Upland Wetland Habitats

Climate Change Vulnerability Assessment Synthesis for O‘ahu

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

Habitat Description

On O‘ahu, upland wetland habitats include bogs, swamps, and marshes that occur above 100 m (328 ft; Vuln. Assessment Workshop, pers. comm., 2016). O‘ahu's upland wetlands receive significant moisture via rainfall, fog, and groundwater (Miller et al. 1989; Schubert 2012), and moisture is trapped by impermeable substrate, promoting highly saturated soils (Cuddihy 1988; Pacific Coast Joint Venture Hawai‘i 2006). Upland wetlands typically occur in openings of the surrounding rainforest, are small in size, and feature a mixture of mud, standing water pockets, and highly endemic and specialized species, including mosses, hummock-forming endemic sedges and grasses, and some dwarf woody plants (Cuddihy 1988; Medeiros et al. 1991; Pacific Coast Joint Venture Hawai‘i 2006).

O‘ahu has two significant natural upland wetland habitats: the Mount Ka‘ala summit plateau and Ka‘au Crater (Vuln. Assessment Workshop, pers. comm., 2016). The summit plateau of O‘ahu's higest mountain, Mount Ka‘ala (1227 m, 4025 ft; Hawai‘i Department of Land and Natural Resources 1990; Hawai‘i Department of Land and Natural Resources 2015), hosts an upland swamp community (Polhemus 2015) consisting of relatively undisturbed ‘ōhi‘a lehua (*Metrosideros polymorpha*; Hawai‘i Department of Land and Natural Resources 1990), as well as uluhe (*Dicranopteris linearis*) and ‘ama‘u ferns (*Sadleria cyatheoides*; Schubert 2012). Ka‘au Crater is found in the windward, southern Ko‘olau Mountains at roughly 460 m (1,509 ft), and features an extensive upland marsh area (Polhemus 2015) harboring ‘ōhi‘a lehua, ‘uki‘uki (*Dianella sandwicensis*), and ‘uki (*Cladium jamaicense*), among other species (Schubert 2012).

---

[1] This information was gathered during a vulnerability assessment and scenario-planning workshop in December 2016 (http://ecoadapt.org/workshops/oahuvulnerabilityworkshop). 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

Upland wetland habitats on Oʻahu were evaluated as having moderate vulnerability to climate change due to moderate-high sensitivity to climate and non-climate stressors, moderate-high exposure to projected future climate changes, and moderate adaptive capacity.

Upland Wetland Habitats	Rank	Confidence
Sensitivity	Moderate-High	Moderate
Future Exposure	Moderate-High	Low
Adaptive Capacity	Moderate	Moderate
Vulnerability	**Moderate**	**Moderate**

Climatic factors including precipitation, soil moisture, height of the lifting condensation level, and drought affect water availability in upland wetlands, which along with air temperature, affects vegetation survival, composition, and peat formation. Wildfire and tropical storms affect wetland sediment input via erosion. Disease increases mortality of upland birds. Non-climate stressors such as invasive species (e.g., ungulates, flammable grasses, trees, and shrubs) can further alter upland wetland vegetative composition by displacing native species. Invasive vegetation also alters ecological processes, such as fire.

Upland wetlands occupy only a small area on Oʻahu and are structurally degraded by invasive species. Upland wetlands have essentially no room to migrate in response to climate change due to their dependence on topographic location and geology. Additionally, the restricted range of component specialist and endemic species undermines overall habitat adaptive capacity. Vegetation appears to be somewhat resistant to invasives in the absence of disturbance, and able to recover from prior disturbance once disturbances (e.g., pigs) are removed. Additionally, vegetation seems somewhat adapted to seasonal variations in water availability, although large shifts in precipitation would likely lead to community composition changes. Management potential in the face of climate change is bolstered by high societal value, regulatory protection, and location of one wetland area within Natural Area Reserve boundaries.

