • Flooding is generally less severe on Lānaʻi (Richmond et al. 2001), reducing the potential for damage to forest areas

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). Non-climate stressors directly and indirectly impact dry forests by reducing species fitness, altering competition dynamics, changing surface hydrology, and causing soil compaction/erosion. Additionally, many human activities destroy dry forest habitat or fragment remaining areas, preventing species recruitment and dispersal that may aid in forest regeneration.

Table 2. Key non-climate stressors that affect the overall sensitivity of dry 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 energy production.

Non-climate stressors High overall impact (high confidence)	
Agriculture	***Potential impacts on habitat*** • Agriculture has contributed to loss, fragmentation, and degradation of the majority of historical dry forest area in the Hawaiian Islands (Pau et al. 2009; Rovzar 2016) • Deforestation for more intensive agriculture in the Kahikinui region of Maui lowered fog-drip capture and aquifer recharge on these arid leeward slopes, resulting in a water table drop of several meters and the loss of perennial seeps and springs (Stock et al. 2003) • Areas cleared for agriculture are also vulnerable to invasion by flammable grasses and other non-native species (Rovzar 2016) ○ However, grazing in non-native grasslands on Hawai‘i Island reduced the biomass of invasive grasses, limiting wildfire intensity and rate of spread (Blackmore & Vitousek 2000); the same may be true on Maui and Lāna‘i • Increased human activity associated with agricultural areas can lead to more wildfire ignitions (Trauernicht et al. 2015) • *Pattern of exposure:* Consistent across habitat, though agriculture is not present on Kaho‘olawe
Residential & commercial development	***Potential impacts on habitat*** • Development and deforestation is a major threat to remaining patches of dry forest, especially within the wildland-urban interface, contributing to habitat loss, fragmentation, and degradation (Rovzar 2016) • Development is also associated with the introduction of invasive plants, wildlife, pests, and disease (Conry & Cannarella 2010) • *Pattern of exposure:* Consistent across habitat in west Maui; localized on the leeward slopes of Haleakalā, Kaho‘olawe, and Lāna‘i
Invasive/ problematic trees & shrubs	***Potential impacts on habitat*** • Invasive trees and shrubs simplify the physical structure of forests, replacing native species within both the canopy and the understory (Asner et al. 2008) • Burned dry forest sites are being invaded by *Morella faya*, a nitrogen-fixing tree species that hosts the two-spotted leafhopper, which can damage many native species including the ‘ōhi‘a tree (Lenz & Taylor 2001) • Studies in other forest types (e.g., mesic and wet forests) have demonstrated

	reductions in cloud water interception (Takahashi et al. 2011b), throughfall (Mair & Fares 2010; Takahashi et al. 2011b), stand transpiration (Kagawa et al. 2009), and streamflow (MacKenzie et al. 2014) in areas dominated by invasive trees • *Pattern of exposure:* Localized
Invasive/ problematic flammable grasses	***Potential impacts on habitat*** • Fountain grass (*Pennisetum setaceum*), guinea grass (*Megathyrsus maximus*), and other invasive grasses have degraded dry forests; they often grow faster, have higher seed counts and recruitment, and outcompete native species for resources (Ammondt et al. 2013; Rovzar 2016), preventing native species recruitment (Cabin et al. 2000) and converting some areas to non-native grasslands (Leopold & Hess 2016) • Flammable invasive grasses increase wildfire severity and area burned (Trauernicht et al. 2015), which in turn promotes additional grass invasion and dominance (D'Antonio et al. 2011) • Fountain grass may alter soil moisture availability for native dry forest vegetation; in dry forest on the island of Hawai'i, lama trees took up less water from shallow soils in areas invaded by fountain grass compared to forest areas without invasive grasses (Cordell & Sandquist 2008) • *Pattern of exposure:* Localized
Invasive/ problematic social insects	• 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; Wilson & Holway 2010) • Introduced ants contribute to the loss of native vegetation by allowing aphids and other piercing/sucking insects to thrive (Conry & Cannarella 2010) • Invasive social insects that affect dry forests include ants, bees, termites, and ants (Vuln. Assessment Workshop, pers. comm., 2016) • *Pattern of exposure:* Variable across habitat (depending on species)
Invasive/ problematic pathogens & parasites	• 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 (Atkinson & LaPointe 2009) • 'Ōhi'a 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 'ōhi'a forest on Hawai'i Island and are a significant threat to trees on Maui and the other Hawaiian Islands (Keith et al. 2015) • *Pattern of exposure:* Variable across habitat (depending on pathogen/parasite)
Invasive/ problematic mammalian predators	• Introduced rodents have contributed to the decline of dry forest species by consuming seeds and stripping bark (Cabin et al. 2000; Becker et al. 2010; Hawai'i Department of Land and Natural Resources 2015) • Introduced rodents prey on bird eggs, nestlings, and incubating adults, preventing successful recruitment (Cabin et al. 2000; Becker et al. 2010; Hawai'i Department of Land and Natural Resources 2015) • Forest restoration efforts may facilitate a shift in the species composition of invasive rodents, with a decline in house mice (*Mus musculus*) and an increase in the abundance of black rats (*Rattus rattus*), which have a greater negative impact on native plants and wildlife (Shier et al. 2012)

