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| Coastal Dune Systems  *Northern California Climate Change Vulnerability Assessment Synthesis* |

***An Important Note About this Document:*** *This document represents an initial evaluation of vulnerability for coastal dune systems in northern California based on expert input and existing information. Specifically, the information presented below comprises vulnerability factors selected and scored by regional experts, relevant references from the scientific literature, and peer-review comments and revisions (see end of document for a glossary of terms and brief overview of study methods). 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.*

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Habitat Description

Northern California coastal dune systems are part of a larger complex of coastal habitats that includes cliffs and sandy beaches and extends from northern California to Alaska (Cooper 1958; Wiedemann 1984; Green 1999; Alpert 2016). Coastal dunes in northern California are distributed in a narrow, discontinuous band that varies in width along the coastline (Wiedemann 1984; Green 1999; Alpert 2016), with dunes ranging in size from <0.01 km2 (0.004 mi2) to >100 km2 (38.6 mi2; Alpert 2016). Approximately ten relatively intact coastal dune areas remain in northern California (Wiedemann 1984; Alpert 2016), with the primary areas located in the Smith River area, Tolowa Dunes, the Humboldt Bay area, and Ten-Mile River (Alpert 2016; Pickart & Sholars 2016). The Humboldt Bay area is the largest and least altered major dune area in northern California (Gordon 2000; Pickart & Barbour 2007; Alpert 2016), and includes coastal dunes located on narrow barrier and spit systems (Green 1999). Although invasive species are common in California coastal dune systems, the Humboldt Bay dune systems likely support the most-intact remnants of native dune vegetation (Pickart et al. 1998; Wiedemann & Pickart 2008; Pickart 2013; Alpert 2016).

Coastal dune systems are subject to harsh conditions, including a low-nutrient substrate, airborne salt spray, desiccating summer winds and gale-force winter storms, fluctuating water tables, and periodic abrasion, erosion, and burial by windblown sand (Cooper 1958; Wiedemann 1984; Pickart & Sawyer 1998; Green 1999; Wiedemann & Pickart 2008). These conditions interact in complex ways to shape coastal dune morphology and ecology (Wiedemann 1984; Green 1999; Hesp & Walker 2013; Pickart & Hesp 2019). Coastal dunes in northern California typically include several zones with differing vegetation communities based on exposure to sand movement and wind as well as land management actions (Pickart & Barbour 2007; Wiedemann & Pickart 2008; Alpert 2016; Pickart & Hesp 2019).

Foredune systems are typically oriented parallel to the beach and begin just above the high water runup elevation (Hesp 2002; Hesp & Martínez 2007; Hesp & Walker 2013; Walker et al. 2017). The foredune can be relatively continuous or interrupted by blowouts that may give rise to narrow, long-walled parabolic dunes that migrate inland (Wiedemann 1984; Hesp 2002; Hesp & Walker 2013). In northern California, the foredune may be partially to fully stabilized by low-growing annual and perennial forbs and grasses known as dune mat vegetation (Wiedemann 1984; Pickart & Sawyer 1998, 1998; Gordon 2000; Hesp & Martínez 2007). Common dune mat species include sand verbena (*Abronia latifolia*),silver beachweed (*Ambrosia chamissonis*; also called beach bur), beach knotweed (*Polygonum paronychia*), coast buckwheat (*Eriogonum latifolium*), and European searocket (*Cakile maritima*; Wiedemann 1984; Pickart & Barbour 2007; CNPS 2018). Many semi-stable coastal dunes in northern California also have been extensively colonized by non-native species, including European beach grass (*Ammophila arenaria*), yellow bush lupine (*Lupinus arboreus*; native south of Sonoma County), iceplant (*Carpobrotus edulis*), European hairgrass (*Aira praecox*), and squirreltail fescue (*Vulpia bromoides*; Pickart et al. 1998; Pickart & Sawyer 1998; California Coastal Conservancy 2007; Wiedemann & Pickart 2008; Pickart 2013; Alpert 2016).

Several distinct ecosystems lie landward (east) of many foredune systems, including low-lying swales, deflation basins of parabolic dunes, sandy plains, or migrating dunefields (Hesp 2002; Hesp & Walker 2013). Some dune swales are filled with water for several months of the year (Alpert 2016) and support herbaceous and woody wetland vegetation, including patches of slough sedge (*Carex obnupta*) and coastal dune willow (*Salix hookeriana*) thickets (Wiedemann 1984; Gordon 2000; Alpert 2016). Farther inland, some older, more stabilized dunes support small patches of forest dominated primarily by short-statured beach pine (*Pinus contorta* *contorta*; also called shore pine; Wiedemann 1984; Green 1999). Other species associated with dune forests include grand fir (*Abies grandis*), Sitka spruce (*Picea sitchensis*), bishop pine (*Pinus muricata*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and Pacific madrone (*Arbutus menziesii*; Green 1999; Alpert 2016; CNPS 2018). The understory of these forests contains lichens, mosses, and shrubs such as salal (*Gaultheria shallon*), evergreen huckleberry (*Vaccinium ovatum*), and silk tassel (*Garrya elliptica*; Green 1999). These forests distinguish northern California dune systems from those of central California (south of Port Arena), where stabilized dune plant communities are dominated by coastal scrub vegetation rather than forest (Vuln. Assessment Reviewer, pers. comm., 2018).

