Alpine & Subalpine Habitats
Climate Change Vulnerability Assessment Synthesis for Hawai’i

An Important Note About this Document: This document represents an initial evaluation of vulnerability for alpine and subalpine habitats on the island of Hawai’i based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by habitat experts, 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

Alpine and subalpine habitats are found in high-elevation areas on the island of Hawai’i, primarily on Mauna Loa and Mauna Kea. These habitats mostly lie above the mean height of the trade wind inversion (TWI), and therefore are arid with very little precipitation or fog (Longman et al. 2015). Unlike many areas of the world, high-elevation vegetation is most likely limited by moisture rather than by low temperatures (Crausbay & Hotchkiss 2010; Gotsch et al. 2014).

Alpine communities are found above the tree line up to the summits of Mauna Loa, Mauna Kea, and Hualālai over 3,000 m (10,000 ft; Hawai’i Department of Land and Natural Resources 2015). Alpine habitats are dry and semi-barren, with large pu‘u (cinder cones) scattered throughout (Gerrish 2013; Hawai’i Department of Land and Natural Resources 2015). Alpine areas are often composed of shrubland, grassland, and stone desert habitats at increasingly high elevations (Gerrish 2013), with many endemic and highly specialized plant and animal species that are adapted to extreme isolation (Hawai’i Department of Land and Natural Resources 2015). Native plant species include pūkiawe (Leptecophylla tameiameiae), Mauna Kea silversword (Argyroxyphium sandwicense ssp. sandwicense), Mauna Kea dubautia (Dubautia arborea), pili uka grass (Trisetum glomeratum), Hawai’i bentgrass (Agrostis sandwicensis), ‘iwa‘iwa ferns (Asplenium capillus-veneris), Douglas’ bladderfern (Cystopteris douglasii), and invertebrates such as Wēkiu bugs (Nysius wekiuicola) and other native arthropod communities (Gerrish 2013; Hawai’i Department of Land and Natural Resources 2015); alpine areas also provide habitat for seabirds such as the ‘ua‘u (Hawaiian Petrel, Pterodroma sandwicensis; Hawai’i Department of Land and Natural Resources 2015).

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.
Subalpine communities lie between 2,000 and 3,000 m (6,560 to 10,000 ft) in elevation, and may consist of shrublands, grasslands, and forests with sparse, short trees; forests are primarily dry, although a subalpine mesic forest area can be found on Mauna Loa (Hawai‘i Department of Land and Natural Resources 2015). These habitats support abundant arthropod diversity and high species endemism (Vuln. Assessment Workshop, pers. comm., 2017), and much of the Hawai‘i nēnē population breeds in open subalpine shrubland and grassland habitats on the south/southeastern flanks of Mauna Loa (Vuln. Assessment Reviewer, pers. comm., 2017); vegetation includes māmane (Sophora chrysophylla), naio (Myoporum sandwicense), aweoweo (Chenopodium oahuense), a‘ali‘i (Dodonaea viscosa), and ‘ōhi‘a lehua (Metrosideros polymorpha) trees, ‘ōhelo (Vaccinium spp.) and pūkiawe shrubs; ‘āhinahina (Mauna Loa silversword; Argyroxiphium kauense); bracken fern (Pteridium aquilinum); and alpine hairgrass (Deschampsia nubigena; Gerrish 2013; Hawai‘i Department of Land and Natural Resources 2015).

Most of Mauna Loa over 3,000 m (10,000 ft) and the northern slope of Mauna Kea from 3,000–4,000 m (10,000–13,000 ft) are rarely visited; on Mauna Kea, only a handful of visitors venture more than 200 yards past the high-elevation astronomy access roads each year (Vuln. Assessment Reviewer, pers. comm., 2017). Comparatively, Lake Wai‘au receives thousands of visitors yearly (Vuln. Assessment Reviewer, pers. comm., 2017). Additional alpine areas with relatively limited human activity include the Mauna Kea Adze Quarry, Moku‘āweoweo caldera area, and springs (Vuln. Assessment Workshop, pers. comm., 2017).

### Habitat Vulnerability

Alpine and subalpine habitats in Hawai‘i were evaluated as having moderate-high vulnerability to climate change due to high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and low-moderate adaptive capacity.

<table>
<thead>
<tr>
<th>Alpine &amp; Subalpine Habitats</th>
<th>Rank</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Future Exposure</td>
<td>Moderate-High</td>
<td>Low</td>
</tr>
<tr>
<td>Adaptive Capacity</td>
<td>Low-Moderate</td>
<td>High</td>
</tr>
<tr>
<td><strong>Vulnerability</strong></td>
<td>Moderate-High</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

Alpine and subalpine habitats are sensitive to factors that contribute to water and thermal stress and allow upslope expansion by invasive plants and animals, such as changes in the amount and timing of precipitation, altered patterns of wind and circulation, increased air temperature, and increased solar radiation. Disturbance events, such as wildfire, disease, and volcanic activity, may cause native plant injury and/or mortality and allow invasive plants to become established. Non-climate stressors reduce habitat extent and fragment or degrade remaining habitat areas by introducing pollutants, increasing wildfire risk and erosion, and introducing invasive plants. Invasive plants, animals, and pathogens threaten native species by causing damage or mortality, inhibiting recruitment, and increasing competition for resources;
invasive species also alter disturbance regimes, surface hydrology, and other ecosystem processes.