Sensitivity and Exposure

Climatic Factors and Disturbance Regimes

Upland wetland vegetation is adapted to highly saturated soils, and thus is sensitive to climatic changes that affect water availability, including precipitation amount and timing, soil moisture, the height of the lifting condensation level, and drought (Table 1). Increased moisture availability may increase vegetation productivity, while decreased moisture availability could shift vegetative composition, decrease plant survival, and affect peat formation. Upland wetland vegetation and peat formation may additionally be influenced by warmer air temperatures. Upland wetlands are also sensitive to wildfire and tropical storms, which affect overall sediment delivery. Upland wetland birds are vulnerable to mortality from avian malaria.

Table 1. Current and projected future trends in climatic factors and disturbance regimes, as well as their potential impacts on upland wetland 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 this habitat.

Climatic factors and disturbance regimes	Moderate-high impact (moderate confidence)	
Precipitation (amount & timing) & soil moisture	***Historical and current trends*** • Since 1920, precipitation has decreased across the Hawaiian Islands, with the strongest drying trends occurring over the last 30 years (Frazier et al. 2016; Frazier & Giambelluca 2017) • From 1920 to 2012, dry-season (May–Oct.) precipitation on Oʻahu declined an average of 0.8% per decade across the island. Declines were greatest at high elevations (up to 4%); some areas on the leeward coast had very slight increases (up to 1%; Frazier & Giambelluca 2017) • From 1920–2012, wet-season (Nov.–April) precipitation on Oʻahu declined an average of 1.68% per decade across the island, with the largest declines at moderate and high elevations, especially on the leeward side (Frazier & Giambelluca 2017) • No information is available about soil moisture trends over time ***Projected future trends*** Precipitation projections are highly uncertain because they vary in projected direction and magnitude, and will be affected by shifts in the El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO), as well as the amount of future greenhouse gas emissions. Possible future scenarios include: • Slight decrease or no change by 2100 (Keener et al. 2013) • Moderate decrease in precipitation across all seasons by 2100 (16% to 22% decrease in wet-season precipitation; 16% to 28% decrease in dry-season precipitation; Elison	***Potential impacts on habitat*** • Rainfall delivers water and sediment to upland wetlands and helps maintain high water table levels (Schubert 2012) • Increased precipitation would benefit upland wetlands (Vuln. Assessment Workshop, pers. comm., 2016): ○ Higher rainfall increases vegetative productivity (Schubert 2012) ○ High soil moisture and nutrient-poor soils likely help prevent forest encroachment (Loope et al. 1991) • Decreased precipitation and drier conditions cause upland wetland desiccation, affecting wetland persistence (Polhemus 2015) ○ Both the Mt. Kaʻala summit swamp and Kaʻau Crater upland marsh are at risk of losing all wetland area by 2100 due to drying conditions (Polhemus 2015) • Significant shifts in precipitation and moisture availability will alter vegetative composition (Hotchkiss & Juvik 1999; Schubert 2012) • Generally, precipitation timing has less impact than precipitation amount, as upland wetlands receive enough precipitation to remain wet year-round (Medeiros et al. 1991; Schubert 2012); however, more prevalent seasonal precipitation changes could cause significant wetland change (Vuln. Assessment Workshop, pers. comm., 2016)

	Timm et al. 2015) • By 2100, slightly increased windward precipitation in the dry season (up to 20%) and slight to moderate decreases in wet-season windward precipitation and leeward precipitation 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)	
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: • Drought risk is likely to increase by 2100 for low-elevation leeward areas, decrease at high elevations, and remain static elsewhere (Keener et al. 2012)	***Potential impacts on habitat*** • Drought can cause foliage dieback or mortality of upland wetland vegetation (Loope et al. 1991; Schubert 2012), particularly if paired with high temperatures (Loope et al. 1991) • Lower water tables may accelerate decomposition rates, affecting peat accumulation (Loope et al. 1991) • Drought may eliminate rainfall-dependent upland wetlands or reduce their size (Vuln. Assessment Workshop, pers. comm., 2016) ○ This could reduce breeding habitat for mosquitoes, with potential benefits to upland birds (Vuln. Assessment Reviewers, pers. comm., 2017) • Drought increases fire risk (Conry & Cannarella 2010)
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)	***Potential impacts on habitat*** • Storms may cause significant sediment input via erosion to upland wetlands, affecting vegetative composition (Schubert 2012) • Upland wetlands may be lost if storm events change the structure of areas responsible for water retention (Vuln. Assessment Workshop, pers. comm., 2016) • Storms (e.g., hurricanes) can reduce canopy cover in