	• *Pattern of exposure:* Consistent across habitat
Invasive/ problematic ungulates	• Intensive grazing by non-native ungulates, including goats (*Capra hircus*), sheep (*Ovis* spp.), and pigs (*Sus scrofa*), is a major factor in the decline of dry forest and other terrestrial Hawaiian habitats (Cabin et al. 2000; Hawai'i Department of Land and Natural Resources 2015) • Ungulate grazing can prevent forest regeneration, contribute to soil disturbances and erosion, and create conditions suitable for the establishment of invasive grasses, leading to habitat conversion (Scowcroft & Hobdy 1987; Cabin et al. 2000; Leopold & Hess 2016) • Even after ungulate removal, disturbed areas must be actively managed over long periods of time to control invasive plants and assist native species reestablishment (Scowcroft & Hobdy 1987; Stone et al. 1992) • *Pattern of exposure:* Localized, although there are no ungulates on Kaho'olawe
Pollution & poisons	• Common sources of pollution and/or poisons include fertilizer, pesticides/herbicides, animal waste, oils, and chemicals that may run off from developed areas, agricultural and rangeland areas, and golf courses (Conry & Cannarella 2010; Vuln. Assessment Workshop, pers. comm., 2016) • Elevated CO_2 levels may increase productivity and success of invasive plant species (Smith et al. 2000) • *Pattern of exposure:* Localized (around development)

Adaptive Capacity

Most historical dry forest area has been lost, and the remaining areas are generally fragmented and degraded, especially near populated areas where human disturbance is high (Table 3). Dry forests require active management to become reestablished, and successful restoration efforts have been demonstrated. Dry forests have extremely high species diversity and are home to a large number of endangered and/or endemic species. Despite being valued by the public, dry forests do not receive strong societal support, and further education on the benefits of protecting this habitat type is needed.

Table 3. Adaptive capacity factors that influence the ability of dry 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	Low-moderate adaptive capacity (high confidence)
Extent, integrity, & continuity Low (high confidence)	- Low-moderate habitat extent: 90% of historical dry forest area has been lost across the Hawaiian Islands, and most of the remaining area is dominated by invasive species (Bruegmann 1996; Cabin et al. 2000) ○ On Maui, 12,950 ha of native-dominated dry forest remains (6.5% of the island's total area); 6,280 ha of that forest (48.5%) is protected within reserves (Rovzar 2016) ○ On Lāna'i, 3,840 ha of dry forest remains (10.5% of the island), with 43.5% protected (Rovzar 2016); no information is available for Kaho'olawe

	○ Between 2000 and 2014 an additional 4,650 ha of forest area in the dry region (both native- and non-native-dominated) were lost in Maui while Lānaʻi gained 20 ha (Rovzar 2016) - Low habitat integrity: In general, dry forest habitats are highly disturbed, degraded, and fragmented, especially in lower-elevation areas where human disturbance and development pressure is highest (Rovzar 2016) - Without active management, dry forests are likely to disappear over the next 50-100 years (Medeiros et al. 2014)
Habitat isolation Moderate (high confidence)	- Roads, agriculture, alien vegetation, residential and commercial development, and energy production 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) - Native vegetation in highly fragmented areas is less able to disperse its seeds (Pau et al. 2009; Medeiros et al. 2014)
Resistance & recovery Low-moderate (high confidence)	+ Some dry forest species may exhibit faster recovery than others, with important implications for restoration objectives; for example, ʻaʻaliʻi shrubs have exhibited high survival relative to other native species in restoration studies, and also are more resilient to fire, implying that they could serve as critical pioneer species to compete with invasive grasses and potentially function as nurse trees in dry forest restoration efforts (Ammondt et al. 2013) + Dry forests may offer refugia for endemic forest birds impacted by mosquito-borne disease due to their lack of mosquito breeding sites; a study found that avian malaria infection rates were significantly lower in lowland dry forest habitat compared to lowland wet forests, and that most mosquito breeding sites were anthropogenic (Tucker-Mohl et al. 2010) - The ability of dry forest species to resist the impacts of climate changes is lowered by the degree of fragmentation that has occurred, reducing plant dispersal and seedling recruitment without the aid of restoration efforts (Pau et al. 2009; Medeiros et al. 2014) - Native species in dry forest habitats grow slowly, and disturbances allow invasive plants to become established before the forest is able to recover (Loope & Giambelluca 1998; D'Antonio et al. 2011) - Loss of native seed dispersers has contributed to dispersal and recruitment failure of both common and rare native plants, limiting natural regeneration of dry forests without the aid of restoration efforts (Chimera & Drake 2010)
Habitat diversity Moderate (high confidence)	+ Dry forests on the Hawaiian islands have high species richness (109 tree species in 29 families), endemism (90% of all species), and structural diversity (Pau et al. 2009) ○ Maui dry forests are home to 64 tree species; 54 (84%) of those are endemics (two are single-island endemics), and 25 (39%) are federally endangered and/or threatened (Pau et al. 2009) ○ Lānaʻi dry forests are home to 49 tree species; 41 (84%) of those are endemics (two are single-island endemics), and 18 (37%) are federally endangered and/or threatened (Pau et al. 2009) ○ Kahoʻolawe dry forests are home to nine tree species; seven (78%) of those are endemics (none are single-island endemics), and two (22%) are