Alpine and subalpine habitats are severely degraded in some areas, particularly in subalpine areas impacted by ungulate grazing. The isolated nature of these habitat types has led to limited native species diversity, but levels of endemism are high and species are typically adapted to harsh conditions. Because there is little to no potential for upslope habitat migration, the loss of high-elevation refugia may make it difficult for many native species to survive. Although societal and public support for these habitat types is high, relatively little can be done to alleviate the impacts of climate change on alpine and subalpine habitats. Management activities focus primarily on minimizing the impacts of invasive species, followed by passive (e.g., allowing natural regeneration) or active (e.g., rare species reintroduction) recovery of native species, and successful habitat restoration efforts are occurring.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Because they typically lie above the height of the TWI, alpine and subalpine habitats are dry and are most sensitive to factors that increase water stress, including changes in the amount and timing of precipitation, and changes in the frequency of the TWI that could contribute to even drier conditions (Table 1). Warmer air temperatures and increased solar radiation may cause additional stress for vegetation, except potentially in the highest elevations where growth is primarily limited by low temperatures; however, reduced soil freezing may also increase invasive plant diversity in alpine areas. Subalpine vegetation is slow to recover following a disturbance, and events such as wildfire may cause plant injury or mortality. Some subalpine birds are also sensitive to mosquito-borne diseases such as avian malaria, with higher-risk transmission zones expanding upslope as temperatures increase.
Table 1. Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on alpine and subalpine 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.

<table>
<thead>
<tr>
<th>Climatic factors and disturbance regimes</th>
<th>Alpine habitats: High impact (high confidence)</th>
<th>Subalpine habitats: High impact (moderate confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Precipitation (amount &amp; timing)</strong></td>
<td><strong>Historical and current trends</strong></td>
<td><strong>Potential impacts on habitat</strong></td>
</tr>
<tr>
<td>• 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 &amp; Giambelluca 2017)</td>
<td>• Rainfall in alpine and subalpine habitats is limited by their position above the TWI, resulting in low relative humidity and arid conditions, especially during the summer months; precipitation often occurs in the form of snow or ice at the highest elevations (de Silva 2012)</td>
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<td>• From 1920 to 2012, dry season (May–Oct.) precipitation on Hawai‘i declined an average of 3.19% per decade across the island; declines were greatest on the leeward side, and declines were at least 6% per decade for most of the Kona region (Frazier &amp; Giambelluca 2017)</td>
<td>• Water stress increases native species mortality, especially where warmer temperatures accelerate evapotranspiration rates, leading to greater water loss (Gotsch et al. 2014; Krushelnicky et al. 2016)</td>
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<tr>
<td>• From 1920–2012, wet season (Nov.–April) precipitation on Hawai‘i 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 &amp; Giambelluca 2017)</td>
<td>o Silversword recruitment and early survival on Mauna Loa is higher in areas and years with more rain, suggesting the species’ recovery may be hampered by reduced precipitation (Robichaux et al. 2017)</td>
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<tr>
<td>• 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 Pu‘u Lā‘au and 71% of months at Halepōhaku (Banko et al. 2013)</td>
<td>o Since 1990, mortality due to water stress has been associated with a 60% decline in a silversword endemic to Maui (Haleakalā silversword; Argyroxiphium sandwicense macrocephalum), with greater losses in the lower-elevation portions of the range (Krushelnicky et al. 2012, 2016); although it is much less well-studied, similar impacts to the Mauna Kea silversword are probably occurring (Vuln. Assessment Reviewer, pers. comm., 2017)</td>
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<tr>
<td>• From 1958–2008, precipitation on the summit of Mauna Loa declined by 34.5 mm (1.36 in) per decade; no significant trends were detected at the summit of Mauna Kea (de Silva 2012)</td>
<td>o High phenotypic plasticity enhances resilience to water stress in some species (e.g., silversword, ‘ōhī’a; Gotsch et al. 2014; Krushelnicky et al. 2016)</td>
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</tbody>
</table>
| • In the 1700s–1800s, snow on Mauna Kea was far more common in both winter and summer than it is today (Schörghofer et al. 2014) | • Māmane trees on Hawai‘i produced up to 76% fewer seed
### Projected future trends

Precipitation projections are highly uncertain because they vary in projected direction and magnitude. At high elevations, precipitation is primarily affected by TWI frequency (occurs when no TWI is in place); across the island, rainfall 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 for Hawai‘i (across all elevations) include:

- Slight increase or no change by 2100 (Keener et al. 2013)
- Decrease in precipitation across all seasons by 2100 (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)
  - At high elevations, increased TWI frequency will correspond to an almost 50% decrease in the fraction of days without a well-defined TWI on which precipitation is more likely to occur (Zhang et al. 2016)
- Ten-fold reduction in mean annual snowfall, resulting in a near-disappearance of snow on the summit of Mauna Kea (Zhang et al. 2017)

### Potential refugia

- Topographic microclimates; however, decreased precipitation could cause a loss of refugia (e.g., seeps, springs, lakes; Vuln. Assessment Workshop, pers. comm., 2017)

### Potential impacts on habitat

- More frequent occurrence of the TWI has likely contributed to trends of decreased rainfall, humidity, and soil moisture,
corresponding with a negative Pacific Decadal Oscillation (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 trade wind inversion (TWI) occurrence increased an average of 16% starting in 1990 (Longman et al. 2015)
- From 1958–2008, wind speed decreased slightly on the summit of Mauna Loa and increased on the summit of Mauna Kea (de Silva 2012)

**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 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 sharply by 2100, with small changes in surface wind speed possible in other seasons (Storlazzi et al. 2015)

and increased solar radiation at high-elevation sites on Maui over the last 25 years (Longman et al. 2015); similar conditions likely apply on Hawai‘i.