	Projected future trends Tropical storm projections are highly uncertain because they are influenced by large-scale patterns within the ocean and atmosphere (Murakami et al. 2013). Possible future scenarios include: • Increased frequency and strength of tropical storm activity around the Hawaiian Islands due to a northwest shift in storm track and increased strength because of large-scale changes in environmental conditions (Murakami et al. 2013)	upland swamps, potentially contributing to drier conditions (Polhemus 2015)
Changes in lifting condensation level	***Historical and current trends*** • No information is available on elevation changes of the lifting condensation level (i.e. cloud base height) ***Projected future trends*** • No projections are available for the lifting condensation level	***Potential impacts on habitat*** • Trade winds and orographic uplift affect the amount of precipitation upland wetlands receive, thereby affecting water levels and vegetative composition (Schubert 2012) • Upland wetlands may be lost if the lifting condensation level elevation changes (Vuln. Assessment Workshop, pers. comm., 2016)
Air temperature	***Historical and current trends*** • From 1975–2006, the rate of air temperature increases has accelerated to 0.2°C (0.36°F) per decade, compared to overall increases of 0.04°C (0.07°F) per decade for all records from 1919–1975; the strongest warming is found at high elevations and in winter minimum temperatures (Giambelluca et al. 2008) ***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)	***Potential impacts on habitat*** • Warmer air temperature may contribute to altered vegetation composition (Schubert 2012) • Warmer air temperatures may increase decomposition rates, affecting peat accumulation (Loope et al. 1991)

	• More frequent and more intense extreme heat days (Keener et al. 2012)	
Wildfire	***Historical and current trends*** • From 1904–2011, the overall trend has been towards increases in area burned across all of the Hawaiian Islands, but with high interannual variability (Trauernicht et al. 2015) ***Projected future trends*** • No regional wildfire projections are available, but increased wildfire is likely if drier conditions and more drought occur (Trauernicht et al. 2015)	***Potential impacts on habitat*** • Wildfire is uncommon in upland wetlands, but can decrease native biomass (Vuln. Assessment Workshop, pers. comm., 2016) • Wildfires may indirectly influence the Kaʻau Crater by altering the broader water catchment; for example, wildfires may reduce water capture and infiltration by native forests and/or increase erosion and sedimentation (Conry & Cannarella 2010)
Disease	***Historical and current trends*** • No information is available for plant disease ***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) ○ Although it is not yet present on Oʻahu, if ʻōhiʻa rust (*Austropuccinia psidii*) spreads to the island, its greatest threat will be to 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*; Krist et al. 2014) • Little change is expected in the suitable climatic space for ʻōhiʻa rust (Hanna et al. 2012)	***Potential impacts on habitat*** • There are several diseases not yet present on Oʻahu (e.g., ʻōhiʻa rust) that could significantly change forest structure and species composition, affecting the broader water catchment (Vuln. Assessment Workshop, pers. comm., 2016) • Upland birds are vulnerable to avian malaria spread by mosquitos (Benning et al. 2002; Atkinson et al. 2014), and mosquitos already occur at all elevations on Oʻahu (Vuln. Assessment Reviewers, pers. comm., 2017)

Non-Climate Stressors

Sensitivity of the habitat to climate change impacts may be highly influenced by the existence and extent of, and current exposure to, non-climate stressors (Table 2). Invasive ungulates can destroy native vegetation and promote the spread of invasive grasses, trees, and shrubs. Invasive vegetation can outcompete and displace native vegetation and alter ecological processes (e.g., fire).