Coastal dune systems are important ecocultural areas for northern California tribes and contain many cultural sites, burial areas, and archaeological artifacts, including ancient gardens and shell middens (HWR Engineering & Science 2010; Chiniewicz 2015; Long et al. 2018). The dunes around Humboldt Bay are a critical resource for the Wiyot tribe, for whom permanent and seasonal villages were once centered around dune, wetland, and marine resources (Loud 1918). Wiyot tribe members continue to gather evergreen huckleberry, salal, California blackberry (*Rubus ursinus*), and salmonberry (*R. spectabilis*; Vuln. Assessment Reviewer, pers. comm., 2018). Beach strawberry (*Fragaria chiloensis*) and bearberry (*Arctostaphylus uva-ursi*; also known locally as sandberry) were also historically gathered by the Wiyot tribe, but have become uncommon (Loud 1918; Vuln. Assessment Reviewer, pers. comm., 2018). The occurrence of several species with edible roots not commonly found in dunes (e.g., dwarf brodiaea [*Brodiaea terrestris*] and checker lily [*Fritillaria affinis*] within Wiyot cultural sites on the north spit of Humboldt Bay highlight the importance of this dune area for food production and ethnobotanical resources (Vuln. Assessment Reviewer, pers. comm., 2018). The Wiyot also hunted for waterfowl within inland dune areas, and gathered Sitka spruce roots for basketry (Vuln. Assessment Reviewer, pers. comm., 2018). Finally, dune areas were important access points for gathering resources (e.g., fish, mollusks, and seaweed) from adjoining riverine and marine habitats (Norgaard 2014; Sloan & Hostler 2014; Norgaard et al. 2016).



Executive Summary

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| **Coastal Dune Systems** | **Rank** | **Confidence** |
| Sensitivity | High | Moderate |
| Future Exposure | Moderate | Low |
| Adaptive Capacity | Low-Moderate | High |
| **Vulnerability** | **Moderate-High** | **Moderate** |

The relative vulnerability of coastal dune systems in northern California was evaluated as moderate-high by regional experts due to high sensitivity to climate and non-climate stressors, moderate exposure to projected future climate changes, and low-moderate adaptive capacity.

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| **Sensitivity & Exposure Summary Summary** | *Climate and climate-driven factors*:   * Precipitation timing, soil moisture, drought, sea level rise, storms, coastal fog   *Disturbance regimes*:   * Flooding (including wave and storm surge flooding), wildfire, wind   *Non-climate stressors*:   * Invasive species, roads/highways/trails, residential and commercial development, livestock grazing, agriculture, pollution |

Coastal dune systems are sensitive to changes in climate factors that decrease water availability (e.g., precipitation timing, soil moisture, drought, fog), especially in the late summer dry period. Increased moisture stress and drought can potentially cause plant die-off and subsequent dune mobilization. Forest and wetland species are particularly vulnerable to drought due to their higher evapotranspiration rates and/or dependence on a shallow water table. Increases in winter precipitation could also allow the expansion of invasive European beach grass, which is more tolerant of summer drought than most native foredune species. Generally, coastal dune systems are adapted to and formed by natural disturbances; however, rapid and/or prolonged changes in these disturbance regimes could alter the biogeomorphic stability of these systems. For instance, sea level rise, combined with wind and waves associated with more frequent and/or more intense storms, may accelerate dune erosion and contribute to the loss of vegetation and subsequent remobilization of some semi-stable dunes. Extreme wind events may also result in tree mortality. Non-climate stressors (e.g., invasive species, the presence and use of roads and trails, development, livestock grazing, agriculture, pollution) have already degraded most coastal dune systems in the region. For instance, invasive European beach grass has overstabilized the dunes, limiting the function of ecological and geomorphic processes necessary to recover quickly from disturbance events and, over the longer-term, migrate landward with sea level rise. Other non-climate stressors fragment and/or eliminate dune areas, damage vegetation, decrease water quality, and negatively impact wildlife movement and habitat quality.

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| **Adaptive Capacity Summary** | *Factors that enhance adaptive capacity*:   * Rapid recovery from disturbances and relatively quick response to restoration activities due to dynamic nature of semi-stable dunes * Many areas protected from commercial/residential development and other anthropogenic stressors * High tribal ecocultural and public value placed on dune resources and rare habitats * Increasing societal interest in coastal resilience planning and action   *Factors that undermine adaptive capacity:*   * Limited ecosystem extent and lack of continuity due to physical constraints, development, and current recreational use * Few funding sources for ongoing invasive species management * Consensus from multiple parties required for local action |

Coastal dune systems in the region are often limited in extent due to their position between the dynamic beach and inland bay environments, more stable terrestrial habitats, and/or developed landscapes. Specifically, habitat fragmentation and dune stabilization due to infrastructure (e.g., urban development, roads, seawalls) and the presence of invasive species have created barriers to plant dispersal and dune migration throughout northern California. In the longer term, rising sea levels are likely to inundate many dunes, although landward shifts of semi-stable dunes may occur where infrastructure does not hinder movement. Depending on the rate of sea level rise and other factors, stabilized dunes that are unable to migrate may erode in place or be buried by sand. High physical and structural diversity in coastal dune systems supports a diverse mix of plants and wildlife. Although most of the component plant species found in coastal dune systems are well-adapted to disturbance, extreme disturbances and stressors may surpass the capacity of this habitat to recover, particularly in degraded systems. Although northern California coastal tribes value coastal dune ecosystems highly, general public understanding of the value of this habitat is primarily limited to the recreational value of the beaches and dunes. Lack of funding for dune restoration and protection and education/outreach activities is a critical limiting factor for coastal dune adaptation, although some successful efforts are underway on public lands. Management strategies focused on restoring natural vegetation and key geomorphic processes in degraded areas (e.g., invasive species removal to allow wind transport of sand in the foredunes) and preventing further fragmentation of coastal dune systems may increase their adaptive capacity. However, local- to regional-scale coordination with owners of adjacent inland parcels will likely be required to preserve this habitat as sea level rise threatens to eliminate or fragment coastal dune systems.