- Changes in the height of the TWI would likely impact forest distribution by increasing water stress at high elevations, preventing subalpine forests from moving upslope in response to warming temperatures (Atkinson & LaPointe 2009; Crausbay & Hotchkiss 2015)
- Fog-intercept species would be particularly vulnerable to more frequent occurrence of the TWI (Vuln. Assessment Workshop, pers. comm., 2017)
- Subalpine vegetation could potentially expand into lower-elevation forests if the trade wind inversion level lowers (Vuln. Assessment Workshop, pers. comm., 2017)

**Potential refugia**

- Topographic microclimates (Vuln. Assessment Workshop, pers. comm., 2017)
### Surface winds in the Hawaiian Islands
- May increase modestly, with a very modest increase in frequency of strong wind days (Zhang et al. 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)
- From 1958–2009, the number of freezing days declined from ~4–5 days per year to ~1 day per year at Hilo (3,150 m elevation) (Diaz et al. 2011)
- From 1958–2008, temperatures on the summit of Mauna Loa increased by 1.5°C (2.7°F) per decade; no significant trends were detected at the summit of Mauna Kea (de Silva 2012)

#### Projected future trends
Projections that air temperature will increase are highly certain, although the magnitude of change is less certain. Possible future scenarios include:
- Air temperature increases by 2°C (3.6°F) to 3.5°C (6.3°F) across the Hawaiian Islands by 2100 (Zhang et al. 2016)
  - Increases of 3.0°C (5.4°F) to 3.5°C (6.3°F) at elevations over 3,000 m (10,000 ft; Zhang et al. 2016)
- Increase in the mean freezing level height of 600–700 m (1,969–2,296 ft; Zhang et al. 2017)
- More frequent and more intense extreme heat days (Keener et al. 2012)

### Potential impacts on habitat
- Increased air temperatures would cause the loss of permafrost habitat types on the summits of Mauna Kea and Mauna Loa (Schörghofer et al. 2017)
- Warmer air temperatures were associated with reduced growth and survival in Haleakalā silversword growing at lower elevations on Maui, but had the opposite effect at higher elevations, suggesting that plants near the summit are limited by low temperatures; however, large temperature increases, such as those projected by climate models, may act as a stressor in these high-elevation sites, limiting growth and survival (Krushelnycky et al. 2016); the same is likely true of the Mauna Loa and Mauna Kea silversword.
- Reflective pubescent leaves and rosette geometry in the Haleakalā silversword increases the temperature of the apical bud, enhancing physiological processes in developing leaves; however, this trait may cause lethal tissue temperatures at lower elevations, limiting the species distribution (Melcher et al. 1994); the same is likely true of the Mauna Loa and Mauna Kea silversword.
- Subalpine forests may be unable to shift upslope in response to warming temperatures if conditions become increasingly dry (Atkinson & LaPointe 2009; Crausbay & Hotchkiss 2015)
- Increased temperatures could also allow existing invasive species to expand their range and/or new species to become established (Vorsino et al. 2014), as invasive species are typically limited by harsh conditions at upper elevations rather than lack of dispersal (Daehler 2005)
  - Increased competition and predation by invasive species is likely to be a major impact for extreme high-elevation insects and plants that are adapted to survive freeze
events (likely to become much less frequent; Vuln. Assessment Workshop, pers. comm., 2017)

- Warmer temperatures may decrease generation times in native arthropods and contribute to shifts or declines in alpine arthropod food sources and increased competition with invasive species, resulting in range contraction or extirpation in high alpine environments (Eiben & Rubinoff 2014; Stephenson et al. 2017)

- Temperature increases are likely to increase the range of mosquitoes that carry avian malaria (Plasmodium spp.), accelerating infection rate and intensity of malaria transmission to endemic forest birds and reducing high-elevation refugia (Benning et al. 2002; Atkinson & LaPointe 2009; Fortini et al. 2015; Liao et al. 2015)

- Although warmer temperatures and lack of freezing may benefit a few native insect and plant species in alpine and subalpine habitats (Vuln. Assessment Workshop, pers. comm., 2017), many are limited by moisture rather than temperature (Krushelnycky et al. 2016)

- Subsurface freezing depth currently prevents many invasive plants from encroaching upslope into high alpine areas (~3,200m elevation line for ~8cm+ depth of freezing); however, the potential for reduced soil-freezing depths and lower frequency of deep freezing events under increasingly warm conditions may allow more species of invasive plants to become established (Vuln. Assessment Reviewer, pers. comm., 2017)