Table 2. Key non-climate stressors that affect the overall sensitivity of upland wetland habitats to climate change. All factors were ranked as having a moderate or higher impact on this habitat.

Non-climate stressors	Moderate impact (high confidence)
Invasive/ problematic ungulates	***Potential impacts on habitat*** • Invasive pigs (*Sus scrofa*) can disturb and destroy upland wetland vegetation — particularly understory vegetation — by rooting and trampling (Cuddihy 1988; Hawaiʻi Department of Land and Natural Resources 1990; Medeiros et al. 1991; Hawaiʻi Department of Land and Natural Resources 2015) • Pig activity may eliminate some vegetation species from the ground, only allowing survival of epiphytic individuals (Hawaiʻi Department of Land and Natural Resources 1990) • Pig activity also promotes the spread of invasive vegetation (Hawaiʻi Department of Land and Natural Resources 1990; Medeiros et al. 1991) • *Pattern of exposure:* Consistent across habitat
Invasive/ problematic flammable grasses	***Potential impacts on habitat*** • Invasive grasses (e.g., *Holcus lanatus*) and sedges (e.g., *Kyllinga brevifolia*) can become locally dominant in upland wetlands (Daehler 2005), particularly following repeated disturbance (e.g., pig rooting; Medeiros et al. 1991) • Invasive grasses can alter fire frequency and intensity, affecting nutrient cycling and persistence of native vegetation (Daehler 2005) • *Pattern of exposure:* Localized – Kaʻau
Invasive/ problematic trees & shrubs	***Potential impacts on habitat*** • Upland wetlands are vulnerable to invasion by blackberry (*Rubus argutus*), strawberry guava (*Psidium cattleianum*) and soapbush (*Clidemia hirta*), which can displace native species (Hawaiʻi Department of Land and Natural Resources 1990) • *Pattern of exposure:* Consistent across habitat

Adaptive Capacity

The adaptive capacity of upland wetlands on Oʻahu is undermined by their small geographic extent, limited migration potential, and structural degradation by invasive species (Table 3). However, upland wetland vegetation is able to recover from low disturbance conditions and is resilient to variable water levels, although large changes in water availability will likely shift community composition. High societal support for management and location of one wetland within Natural Area Reserve boundaries may enhance management opportunities in the face of climate change.

Table 3. Adaptive capacity factors that influence the ability of upland wetland 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	Moderate adaptive capacity (moderate confidence)
Extent & integrity Low-moderate (high confidence)	+ Kaʻala Bog is structurally and functionally intact (Vuln. Assessment Workshop, pers. comm., 2016) +/- Kaʻau Crater maintains functionality, but is structurally degraded (Vuln. Assessment Workshop, pers. comm., 2016) - Oʻahu has only two upland wetlands and these wetlands cover only a small area (5.58 km^2, 1,378 acres; Van Rees & Reed 2014) - Oʻahu has lost roughly 9% (0.55 km^2, 135 acres) of mid- to upper-elevation wetland area since human settlement (Van Rees & Reed 2014)
Habitat isolation Moderate-high (high confidence)	- Upland wetlands exist in forest openings and typically are not connected to other similar habitat types (Medeiros et al. 1991) - Geologic/water/atmospheric features serve as the primary barriers to habitat dispersal; upland wetlands have nowhere to shift to because they already exist at high elevations (Vuln. Assessment Workshop, pers. comm., 2016) and because their location is dependent on topography and geology (Vuln. Assessment Reviewers, pers. comm., 2017)
Resistance & recovery Moderate (low confidence)	+ Native bog vegetation appears resilient to invasion in the absence of disturbance (Loope et al. 1991) + Vegetation has been shown to recover when ungulate disturbance is removed (Hawaiʻi Department of Land and Natural Resources 1990; Medeiros et al. 1991) +/- Vegetation is likely adapted to seasonal fluctuations in water availability, but significant community shifts are likely if Oʻahu changes to a much wetter or much drier climate (Schubert 2012) - Native vegetation is not resilient to repeated disturbance (Medeiros et al. 1991)
Habitat diversity Moderate (moderate confidence)	+/- Upland wetlands host a variety of specialized and endemic species (Cuddihy 1988; Hawaiʻi Department of Land and Natural Resources 2015); restricted distributions may enhance the vulnerability of these unique species to climate and non-climate impacts (Sakai et al. 2002) +/- Kaʻala Bog maintains many native species and is more diverse, although native species may not be well-adapted to drier conditions (Vuln. Assessment Workshop, pers. comm., 2016) - Kaʻau Crater features mostly invasive species (Vuln. Assessment Workshop, pers. comm., 2016)
Management potential Moderate (moderate confidence)	+ Kaʻala Bog is protected within the Mount Kaʻala Natural Area Reserve, which may help buffer some climate and non-climate impacts (Hawaiʻi Department of Land and Natural Resources 1990) + High societal support for conserving habitat: There is support from the