Sensitivity and Exposure

Coastal dune systems were evaluated by regional experts as having high overall sensitivity (moderate confidence in evaluation) and moderate overall future exposure (low confidence) to climate and climate-driven factors, changes in disturbance regimes, and non-climate stressors.

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| **Potential Changes in Habitat Distribution** |
| * Mobile and semi-stable dunes likely to migrate inland where development or land use allows * Stabilized forested dunes are unable to move and are likely to experience erosion or burial |
| Source(s): Titus 1986; Alpert 2016; Vuln. Assessment Reviewer, pers. comm., 2018 |

As sea levels rise over the next century, many coastal dunes will likely be lost to erosion and inundation unless adjacent land parcels can accommodate landward migration (Titus 1986; Cayan et al. 2009; Alpert 2016). Dynamic foredunes are more likely to migrate inland in response to rising sea levels than stabilized dunes, depending on rates of onshore sediment supply, persistence of wind-related processes, and accommodation space for landward migration (Vuln. Assessment Reviewer, pers. comm., 2018). Thus, stabilized forested dunes are vulnerable to erosion and/or burial if inland migration of semi-stable dunes accelerates and sediment replenishment is insufficient to compensate for loss (Vuln. Assessment Reviewer, pers. comm., 2018). However, many widely distributed species found within dune forest communities (e.g., beach pine, Sitka spruce, huckleberry, willow) are likely to persist in other ecosystems even if climatic stresses become too great in coastal areas (Gordon 2000; Aitken et al. 2008).

### Sensitivity and future exposure to climate and climate-driven factors

Regional experts evaluated coastal dune systems as having high sensitivity to climate and climate-driven factors (high confidence in evaluation), with an overall moderate future exposure to these factors within the study region (low confidence). Key climatic factors that affect coastal dune systems include precipitation timing, soil moisture, drought, sea level rise, storms, and coastal fog.[[1]](#footnote-1)

Precipitation timing and soil moisture

In the maritime climate of coastal northern California, up to 90% of the annual precipitation falls between October and April (Wiedemann 1984; Alpert 2016). High humidity is maintained during the rest of the year, with May through September characterized by fog and clouds (Wiedemann 1984; Alpert 2016). Patterns of soil moisture availability, which affect the establishment and growth of plants, are influenced by substrate and the elevation of the groundwater table as well as precipitation (Wiedemann 1984; Maun 1994; Alpert 2016). In general, coastal dune vegetation is adapted to periodic moisture stress associated with rapid drainage and evaporation from coarsely textured soils (Maun 1994; Pickart & Barbour 2007; Alpert 2016). However, projected changes in precipitation timing suggest drier summers and wetter winters are likely (Flint et al. 2013; Neelin et al. 2013; Flint & Flint 2014), which may reduce overall growth and recruitment of semi-stabilized dune vegetation due to late summer water stress (Johnstone & Dawson 2010; Alpert 2016). Dry conditions are particularly likely to limit seedling establishment and the growth of plants with shallow roots (Alpert 2016).

Wetland vegetation typically occurs in areas where the water table is high enough to reach the ground surface, and these species become experience water stress as soil moisture and water tables drop, particularly during the growing season (Gordon 2000; Alpert 2016). Plant growth is also more limited in forested dunes compared to more open dunes during low-precipitation periods (Ensign et al. 2006), perhaps because of higher evapotranspiration rates in forested areas (Stratford et al. 2007). However, the higher water-holding capacity of soils in the stabilized dune forests may protect against mortality (Vuln. Assessment Reviewer, pers. comm., 2018). For instance, ecoculturally important checker lily bulbs were found more than 0.6 m (2 ft) below the soil surface under beach pine-dominated canopy at a Wiyot cultural site in the Ma-l’el Dunes, confirming the presence of water at that depth (Vuln. Assessment Reviewer, pers. comm., 2018).

Increased precipitation in the winter months would likely stimulate early growth of native and non-native plants in semi-stable dunes (Maun 1994; Vuln. Assessment Workshop, pers. comm., 2017), potentially counteracting some of the impacts of winter storm erosion (Vuln. Assessment Reviewer, pers. comm., 2018). However, invasive plants such as European beach grass and iceplant are generally better adapted to dry conditions than American dunegrass (*Elymus mollis*) and other native species (Pickart & Sawyer 1998). As a result, drier summer conditions would likely encourage the increased recruitment and spread of invasive species due to their competitive advantage during the summer months (Vuln. Assessment Reviewer, pers. comm., 2018).

| **Regional Precipitation & Soil Moisture Trends**[[2]](#footnote-2) | |
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| *Historical & current trends:*   * 7.2 cm (2.8 in) increase in mean annual precipitation between 1900 and 2009 for the Northwestern California ecoregion (Rapacciuolo et al. 2014) * No trends available for soil moisture | *Projected future trends:*   * 20% decrease to 27% increase in mean annual precipitation by 2100 (compared to 1951–1980) for the North Coast ecoregion (Flint et al. 2013; Flint & Flint 2014)[[3]](#footnote-3) * Seasonal changes are projected to be more significant as the wet season becomes wetter and shorter (i.e., later onset of fall rains and earlier onset of summer drought) and the dry season becomes drier and longer (Pierce et al. 2018; Swain et al. 2018) * Overall, interannual variability is expected to increase (Pierce et al. 2018; Swain et al. 2018) * Decreased top-level soil moisture is likely even if precipitation increases due to temperature-related changes in evaporative demand (Pierce et al. 2018) |
| **Summary of Potential Impacts on Habitat** *(see text for citations)* | |
| * Reduced growth and recruitment of coastal dune vegetation due to late summer water stress * Increased invasive species recruitment and spread | |