**Geographic variation**

- Freezing threshold (0°C [32°F] and cold air ponding (Schörghofer et al. 2017; Vuln. Assessment Workshop, pers. comm., 2017)
<table>
<thead>
<tr>
<th>Solar radiation</th>
<th><strong>Historical and current trends</strong></th>
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<tbody>
<tr>
<td></td>
<td>No trends are available for solar radiation</td>
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<tr>
<td></td>
<td>Solar radiation increases with elevation, but varies depending on factors such as season, time of day, and cloudiness (Juvik &amp; Nullet 1994)</td>
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<tr>
<td></td>
<td>Although solar radiation is important, lots of uncertainty exists on this topic (Vuln. Assessment Workshop, pers. comm., 2017)</td>
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</table>

**Projected future trends**

- A significant decrease in days without a well-defined TWI (almost 50% decrease) by 2100 implies fewer cloudy days will occur (Zhang et al. 2016)

<table>
<thead>
<tr>
<th>Potential refugia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topographic microclimates; subalpine vegetation could move up slope into alpine areas (Vuln. Assessment Workshop, pers. comm., 2017)</td>
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<table>
<thead>
<tr>
<th>Wildfire</th>
<th><strong>Historical and current trends</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>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)</td>
</tr>
</tbody>
</table>

**Potential impacts on habitat**

- Increased solar radiation is associated with more frequent occurrence of the TWI, and changes in the TWI are also likely to increase solar radiation in alpine habitats (Longman et al. 2015) |
- The impacts of solar radiation on subalpine habitats are presumably attenuated by atmospheric moisture (Vuln. Assessment Workshop, pers. comm., 2017) |
- Arthropods need intense solar radiation to heat substrate for exothermic growth, but they also need to hide from direct UV effects; however, this intense heating only matters for insect growth when the air temperatures are below developmental thresholds (Eiben & Rubinoff 2014) |

**Geographic variation**

- Free atmospheric water vapor within 100 m (328 ft) of boundary layer (as opposed to attenuation by TWI frequency; Vuln. Assessment Workshop, pers. comm., 2017) |

<table>
<thead>
<tr>
<th>Potential refugia</th>
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<tbody>
<tr>
<td>Shelter under rocks, northern slope aspects in alpine habitats (Vuln. Assessment Workshop, pers. comm., 2017)</td>
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<thead>
<tr>
<th>Wildfire</th>
<th><strong>Potential impacts on habitat</strong></th>
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<tbody>
<tr>
<td></td>
<td>Invasive flammable grasses, which are increasingly colonizing subalpine habitats, may increase the risk of wildfire ignitions and contribute to more frequent, larger, or more severe fires (Cabin et al. 2000; Banko et al. 2002; Hawai‘i Department of Land and Natural Resources 2015; Trauernicht et al. 2015)</td>
</tr>
<tr>
<td></td>
<td>More frequent fires may promote the dominance and</td>
</tr>
</tbody>
</table>
### 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)
- Continued expansion of invasive grasses, which can perpetuate fire regime alterations (D’Antonio et al. 2011)
- Longer and/or more severe droughts are associated with an increase in the likelihood of wildfires (Loope & Giambelluca 1998; Dolling et al. 2005)
- Wildfire increases erosion by removing vegetation and exposing bare soil (Ice et al. 2004)
- Post-burn native species recruitment in subalpine habitats is slow (Smith & Tunison 1992)
- Alpine habitats have low sensitivity to wildfire, due to their sparse vegetation and resulting low fuel loads (Smith & Tunison 1992)

### 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 mosquitoes, 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 (Benning et al. 2002); the same is likely true on Hawai’i Island.
- 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 ‘ōhi’a rust (*Austro Buccinia psidii*) are the greatest disease threats on Hawai’i, primarily on mid-

### Potential impacts on habitat
- Warming temperatures and changes in precipitation may alter the distribution and severity of fungal diseases and other pathogens that can affect subalpine trees by increasing reproductive potential (Rosenzweig et al. 2001; Conry & Cannarella 2010; Hawai’i Department of Land and Natural Resources 2015)
  - This general trend is occurring worldwide, and is likely to also occur in alpine areas, especially where there are no refugia (Vuln. Assessment Reviewer, pers. comm., 2017)
- Introduced vegetative diseases such as ‘ōhi’a rust have the potential to significantly alter species composition in subalpine forests (Conant et al. 2010; Loope 2010; Krist et al. 2014)
- Many diseases are dispersed by insect vectors, such as rapid ‘ōhi’a death (caused by the fungus *Ceratocystis fimbriata*) which is likely spread by wood-boring beetles (Loope 2016)
- Avian malaria and avian pox (*Avipoxvirus* spp.) are expanding into subalpine forests due to upslope shifts of mosquito vectors; these diseases have drastically reduced native...
<table>
<thead>
<tr>
<th>elevation windward slopes (Krist et al. 2014)</th>
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<tbody>
<tr>
<td>• 53,000 acres across the Hawaiian Islands are at risk due to koa wilt (Krist et al. 2014)</td>
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<tr>
<td>• Little change is expected in the suitable climatic space for ‘ōhi’a rust (Hanna et al. 2012)</td>
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<tr>
<td>honeycreepers and other endemic forest bird populations over the last century (Atkinson &amp; LaPointe 2009)</td>
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</tbody>
</table>
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 (e.g., roads/highways, recreation, development, agriculture, military activity) impact alpine and subalpine habitats by reducing habitat extent and fragmenting or degrading remaining habitat areas by introducing pollutants, increasing erosion, increasing the risk of wildfire, and introducing invasive plants and arthropods. Many invasive species, including trees/shrubs, flammable grasses, ungulates, mammalian predators, parasites/pathogens, and insects, may increasingly shift upslope into alpine and subalpine ecosystems, altering habitat composition and degrading high-elevation areas 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).