	conservation district and there is regulatory oversight (Vuln. Assessment Workshop, pers. comm., 2016) + Extreme events would have a moderate-high influence on societal support for managing and conserving habitat (Vuln. Assessment Workshop, pers. comm., 2016) +/- Low-moderate public value: Upland wetlands may be valued by hikers and hunters (Vuln. Assessment Workshop, pers. comm., 2016) +/- Low-moderate manager capacity/ability to cope with habitat impacts: Managers need more funding (Vuln. Assessment Workshop, pers. comm., 2016) +/- Low-moderate likelihood of alleviating climate impacts (Vuln. Assessment Workshop, pers. comm., 2016)

Recommended Citation

Reynier WA, Hilberg LE, Kershner JM, Gregg RM. 2018. Upland Wetland Habitats: A Habitat Climate Change Vulnerability Assessment Synthesis for Oʻahu. EcoAdapt, Bainbridge Island, WA.

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

Literature Cited

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

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

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

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

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

Cuddihy LW. 1988. Vegetation zones of the Hawaiian Islands. Pages 27–37 in C. P. Stone and D. B. Stone, editors. Conservation biology in Hawaiʻi. Cooperative National Park Resources Studies Unit, University of Hawaiʻi, Honolulu, HI. Available from http://manoa.hawaii.edu/hpicesu/book/1988_chap/13.pdf.

Daehler CC. 2005. Upper-montane plant invasions in the Hawaiian Islands: Patterns and opportunities. Perspectives in Plant Ecology, Evolution and Systematics **7**:203–216.

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

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

England MH, McGregor S, Spence P, Meehl GA, Timmermann A, Cai W, Gupta AS, McPhaden MJ, Purich A, Santoso A. 2014. Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus. Nature Climate Change **4**:222–227.

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

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

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

Garza JA, Chu P-S, Norton CW, Schroeder TA. 2012. Changes of the prevailing trade winds over the islands of Hawaiʻi and the North Pacific. Journal of Geophysical Research: Atmospheres **117**:D11109.

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

Hanna JW, Graca RN, Kim MS, Ross-Davis AL, Hauff RD, Uchida JW. 2012. A bioclimatic approach to predict global regions with suitable climate space for Puccina psidii. In S. Zeglen & P. Palacios (Eds.), Proc. 59th Annual Western International Forest Disease Work Conference (pp. 131–136). Leavenworth, WA, US: Department of Agriculture, Forest Service, Forest Health Protection. October 11-14, 2011.