Drought

Increased drought stress is likely to play a key role in determining which native foredune and semi-stable backdune species persist in a changing climate (Stuart & Stephens 2006; Clarke & Ayutthaya 2010; Alpert 2016). Several dune mat species. including beach knotweed, coast buckwheat, and silver beachweed, in northern California experienced particularly high adult mortality during the 2012–2016 drought; however, observations of regeneration by young plants suggest that recovery is occurring (Vuln. Assessment Reviewer, pers. comm., 2018). In the well-drained, coarse soils typical of dunes, backdune species are often less tolerant of prolonged periods of drought (Stuart & Stephens 2006; Clarke & Ayutthaya 2010; Alpert 2016).

Drought may also change competition dynamics between native and invasive dune vegetation in unpredictable ways (Pickart 1997). American dunegrass also appears to be more vulnerable than European beach grass to moderate and severe drought (Pickart 1997; Boudreau & Faure-Lacroix 2009). Barbour et al. (1977) found that European beach grass had twice the root density of American dunegrass, which likely contributes to greater drought resistance and more efficient soil water tapping. In addition, the leaves of European dune grass can roll inward during drought, reducing water loss through transpiration (Huiskes 1979).

Coastal dune vegetation in deflation plain wetlands and forests is particularly vulnerable to drought (Pickart 1997; Alpert 2016) due to higher evapotranspiration rates (Ensign et al. 2006), and they can endure long periods of low water tables (Clarke & Ayutthaya 2010). For these species, changes in surface water and groundwater availability are likely to disrupt the establishment and persistence of vegetation (Curreli et al. 2013), depending on the physiological ability of their root systems to access a lowered water table (Clarke & Ayutthaya 2010; Curreli et al. 2013; Alpert 2016). Although sea level rise and associated coastal erosion may gradually raise the water table over time (Clarke & Ayutthaya 2010), saltwater intrusion is likely to negate any benefit of higher water tables to vegetation (NHE 2015; Laird 2018). Over the longer term, relatively rapid rates of reproduction in beach pine and Sitka spruce may enhance local adaptation to drought (Rehfeldt et al. 1999; Aitken et al. 2008). Genetic diversity, phenotypic variation, and interspecific competition will also likely influence the extent to which these species adapt to unprecedented rates of change in water availability (Aitken et al. 2008). Plant species that can compensate for lack of moisture through fog use will likely be at an advantage (Corbin et al. 2005; Baguskas et al. 2016).

| **Regional Drought Trends** | |
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| *Historical & current trends:*   * Drought years have occurred twice as often over the last two decades compared to the previous century (Diffenbaugh et al. 2015) * 2012–2014 drought set records for lowest precipitation, highest temperatures, and most extreme drought indicators on record (Griffin & Anchukaitis 2014; Diffenbaugh et al. 2015) | *Projected future trends:*   * Drought years are twice as likely to occur over the next several decades due to increased co-occurrence of dry years with very warm years (Cook et al. 2015) * 80% chance of multi-decadal drought by 2100 under a high-emissions scenario (Cook et al. 2015) * Severe droughts that now occur once every 20 years will occur once every 10 years by 2100 and once-in-a-century drought will occur once every 20 years (Pierce et al. 2018) |
| **Summary of Potential Impacts on Habitat** *(see text for citations)* | |
| * Loss of native dune species due to competition from invasive species such as European beach grass * Reduced plant growth, particularly for wetland and forest vegetation due to lowered water tables * Potential for long-term adaptation to drought by some dune forest trees | |

Sea level rise

In the near term, sea level rise may alter coastal dune systems in northern California through increased erosion and flooding, especially in conjunction with storms and strong El Niño seasons (Barbour & DeJong 1977; Barnard et al. 2015; Alpert 2016). Over longer time scales, coastal dunes may be subject to elimination or landward movement from sea level rise depending on large-scale processes that control sediment supply along the coast (Heady et al. 2018; Laird 2018; Ocean Protection Council 2018). Sea level rise impacts will likely vary across coastal dune systems of northern California based on relative sea level rise rates, site geology and exposure to erosion, extent of coastal armoring, development that prevents dune migration, and other factors (Heady et al. 2018; Laird 2018; Ocean Protection Council 2018).

Coastal dune systems in northern California lie within an area where actively shifting tectonic plates are causing inter-seismic land level changes (National Research Council 2012; Chiniewicz 2015; Patton et al. 2017). In the Humboldt bay region, land subsidence is increasing relative sea level rise compared to the rest of the Pacific Coast (NRC 2012; NHE 2015; Patton et al. 2017; Chiniewicz 2015; Laird 2018). However, the rate of vertical land movement is not uniform, and the southern end of Humboldt Bay will likely be inundated before the northern portion, although the exact timeline is unknown (NHE 2015; Patton et al. 2017). Many of the Bay’s low-lying areas, which include coastal dune systems, would flood during high tides if the levees or road grades were to fail or breach (Laird 2013, 2018; NHE 2015).