Table 2. Key non-climate stressors that affect the overall sensitivity of alpine and subalpine habitats to climate change. All factors were ranked as having a moderate or higher impact on these habitats.

<table>
<thead>
<tr>
<th>Non-climate stressors</th>
<th>Alpine habitats: Moderate overall impact (high confidence)</th>
<th>Subalpine habitats: Moderate-high overall impact (high confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Roads, highways, &amp; trails</strong></td>
<td></td>
<td></td>
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<tr>
<td><strong>Potential impacts on habitat</strong></td>
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<tr>
<td>• Roads contribute to the spread of invasive plants to high-elevation sites, and may allow the spread of temperate weeds into higher elevations where they are less likely to be out-competed by tropical weeds (Daehler 2005)</td>
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<tr>
<td>o A 2008 survey on Mauna Loa found an additional eight invasive species not seen in 1958, most of them represented by just a few plants found near the road (Juvik et al. 2011)</td>
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<tr>
<td>• Roads and highways increase impervious surface, increasing polluted runoff and erosion and reducing water infiltration in forests (Conry &amp; Cannarella 2010)</td>
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<tr>
<td>• Nēnē can be struck by cars, with most or all strikes occurring near water sources such as ranching water ponds (Vuln. Assessment Reviewer, pers. comm., 2017)</td>
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<tr>
<td>• <strong>Pattern of exposure:</strong> Localized</td>
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<td></td>
</tr>
<tr>
<td><strong>Invasive/ problematic social insects</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Potential impacts on habitat</strong></td>
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<tr>
<td>• 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 &amp; Evenhuis 2000; Wilson &amp; Holway 2010; Medeiros et al. 2013)</td>
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<tr>
<td>• Warmer temperatures may promote invasion into subalpine shrublands by Argentine ants (<em>Linepithema humile</em>; Hartley et al. 2010), negatively impacting the abundance and diversity of native arthropods and other invertebrates (Nishida &amp; Evenhuis 2000; Krushelnick &amp; Gillespie 2008)</td>
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<tr>
<td>• Highly invasive western yellowjackets (<em>Vespula pensylvanica</em>) prey on and displace pollinators (both introduced and endemic) and rob nectar (Wilson &amp; Holway 2010; Hanna et al. 2013), significantly decreasing pollination and seed set of ‘ōhi’a (Hanna et al. 2013)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• <strong>Pattern of exposure:</strong> Variable across habitat (species-specific)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Invasive/problematic ungulates

**Potential impacts on habitat**
- Invasive ungulates, including sheep (*Ovis aries, O. gmelini musimon*), pigs (*Sus scrofa*), and goats (*Capra hircus*), are a major cause of degradation in subalpine habitats (Banko et al. 2014)
- Ungulate browsing and bark-stripping can prevent forest regeneration and cause injury or mortality in native trees, especially māmane, which is preferred by sheep (Scowcroft & Conrad 1992; Banko et al. 2014); these impacts can alter species composition, native abundance, and increase the introduction and establishment of invasive plants in disturbed areas (Scowcroft & Conrad 1992; Stone et al. 1992)
- **Pattern of exposure:** Consistent across habitat

### Invasive/problematic mammalian predators

**Potential impacts on habitat**
- Mammalian predators, including rats (*Rattus* spp.), mongooses (*Herpestes* spp.), and feral cats (*Felis catus*) are among the primary predators of forest bird eggs, nestlings, and incubating adults (Banko et al. 2002; Becker et al. 2010; Hawai‘i Department of Land and Natural Resources 2015); they also prey on nesting seabirds (Simons & Hodges 1998; Hawai‘i Department of Land and Natural Resources 2015)
- Rats and mice consume the seeds of native plant species, reducing seedling recruitment (Juvik & Juvik 1998; Banko et al. 2002; Hawai‘i Department of Land and Natural Resources 2015)
- **Pattern of exposure:** Consistent across habitat

### Recreation

**Potential impacts on habitat**
- Game animals were introduced and maintained for the purposes of public hunting; these include sheep and goats that caused severe degradation of subalpine habitats as their numbers multiplied (Banko et al. 2014)
- Recreational visitors traveling on trails and roads increase the likelihood of introducing invasive plant seeds, pathogens, and insects from lower-elevation areas (Daehler 2005); for instance, rapid ‘ōhi‘a death can be spread through the movement of infected soil by human activity, such as on boots and car undercarriages (Loope 2016)
- **Pattern of exposure:** Localized