	federally endangered and/or threatened (Pau et al. 2009) +/- Endangered wildlife species found in Maui dry forests include the ʻōpeʻapeʻa (Hawaiian hoary bat; *Lasiurus cinereus semotus*) and many forest birds (Hawaiʻi Department of Land and Natural Resources 2015); Blackburn's sphinx moth (*Manduca blackburni*) is a federally listed endangered species endemic to Hawaiʻi whose native host tree is found in dry forests of Maui (Rubinoff et al. 2012) - Species employing autochorous dispersal (i.e. dispersal unaided by external forces) and those with conspicuous flowers are more likely to be endangered (Pau et al. 2009) - Hawaiian ecosystems have a high proportion of specialist and endemic species and are often unable to compete with generalist invaders (Harter et al. 2015) - Because a high proportion of species are rare and/or do not successfully reproduce on their own (i.e. without human intervention), dry forest diversity would decline dramatically without active management due to habitat loss and species extinction; therefore, high species diversity within this habitat type does not significantly enhance the ability of dry forest habitats to adapt to projected future climate changes (Vuln. Assessment Reviewer, pers. comm., 2017) - A modeling study found that dry forest species and single-island endemics were two of the plant species groups most vulnerable 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)
Management potential Moderate (high confidence)	+ Moderate public value: Many species found within dry forests have cultural, ethnobotanical, and aesthetic value, and this habitat type provides multiple ecosystem services including fresh water, biodiversity, and open space (Medeiros et al. 1998; Vuln. Assessment Workshop, pers. comm., 2016) + Moderate likelihood of alleviating climate impacts: Management actions could include seed banking and storage, stabilizing stream banks, restoring riparian areas, protecting potential climate refugia, increasing tree canopy, creating windbreaks and firebreaks, mitigating erosion, and distributing rare species and/or establishing multiple populations; consideration of climate change should be incorporated into land management and development plans (Vuln. Assessment Workshop, pers. comm., 2016) + Restoration efforts in the Auwahi dry forest (e.g., planting native species, excluding ungulates, removing invasive weeds) successfully increased native species cover, stem count, and diversity, reduced non-native cover, and resulted in the natural reproduction of seven rare dry forest tree species (Medeiros et al. 2014) +/- Constituency groups that influence support include the Kahoʻolawe Island Reserve Commission (KIRC) and watershed, cultural, hunting, and ranching interest groups (Vuln. Assessment Workshop, pers. comm., 2016) +/- Extreme events (e.g., fires, floods, droughts, storms, and disease) would likely have a high impact on societal support for the management and conservation of this habitat, especially if they impact infrastructure (Vuln. Assessment

	Workshop, pers. comm., 2016) - Low-moderate societal support for conserving habitat: Political instability, lack of public funding, and conflicting mandates prevent more effective habitat protection and restoration efforts; in order to protect remaining habitat area, legislation and funding are needed (Vuln. Assessment Workshop, pers. comm., 2016) - Management costs for stabilization and restoration of dry forests are relatively high because most dry forests are highly disturbed (Vuln. Assessment Reviewer, pers. comm., 2017) - Many dry forest areas are unlikely to be managed for their native resource values in the foreseeable future, if ever; however, dry forest area within reserve is less likely to be lost (Rovzar 2016), and examining the location of dry forest areas in relation to reserves and managed areas may clarify management needs and gaps (Vuln. Assessment Reviewer, pers. comm., 2017) - There is a general lack of public and decision-maker knowledge of the importance of ecosystems, biosecurity, and economic value, as well as a lack of ecologically responsible development and enforcement (Vuln. Assessment Workshop, pers. comm., 2016) - Conflicting/competing interests for this habitat type include development, real estate, hunting, agriculture, and power generation (Vuln. Assessment Workshop, pers. comm., 2016) - Low water availability or significant variability in water availability across years (e.g., due to drought) could undermine dry forest restoration efforts (Rovzar 2016), although utilizing native species able to compete under low or variable resource conditions may aid restoration efforts in a variable climate future (Cordell et al. 2002) - New invasive species and/or disease may also undermine adaptive capacity (Vuln. Assessment Workshop, pers. comm., 2016)

Recommended Citation

Hilberg LE, Reynier WA, Kershner JM, Gregg RM. 2018. Dry Forest Habitats: A Habitat Climate Change Vulnerability Assessment Synthesis for Maui, Lānaʻi, and Kahoʻolawe. EcoAdapt, Bainbridge Island, WA.

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

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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 evaluated sensitivity, whether the habitat or ecosystem service is currently exposed to that stressor, and whether the pattern of exposure is widespread and/or consistent across the study area or is highly localized (e.g., exposure to aquaculture is highly localized but exposure to invasive grasses was often widespread).

Adaptive Capacity (Habitats)

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

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

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

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

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

Adaptive Capacity (Ecosystem Services)

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

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