Over the next century, sea level rise is likely to alter sediment supply, deposition, and erosion on beaches and dunes, shaping future coastal dune systems and the ability of dune systems to move in response to changing ocean processes (Vitousek et al. 2017a; Heady et al. 2018). As sea levels continue to rise, coastal habitats must have periodic sediment replenishment to remain above sea level or have the space available to move landward (Vitousek et al. 2017a; Heady et al. 2018). Dune systems naturally experience seasonal fluctuations in sediment deposition, with accretion occurring during the summer and erosion occurring during winter storms (Hutto et al. 2015; Alpert 2016; Rader et al. 2018). However, gradual inundation due to sea level rise in combination with changes in storm frequency and intensity will increase future erosion over deposition in some areas (Yoshiyama & Moyle 2010).

Plant communities within higher areas of the dunes that have not historically experienced frequent inundation will likely be affected by increasing saltwater inundation and salt spray impacts as sea levels rise (Russell & Griggs 2012; NHE 2015; Alpert 2016; Laird 2018). In addition, sediment carried during storm-related flooding events may result in sand inundation events that smother dune vegetation (Hesp & Martínez 2007). The most severe of these impacts are likely to occur during extreme storms that coincide with king tides (Russell & Griggs 2012; NHE 2015; Alpert 2016; Laird 2018).

Tribal cultural sites in coastal dune systems are also vulnerable to damage and erosion from sea level rise (Chiniewicz 2015; Laird 2018). Around Humboldt Bay, 52 Wiyot cultural sites in the coastal dune and bluff landscape are vulnerable to tidal inundation from sea level rise (Laird 2018). Many of these sites hold immense importance to the Wiyot Tribe as ceremonial and gathering areas, and are part of the larger Wiyot ecocultural landscape (Vuln. Assessment Reviewer, pers. comm., 2018). In Tolowa Dunes State Park, located in extreme northwestern California, dune system erosion due to sea level rise has already begun to expose tribal cultural sites and archeological resources to damage, and this pattern is likely to continue (Chiniewicz 2015). Except in areas of exposed bedrock cliffs, the Tolowa Dunes area is at risk for continued erosion from sea level rise because the high groundwater table and morphology of the barrier dune system increase vulnerability to storm surge that erodes the mouth of the Smith River and floods seasonal ponds (Chiniewicz 2015).

| **Regional Sea Level Rise Trends** | |
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| *Historical & current trends:*   * At the Crescent City station, sea levels decreased by an average of 0.08 cm (0.03 in) per year from 1933–2018 (equivalent to a decrease of 0.08 m [0.26 ft] in 100 years; NOAA/National Ocean Service 2019) * At the Humboldt Bay (North Spit) station, sea levels increased by an average of 0.49 cm (0.19 in) per year from 1977–2018 (equivalent to an increase of 0.49 m [1.6 ft] in 100 years; NOAA/National Ocean Service 2019) * At the Arena Cove station, sea levels increased by an average of 0.08 cm (0.03 in) per year from 1978–2018 (equivalent to a change of 0.08 m [0.27 ft] in 100 years; NOAA/National Ocean Service 2019) | *Projected future trends:*   * Sea level rise trends by 2100 (compared to 2000), based on likelihood of occurrence (range includes projections linked to low-, moderate-, and high-emissions scenarios; Kopp et al. 2014; Griggs et al. 2017; Sweet et al. 2017; Anderson 2018):   + For the Crescent City station, likely (66% probability) range of 0.03–0.65 m (0.1–2.1 ft), 0.5% probability will meet or exceed 1.55 m (5.1 ft); extreme scenario (representing ice sheet collapse) of 2.79 m (9.1 ft)   + For the Humboldt Bay (North Spit) station, likely (66% probability) range of 0.62–1.24 m (2.0–4.1 ft), 0.5% probability will meet or exceed 2.15 m (7.0 ft); extreme scenario (representing ice sheet collapse) of 3.37 m (11.0 ft)   + For the Arena Cove station, likely (66% probability) range of 0.21–0.94 m (0.7–3.1 ft), 0.5% probability will meet or exceed 2.04 m (6.7 ft); extreme scenario (representing ice sheet collapse) of 3.02 m (9.9 ft) |
| **Summary of Potential Impacts on Habitat** *(see text for citations)* | |
| * Increased flooding in low-lying dune areas * Increased sediment erosion and reduced deposition in some areas, causing the loss of foredunes * Physical damage to vegetation from waves, salt spray, and sand burial * Loss of habitat and cultural sites due to erosion | |

Storms

Storms continually shape beaches and foredunes, contributing to the dynamic nature of these systems (Barbour & DeJong 1977; Alpert 2016). The plant communities in these areas protect dunes farther inland from storm impacts such as erosion, flooding, and the effects of waves and salt spray on vegetation (Barbour & DeJong 1977; Alpert 2016). In conjunction with sea level rise, changes in the frequency and/or severity of storms are likely to increase erosion and flooding associated with storm surge (Hutto et al. 2015; Alpert 2016). Greater erosion impacts are likely during El Niño years when extreme precipitation and severe storm events are more likely (Neelin et al. 2013; Barnard et al. 2015; NHE 2015). Higher storm surge, especially during king tides, will likely accelerate erosion and weakening of foredunes (Russell & Griggs 2012; NHE 2015; Alpert 2016; Anderson 2018; Laird 2018), although the intensity of these impacts will vary based on dune exposure, site geology, and wave direction (Hesp 2002; Rader et al. 2018). Dune systems adjacent to rivers (e.g., Tolowa Dunes State Park near the Smith River) may be flooded more frequently following intense rainstorms (Green 1999; Chiniewicz 2015).