### Development

**Potential impacts on habitat**
- Localized construction on Mauna Kea and Mauna Loa has disturbed sensitive alpine habitats, reducing available habitat for endemic Wēkiu bugs (Porter & Englund 2006); the presence of hazardous materials and waste and the potential for aquifer contamination are additional concerns (Vuln. Assessment Reviewer, pers. comm., 2017)
- Most alpine and subalpine habitats in Hawai‘i are in the Conservation District with nominal development pressures (Vuln. Assessment Workshop, pers. comm., 2017)
- **Pattern of exposure:** Highly localized – observatories (Mauna Kea, Mauna Loa), Mars habitat (Mauna Loa)
<table>
<thead>
<tr>
<th>Invasive/problematic trees &amp; shrubs</th>
<th><strong>Potential impacts on habitat</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Gorse (<em>Ulex europaeus</em>), apple (<em>Malus domestica</em>), <em>Eucalyptus</em> spp., and broom (<em>Cytisus palmensis</em>) have invaded alpine and subalpine habitats, limiting native plant growth and recruitment (Daehler 2005; Gerrish 2013)</td>
<td></td>
</tr>
<tr>
<td>• Additional non-woody invasive plants, such as fireweed (<em>Senecio madagascariensis</em>) and mullein (<em>Verbascum thapsus</em>), may also negatively impact alpine and subalpine habitat composition and ecosystem functioning (Benitez et al. 2012; Gerrish 2013)</td>
<td></td>
</tr>
<tr>
<td>• <strong>Pattern of exposure:</strong> Localized (Mauna Kea, Mauna Loa, Hualālai)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Agriculture</th>
<th><strong>Potential impacts on habitat</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Sheep and cattle grazing has occurred in subalpine areas around Mauna Kea since the 1820s, and ranching continued in the region until 2002; this resulted in the loss of subalpine tree cover and conversion of forest area to grasslands dominated by non-native species (Ho’okuleana LLC 2009; Banko et al. 2014)</td>
<td></td>
</tr>
<tr>
<td>• 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)</td>
<td></td>
</tr>
<tr>
<td>• Ungulates spread invasive species (e.g., gorse) and inhibit native forest regeneration (Ho’ookuleana LLC 2009; Banko et al. 2014); however, māmane can regenerate following ungulate exclusion (Banko et al. 2013)</td>
<td></td>
</tr>
<tr>
<td>• Pine tree trials on Dept. of Hawaiian Homelands (DHHL) property could increase the establishment of invasive conifers in subalpine habitats (Vuln. Assessment Reviewer, pers. comm., 2017)</td>
<td></td>
</tr>
<tr>
<td>• <strong>Pattern of exposure:</strong> Localized (Mauna Kea, Mauna Loa, Hualālai)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Military activity</th>
<th><strong>Potential impacts on habitat</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Military training activities may increase fire risk in subalpine forest areas within the Pōhakuloa Training Area (Hawai‘i Department of Land and Natural Resources 2015)</td>
<td></td>
</tr>
<tr>
<td>• High-elevation helicopter training, which occurred around 2009, slightly increased the risk of moving invasive plants, seeds, and insects (Portage 2011; Vuln. Assessment Reviewer, pers. comm., 2017)</td>
<td></td>
</tr>
<tr>
<td>• <strong>Pattern of exposure:</strong> Localized</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Invasive/problematic flammable grasses</th>
<th><strong>Potential impacts on habitat</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Non-native flammable grasses such as fountain grass (<em>Pennisetum setaceum</em>), needlegrass (<em>Nassella cernua</em>), <em>Bromus</em> spp., and <em>Rytydosplerma</em> spp. are primarily found in subalpine māmane forest and pūkiawe shrublands, though they also occur at much lower densities in barren alpine areas (Gerrish 2013)</td>
<td></td>
</tr>
<tr>
<td>• Invasive grasses increase wildfire severity and area burned (Traurnicht et al. 2015) and compete with native plant species, preventing successful recruitment (Cabin et al. 2000)</td>
<td></td>
</tr>
<tr>
<td>• <strong>Pattern of exposure:</strong> Localized depending on flow age</td>
<td></td>
</tr>
</tbody>
</table>
**Invasive/ problematic parasites & pathogens**

**Potential impacts on habitat**
- Introduced diseases may alter species composition in subalpine forests by targeting one or two dominant native species (Conant et al. 2010); for instance, rapid ʻōhiʻa death can cause high rates of tree mortality, potentially shifting forest species composition (Mortenson et al. 2016)
- It is unknown whether invasive parasites and pathogens affect alpine communities (Vuln. Assessment Workshop, pers. comm., 2017)
- *Pattern of exposure:* Consistent across habitat

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**Other Sensitivities**

Alpine and subalpine habitats are also sensitive to volcanic activity, which may cause plant injury or mortality (Table 3).