Hawaiʻi Department of Land and Natural Resources. 1990. Mount Kaala Natural Area Reserve Management Plan. Hawaiʻi Department of Land and Natural Resources, Division of Forestry and Wildlife, Natural Area Reserves System Program. Available from http://dlnr.hawaii.gov/ecosystems/files/2013/08/Mount-Kaala-Management-Plan.pdf.

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

Hotchkiss SC, Juvik J. 1999. A Late-Quaternary pollen record from Kaʻau Crater, Oʻahu, Hawaiʻi. Quaternary Research **52**:115–128.

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

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

Krist FJ, Ellenwood JR, Woods ME, McMahan AJ, Cowardin JP, Ryerson DE, Sapio FJ, Sweifler MO, Romero SA. 2014. 2013–2027 National Insect and Disease Forest Risk Assessment. FHTET 14-01. USDA Forest Service Forest Health Technology Enterprise Team, Fort Collins, CO.

Lauer A, Zhang C, Elison Timm O, Wang Y, Hamilton K. 2013. Downscaling of climate change in the Hawaiʻi region using CMIP5 results: On the choice of the forcing fields. Journal of Climate **26**:10006–10030.

Longman RJ, Diaz HF, Giambelluca TW. 2015. Sustained increases in lower-tropospheric subsidence over the central tropical North Pacific drive a decline in high-elevation rainfall in Hawaiʻi. Journal of Climate **28**:8743–8759.

Loope LL, Medeiros AC, Gagne BH. 1991. Aspects of the history and biology of the montane bogs. Studies in the montane bogs of Haleakala National Park. Technical Report 76. University of Hawaiʻi at Mānoa and National Park Service, Honolulu, HI. Available from https://scholarspace.manoa.hawaii.edu/bitstream/10125/5889/1/076.pdf.

Medeiros AC, Loope LL, Gagne. 1991. Degradation of vegetation in two montane bogs: 1982-1988. Studies in the montane bogs of Haleakala National Park. Technical Report 78. University of Hawaiʻi at Mānoa and National Park Service, Maui, HI. Available from http://manoa.hawaii.edu/hpicesu/techr/078.pdf.

Miller JN, Armann SS, Chan-Hui SSC, Sakamoto R, Chiang J. 1989. Ecologically sensitive wetlands on Oʻahu: Groundwater protection strategy for Hawaiʻi. Technical Report No. 184. University of Hawaiʻi at Mānoa, Honolulu, HI.

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

Pacific Coast Joint Venture Hawaiʻi. 2006. Strategic plan for wetland conservation in Hawaiʻi. Ducks Unlimited. Available from http://www.pacificbirds.org/wp-content/uploads/2014/12/HWJVStrategicPlan-3.pdf.

Polhemus DA. 2015. The effects of climate change on wetlands in the Main Hawaiian Islands: An initial assessment. Available from https://doi.org/10.21429/C9890F.

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

Schubert O. 2012. Changes in vegetation and environment over the Holocene: Kaʻau Crater, Oʻahu, Hawaiʻi. Master of Arts. University of Hawaiʻi at Mānoa. Available from https://scholarspace.manoa.hawaii.edu/bitstream/10125/100816/1/Schubert_Olivia_r.pdf.

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

Van Rees CB, Reed JM. 2014. Wetland loss in Hawaiʻi since human settlement. Wetlands **34**:335–350.

Wentworth CK. 1949. Directional shift of trade winds at Honolulu. Available from http://scholarspace.manoa.hawaii.edu/handle/10125/8917 (accessed March 24, 2017).

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

Hawaiian Islands Climate Synthesis Project:
Vulnerability Assessment Methods and Application

Defining Terms

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

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

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

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

Vulnerability Assessment Model

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

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

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

---

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

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

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

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

Habitat & Ecosystem Service Elements

Sensitivity & Exposure (Applies to Habitats and Ecosystem Services)

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

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

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

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

Adaptive Capacity (Habitats)

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

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

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

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

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

Adaptive Capacity (Ecosystem Services)

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

Literature Cited

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

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

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

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

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

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

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

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

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