More storms and higher storm surge are also likely to increase the intensity of salt spray in both the foredune community and farther inland in areas usually more protected from storms (Oosting 1945; Kumler 1963; Barbour & DeJong 1977). The salt tolerance of herbaceous plants on semi-stable foredunes is greater than that of plants growing in the backdune areas (Kumler 1963). American dunegrass has a higher salt spray tolerance than the invasive European beach grass (Pickart 1997). However, European beach grass is capable of storm-induced marine transport of dormant rhizomes that can withstand submersion for long periods (Pickart 1997).

Although dune shrubs and are often quite tolerant of salt spray at moderate intensities (Oosting 1945; Kumler 1963), during severe storms plants may be killed or have their tops pruned by salt spray (Kumler 1963; Wiedemann 1984). Seedlings and new vegetative growth are particularly vulnerable (Oosting 1945; Kumler 1963; Wiedemann 1984). Rain occurring during and after storm events can reduce the impact of salt spray by diluting it; without rain, the damage can be severe (Oosting 1945; Kumler 1963). More frequent storms with high winds may increase tree mortality and limit the ability of these habitats to recover (Vuln. Assessment Reviewer, pers. comm., 2018).

| **Regional Storm Trends** | |
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| *Historical & current trends:*   * Decline in the frequency of extreme two-day precipitation events between 1950 and 2009, with a slight decrease in the amount of precipitation received during extreme two-day events (Mass et al. 2010) | *Projected future trends:*   * Increase in storm intensity and duration, resulting in greater maximum precipitation rates and volume (Dettinger 2011; Shields & Kiehl 2016; Prein et al. 2017) * Slight to moderate increase in storm frequency (up to 30% increase in atmospheric river days, or ~2.5 days per year; Dettinger 2011) * Projected statewide increases in daily extreme precipitation values of 5–20% by 2100 (Pierce et al. 2018) |
| **Summary of Potential Impacts on Habitat** *(see text for citations)* | |
| * Increased dune erosion and changes in sediment supply, with impacts varying based on dune morphology and wave characteristics * Increased salt spray exposure, which may favor American dunegrass over European beach grass * Increased propagation of European beach grass through rhizome transport * Top pruning or mortality in trees, shrubs, and herbaceous plants from salt spray, sand and water inundation, and wind | |

Coastal fog

Fog is a significant source of summer moisture for vegetation in northern California coastal dune systems between April and October (Glavich 2003; Johnstone & Dawson 2010), potentially providing up to 0.3 cm (0.12 in) of water on a normal foggy day (Azevedo & Morgan 1974). Fog water inputs can offset seasonal drought stress in coastal California climates and may be critical to the persistence of many endemic plant species, including Bishop pine (Baguskas et al. 2016). Reduced coastal fog would decrease water inputs from fog drip and foliar wetting and increase plant exposure to solar radiation, enhancing evapotranspiration rates and reducing available soil moisture in coastal dune systems (Carbone et al. 2012; Fischer et al. 2016; Baguskas et al. 2017). The potential impacts of reduced coastal fog on individual species would likely vary, depending on plant physiology and life stage, the degree and direction of change that occurs, and groundwater table elevation (Clarke & Ayutthaya 2010; Alpert 2016; Baguskas et al. 2016). For instance, seedling establishment and survival of shallow-rooted species would likely be impacted heavily by the loss of fog moisture (Alpert 2016). Additionally, seedlings and saplings are more sensitive to changes in shallow soil moisture inputs compared to adult trees, and likely benefit to a greater degree from fog water deposition that augments late-season water availability (Baguskas et al. 2017).

Lichens may be even more reliant on fog water input than most other plant species (Johnstone & Dawson 2010). Lichen distribution in coastal forests corresponds to the distribution of the heavy fog zone, suggesting that lichen species in the more established beach pine forests are vulnerable to changes in fog and precipitation regimes (Johnstone & Dawson 2010).

| **Regional Coastal Fog Trends** | |
| --- | --- |
| *Historical & current trends:*   * 3–4% decline per decade in the frequency of California coastal fog and low clouds under 400 m (1,312 ft) from 1920–1950, then 0.5–1% decline per decade from 1950–2008 (O’Brien 2011) * Observed 33% decrease in the frequency of days with coastal fog and low clouds at two locations on the northern and central California coast over the past century (Johnstone & Dawson 2010) | *Projected future trends:*   * Weak decline (0.1% per decade) in the frequency of California coastal fog and low clouds by 2100, driven primarily by warming sea surface temperatures (O’Brien 2011) * Potential changes in global circulation patterns (e.g., the jet stream), the timing and strength of upwellings, wind intensity, and other interacting oceanic and atmospheric factors that influence coastal fog are largely unknown (Grantham 2018) |
| **Summary of Potential Impacts on Habitat** *(see text for citations)* | |
| * Increased water stress in coastal vegetation if summer fog declines, particularly for shallow-rooted species and lichens | |

### Sensitivity and future exposure to changes in natural disturbance regimes

Regional experts evaluated coastal dune systems as having high sensitivity to changes in natural disturbance regimes (moderate confidence in evaluation), with an overall moderate future exposure to these stressors within the study region (low confidence). Key natural disturbance regimes that affect coastal dune systems include flooding (including wave and storm surge flooding), wildfire, and wind. [[4]](#footnote-4)

Flooding (including wave and storm surge flooding)