**Table 3.** Other sensitivities that may affect the vulnerability of alpine and subalpine habitats to climate change.

<table>
<thead>
<tr>
<th>Other sensitivities</th>
<th>Alpine and subalpine habitats: High sensitivity (high confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volcanic activity</strong></td>
<td><strong>Potential impacts on habitat</strong></td>
</tr>
<tr>
<td>Lava flows are a natural source of wildfire ignitions in forest areas, resetting plant succession in burned areas (Ainsworth &amp; Kauffman 2008)</td>
<td></td>
</tr>
<tr>
<td>Volcanic emissions (VOG, or volcanic smog) contains high levels of sulfur dioxide (SO₂), a harmful gas that can be absorbed by plants through their stomata, where it is converted to sulfuric acid and burns plant tissue; forest vegetation downwind of active vents is most affected, although some species are SO₂-resistant (e.g., ʻōhiʻa; Nelson &amp; Sewake 2008)</td>
<td></td>
</tr>
<tr>
<td>SO₂ 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 &amp; Sewake 2008)</td>
<td></td>
</tr>
<tr>
<td>Pollutants from volcanic activity can interact with other stressors (e.g., insect outbreaks) to cause greater damage to forest vegetation (Conry &amp; Cannarella 2010)</td>
<td></td>
</tr>
<tr>
<td>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 (Hawai‘i Department of Land and Natural Resources 2015)</td>
<td></td>
</tr>
<tr>
<td>Lava flows can destroy or fragment small populations of native species such as the Mauna Loa silversword (U.S. Fish &amp; Wildlife Service 1995)</td>
<td></td>
</tr>
<tr>
<td><strong>Geographic variation</strong></td>
<td></td>
</tr>
<tr>
<td>Exposure is higher on Mauna Loa (last eruption 1984) than on Mauna Kea (last eruption ~3,500 years ago) or Hualalai (last eruption 1801; Vuln. Assessment Reviewer, pers. comm., 2017)</td>
<td></td>
</tr>
<tr>
<td>Impacts related to air quality are typically limited in alpine and subalpine as the TWI restricts dispersion of pollutants (Vuln. Assessment Workshop, pers. comm., 2017)</td>
<td></td>
</tr>
</tbody>
</table>
Adaptive Capacity

Alpine and subalpine habitats are severely degraded in some areas, primarily due to invasive ungulates in subalpine forests and by human activity associated with mountaintop observatories (Table 4). Their isolated nature has led to high levels of endemism and species adapted to harsh conditions, but this also limits native species dispersal and the potential for upslope habitat migration. Warmer and drier conditions, the loss of high-elevation microclimates, and further alpine development may threaten species such as the endemic Wēkiu bug and palila. Although societal and public support for these habitat types is high, relatively little can be done to alleviate the impacts of climate change. Management of these protected areas focuses primarily on minimizing the impacts of invasive species, followed by passive (e.g., allowing natural regeneration) or active (e.g., rare species reintroduction) recovery of native species, and successful habitat restoration efforts are occurring.

Table 4. Adaptive capacity factors that influence the ability of alpine and subalpine 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 (-).

<table>
<thead>
<tr>
<th>Adaptive capacity factors</th>
<th>Moderate-high adaptive capacity (high confidence)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Extent &amp; integrity</strong></td>
<td></td>
</tr>
<tr>
<td>Alpine &amp; subalpine habitats:</td>
<td>Subalpine forests on Hawai’i have been severely degraded by invasive plants, ungulates, insects, and conversion to agricultural pastures (Krushelnicky &amp; Gillespie 2008; Banko et al. 2014)</td>
</tr>
<tr>
<td>Low-moderate (high confidence)</td>
<td></td>
</tr>
<tr>
<td>Alpine habitats:</td>
<td>Alpine habitats are impacted directly by development of roads, scientific infrastructure (e.g., observatories), and visitor support facilities (e.g., visitor centers, trails, etc.; Gerrish 2013; Vuln. Assessment Reviewer, pers. comm., 2017); less direct impacts from invasive species and recreational uses (e.g., informal trails, species introductions, nutrient additions) are more pervasive but less well understood (Vuln. Assessment Reviewer, pers. comm., 2017)</td>
</tr>
<tr>
<td>High (moderate confidence)</td>
<td></td>
</tr>
<tr>
<td>Subalpine habitats:</td>
<td>The isolated nature of alpine and subalpine habitats has led to very high levels of endemic species (Vuln. Assessment Workshop, pers. comm., 2017)</td>
</tr>
<tr>
<td>Moderate-high (moderate confidence)</td>
<td>Alpine and subalpine vegetation and insects generally have high dispersal capacity (Gerrish 2013; Vuln. Assessment Reviewer, pers. comm., 2017); however, insects often have a specialized habitat or host plant that may limit suitable areas for dispersal (Vuln. Assessment Reviewer, pers. comm., 2017)</td>
</tr>
<tr>
<td><strong>Habitat isolation</strong></td>
<td></td>
</tr>
<tr>
<td>Alpine habitats:</td>
<td>Barriers to alpine and subalpine vegetation dispersal include invasive vegetation and, to a lesser extent, agriculture (Vuln. Assessment Workshop, pers. comm., 2017); extirpated and/or rare dispersal agents (e.g., native insect and bird species) may also limit seed dispersal (Vuln. Assessment Reviewer, pers. comm., 2017)</td>
</tr>
<tr>
<td>High (moderate confidence)</td>
<td>Roads could act as a barrier to dispersal for some animals (Vuln. Assessment Workshop, pers. comm., 2017)</td>
</tr>
<tr>
<td>Subalpine habitats:</td>
<td>Alpine habitats are unable to expand upslope, preventing range shifts in response to changing climate conditions (Vuln. Assessment Workshop, pers. comm., 2017)</td>
</tr>
<tr>
<td>Moderate-high (moderate confidence)</td>
<td></td>
</tr>
</tbody>
</table>
### Resistance & recovery