Increased flooding in coastal dune systems may occur over the coming century from the combined impacts of sea level rise, storm surge, and riverine flooding following heavy precipitation events (Cayan et al. 2009; Chiniewicz 2015; NHE 2015; Laird 2018). Although all flooding events are likely to cause dune erosion, the source and timing of floodwater and the magnitude of local tidal stages determine the severity of impacts on coastal dune systems (NHE 2015; Laird 2018). For instance, intense precipitation events can cause riverine (freshwater) flooding in dune habitats, while coastal flooding due to storm surge can inundate dunes with high-energy saltwater waves (Alpert 2016). Large flooding events, in conjunction with sea level rise, may rapidly accelerate coastal erosion, displacing dunes inland and/or causing habitat loss where foredune migration is not possible (Green 1999; Feagin et al. 2005; Alpert 2016).

| **Regional Flooding Trends** | |
| --- | --- |
| *Historical & current trends:*   * No trends available for flooding | *Projected future trends:*   * More frequent/severe winter flooding due to an increase in extreme precipitation events (Dettinger 2011; AghaKouchak et al. 2018; Swain et al. 2018; Grantham et al. 2018) * State-wide, 200-year floods are expected to increase in frequency by 300–400%, becoming 50-year floods (Swain et al. 2018) |
| **Summary of Potential Impacts on Habitat** *(see text for citations)* | |
| * Increased erosion and/or possible inland migration of mobile and semi-stable dunes due to coastal flooding * Increased dune erosion and inundation of wetland and forest habitats from riverine flooding | |

Wildfire

Wildfire occurs less frequently in coastal dune systems compared to many other habitat types in California, likely due to cooler, moister conditions and relatively fewer lightning strikes (Cooper 1958; Green 1999; Stuart & Stephens 2006; Forrestel et al. 2011). Fog, in particular, may be an important factor limiting wildfire disturbance in coastal areas because it decreases fuel moisture loss in coastal shrubs that are able to utilize fog water (Emery et al. 2018). Large fires do occasionally occur in coastal areas, and they are typically associated with Pacific high pressure systems that produce warm, dry east winds (i.e., foehn winds; Schroeder et al. 1964; Stuart & Stephens 2006).

Prior to Euro-American settlement around 1850, large fires likely spread into coastal dune habitats more frequently than they do today (Wiedemann 1984; Green 1999; Forrestel et al. 2011). Frequent cultural burning of coastal dune vegetation also occurred to support the production of culturally-valued resources such as evergreen huckleberry (Stuart & Stephens 2006). However, fire has likely not disturbed northern California coastal dunes significantly during the last 150 years (Cooper 1958; Agee 1996; Green 1999). A lack of evidence of widespread fire in beach pine stands containing trees estimated at 140 to 150 years old (Green 1999) suggests that fires ignited in the foredunes during this period did not spread into dune forest stands, likely due to moist conditions and lack of fuel in the sparsely vegetated foredunes (Varga 1989; Green 1999; Stuart & Stephens 2006). In the coastal dune forests at Humboldt Bay, charcoal layers found in exposed paleosoil profiles indicate that some trees buried by wind and waves had previously burned, although the trees may have been killed by other disturbances before they burned (Varga 1989; Green 1999).

Future increases in drought may contribute to more frequent fires if sufficient fuel loads and wind conditions are present, potentially affecting semi-stabilized herbaceous dune communities (Alpert 2016). Likewise, forests on stabilized dunes may also be vulnerable to changing fire regimes if high-intensity wildfires in adjacent inland areas spread toward the coast (CNPS 2019). Both beach pine, which has moderately flammable foliage, and Sitka spruce, which has thin bark, typically experience complete mortality from high-intensity fire (CNPS 2019). However, Sitka spruce regenerates relatively rapidly via wind-dispersed seed from unburned trees in the area (CNPS 2019). Additionally, evergreen huckleberry is able to recolonize burned landscapes through post-fire sprouting and/or germination of buried seed (Tirmenstein 1990; Stuart & Stephens 2006).

| **Regional Wildfire Trends** | |
| --- | --- |
| *Historical & current trends:*   * Prior to Euro-American settlement in the 1850s, fire spread more frequently into coastal forests from inland areas (Wiedemann 1984; Green 1999; Forrestel et al. 2011) * Relatively few wildfires have likely occurred in coastal dune forests during the past 150 years (Agee 1996; Green 1999) * Changes in fire size, area burned, and fire frequency over the past several decades remain well below historical tribally-influenced frequency and extent of burning in California (Stephens et al. 2007) * No significant trends in the average areal proportion of high-severity fire were documented in northwestern CA from 1984–2008 (Parks et al. 2015; Law & Waring 2015; Keyser & Westerling 2017)   + The relatively short period of record for fire severity data may obscure long-term trends   + To date, there are no peer-reviewed studies on trends in northern California fire severity that include data from the last ten years | *Projected future trends:*   * State-wide, up to 77% increase in mean annual area burned and 50% increase in the frequency of extremely large fires (>10,000 ha) by 2100 (Westerling 2018)   + Less significant increases or possible decrease along the North Coast (Westerling et al. 2011) * Little projected change in fire severity in northwestern California by 2050 in models based solely on historical fire-climate relationships (Parks et al. 2016)   + However, human activity and fuel buildup from decades of fire suppression have altered historical fire-climate relationships (Taylor et al. 2016; Syphard et al. 2017; Wahl et al. 2019), and projections that incorporate these factors suggest that more significant increases in fire severity and size may occur (Mann et al. 2016; Wahl et al. 2019) * The majority of impacts to natural and human ecosystems come from extreme fire events (i.e., fires that have a low probability of occurring in any given place and time), which are likely to increase over the coming century (Westerling 2018)   + Generally, these patterns are not well-represented in studies that evaluate indices of mean fire size, intensity/severity, etc. |
| **Summary of Potential Impacts on Habitat** *(see text for citations)* | |
| * Reduced survival of herbaceous dune plants where fires become more frequent * Increased mortality in beach pine forests if high-intensity wildfires spread from inland areas, although propagation of Sitka spruce and evergreen huckleberry will likely continue | |