**Alpine & subalpine habitats:**

- Low-moderate (high confidence)

| + | Some endemic forest bird species may be able to develop resistance to avian malaria (Kilpatrick 2006; Liao et al. 2017) |
| + | High phenotypic plasticity and evidence of rapid microevolution in some plant alliances (e.g., silversword, lobelid) increases their capacity to tolerate and/or adapt to changing climate conditions (Robichaux et al. 2017) |
| +/- | Vegetation resistance to the impacts of stressors is largely dependent on ongoing habitat protection and management; most plant species are vulnerable to reduced suitable habitat area as moisture and temperature stress increase, and high-elevation refugia are likely to disappear over time (Crausby & Hotchkiss 2015; Krushelnycky et al. 2016) |
| - | Reduction and loss of pollinator and dispersal species may impede the ability of native species to reproduce and colonize disturbed areas, potentially elevating their risk of extirpation (Sakai et al. 2002; Krushelnycky 2014) |

### Habitat diversity

**Alpine & subalpine habitats:**

- Low-moderate (high confidence)

| + | Although species diversity in alpine and subalpine habitats is relatively low, many species within these habitats are endemic, and include many site-specific species and adaptively radiated groups (e.g., silversword alliance) (Medeiros et al. 2013; Robichaux et al. 2017) |
| +/- | Alpine and subalpine habitats are characterized by specialized native species, endemism, and harsh environmental conditions (Vuln. Assessment Workshop, pers. comm., 2017) |
| +/- | Keystone or foundational species within alpine and subalpine habitats vary, with localized dominant species in different areas (e.g., pūkiawe or māmānane and naio; Vuln. Assessment Workshop, pers. comm., 2017) |
| +/- | Other factors that may affect habitat diversity include substrate age/type (e.g., cinder, a’a, pahoehe) and maintaining genetic integrity/avoiding crossbreeding (Eiben & Rubinoff 2014; Stephenson et al. 2017; Vuln. Assessment Workshop, pers. comm., 2017) |
| - | Component species and/or functional groups that are particularly sensitive to climate change include silverswords (alpine/subalpine habitats), Wēkiu bugs (alpine habitats), and palila (subalpine habitats; Vuln. Assessment Workshop, pers. comm., 2017) |
| - | Many species of Hawaiian honeycreepers that utilize subalpine forests are in decline (Banko et al. 2013; Hawai‘i Department of Land and Natural Resources 2015), and additional species extinctions are likely to occur due to increasing avian malaria transmission and range contractions under future climate conditions (Benning et al. 2002; Atkinson & LaPointe 2009; Fortini et al. 2015) |

### Management potential

**Alpine & subalpine habitats:**

- Moderate-high (moderate confidence)

| + | High societal support for managing and conserving alpine and subalpine habitats: Mostly undeveloped land under the influence of a limited number of constituencies; alpine/subalpine habitats are largely managed as public land with a public purpose (Vuln. Assessment Workshop, pers. comm., 2017) |
| + | Moderate-high public value: Alpine and subalpine habitats are considered iconic and/or unique, and are valued for their undeveloped/rural status, endemic species, opportunities for recreation, and as sacred sites (Vuln. Assessment Workshop, pers. comm., 2017) |
| + | Moderate-high manager capacity and ability to cope with habitat impacts: Management activities focus primarily on minimizing the impacts of invasive activities |

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species, followed by passive (e.g., allowing natural regeneration) or, where necessary and resources permit, active recovery (e.g., rare species augmentation or reintroduction; Belfield & Pratt 2002; Robichaux et al. 2017; Vuln. Assessment Reviewer, pers. comm., 2017)

* Mitigation strategies to reduce avian malaria (e.g., mosquito reduction, malaria transmission control by refractory mosquitoes) in high-elevation forests may support endemic forest bird populations (Liao et al. 2017)

* +/- Improving coordination, ensuring a clear understanding of responsibility and jurisdiction, and increasing stakeholder responsiveness would likely allow more effective implementation of multi-jurisdictional management actions (Vuln. Assessment Reviewer, pers. comm., 2017)

* +/- Constituency groups that influence support for alpine habitats include cultural, scientific, and recreational groups; hunting and bird-watching groups influence support for subalpine habitats (Vuln. Assessment Workshop, pers. comm., 2017)

* +/- Extreme events (e.g., volcanic eruption) would likely have a low-moderate impact on societal support for the management and conservation of this habitat. Severe drought could influence societal support by drying Lake Wai‘au and killing vegetation (Vuln. Assessment Workshop, pers. comm., 2017)

- Low-moderate likelihood of managing or alleviating climate change impacts on alpine and subalpine habitats. Management efforts should likely focus on removing invasive species; little can be done for hydrology (Vuln. Assessment Workshop, pers. comm., 2017)

- User conflicts/competing interests for alpine habitat are variable (i.e. dependent on the specific location); ranching is the primary competing interest for subalpine habitats (Vuln. Assessment Workshop, pers. comm., 2017)

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**Recommended Citation**

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

**Literature Cited**


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 EcoAdapt² (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:

\[
\text{Vulnerability} = \left(\text{Climate Exposure} \times 0.5\right) \times \text{Sensitivity} - \text{Adaptive Capacity}
\]

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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**Literature Cited**

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


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