Wind

The structure and health of coastal dune systems are controlled by regional wind regimes that transport, erode, and deposit sand on daily to seasonal timescales (Cooper 1958; Green 1999; Hesp & Walker 2013; Alpert 2016). Wind also shapes vegetation communities by creating disturbed areas for plant colonization, dispersing seeds, desiccating or burying plants, breaking limbs and felling trees in the forest, and increasing plant exposure to salinity by blowing ocean spray inland (Green 1999; Alpert 2016). Under more extreme storm conditions, dunes may experience extensive morphological change due to erosion, and burial and wind damage may occur outside of annual norms for some plant species (Alpert 2016).

Sand movement from wind (aeolian processes) is one of the primary factors affecting plant community distribution from the mobile foredunes to more stationary inland dunes (Moreno-Casasola 1986). Foredune plants typically have a higher tolerance for a deep covering of wind-blown sand (Moreno-Casasola 1986), and native species, such as American dunegrass, also have an open growth pattern, allowing sand movement that keeps the dune face relatively low and punctuated by blowouts (Pickart 1997; McDonald 2015; Alpert 2016). Where invasion and anchoring by densely rooted European beach grass has occurred, a steeper, narrower foredune may develop (McDonald 2015), limiting landward sand transfers and natural dune migration patterns (Pickart 1997; Alpert 2016). European beach grass is more tolerant of wind-blown sand burial than American dunegrass (Pickart 1997), and wind can contribute to the spread of this species because burial stimulates rhizome production and inhibits the buildup of pathogens that reduce the formation of new tillers (Van der Putten et al. 1988; Pickart 1997).

Seedling establishment in forest patches on stabilized dunes is facilitated by strong gusts of wind, and small-scale windfall events have likely been an important disturbance factor that created canopy gaps for seedling establishment (Green 1999). Low- to moderate-intensity windfall events occur frequently, felling individual trees or small clusters, which increases the age and patch size diversity in coastal dune forests (Green 1999).

| **Regional Wind Trends** | |
| --- | --- |
| *Historical & current trends:*   * Alongshore winds increased from 1940-1990 (Bakun 1990; Schwing & Mendelssohn 1997; Mendelssohn & Schwing 2002) * No trends available for storm-related wind events | *Projected future trends:*   * Winds are expected to increase in all seasons, particularly in summer and fall, due to increasing differences in land-ocean pressures and temperatures (Bakun 1990; Snyder et al. 2003; Auad et al. 2006; Largier et al. 2010) * No projections available for storm-related wind events |
| **Summary of Potential Impacts on Habitat** *(see text for citations)* | |
| * Increased dune erosion during more extreme wind events * Reduced plant growth due to sand burial, abrasion, and wind damage | |

### Sensitivity and current exposure to non-climate stressors

Regional experts evaluated coastal dune systems as having moderate-high sensitivity to non-climate stressors (moderate confidence in evaluation), with an overall low-moderate current exposure to these stressors within the study region (moderate confidence). Key non-climate stressors that affect coastal dune systems include invasive species, roads/highways/trails, residential and commercial development, livestock grazing, agriculture, and pollution.[[5]](#footnote-5)

Invasive species

Healthy dune ecosystems are physically and biologically dynamic habitats, and invasive plant species inhibit natural foredune movement and threaten the survival of native and rare species (Pickart & Sawyer 1998; Alpert 2016). Invasive plants are widespread in California’s coastal dune systems, particularly in the foredunes (Pickart & Sawyer 1998; HWR Engineering & Science 2010; Alpert 2016). The two invasive plant species with the greatest abundance in the vegetative foredunes are European beach grass and yellow bush lupine (native to southern and central California), which were originally introduced in the early 1900s to stabilize dunes (Pickart & Sawyer 1998). Since that time, these two species have come to dominate 83% of the 1,077 ha (4.2 mi2) of vegetated foredune area in Humboldt County (Pickart et al. 1998; Pickart & Sawyer 1998; Pickart 2013). Although it affects coastal dune systems to a lesser degree, the non-native iceplant, which was also introduced to help stabilize dunes, can also spread rapidly and outcompete native plants (Pickart 1997; Alpert 2016).

Invasive plants can substantially alter the habitat structure in coastal dune systems (Hesp 2002; Zarnetske et al. 2012; Alpert 2016). For instance, European beach grass covers dunes in a tall, dense vegetation layer held in place by deep root and rhizome systems, hindering the growth of American dunegrass (Hesp 2002; Zarnetske et al. 2012; Alpert 2016). The dense growth form and extensive rooting system of European beach grass also captures and anchors more sand compared to native vegetation, eventually causing the development of a steep, peaked foredune that is less mobile in response to wind and waves (Pickart & Sawyer 1998; Alpert 2016). In general, native plant recruitment and growth is reduced on overstabilized dunes, both on and behind the foredune area (Pickart & Sawyer 1998; Alpert 2016).

Non-native annual grasses (e.g., European hairgrass, squirreltail fescue, pampas grass [*Cortaderia jubata*]) also compete with native dune mat species and wetland vegetation in dune swales (Pickart & Sawyer 1998; HWR Engineering & Science 2010; Office of National Marine Sanctuaries 2014; Alpert 2016). Stabilized dune forests have been invaded primarily by English ivy (*Hederal helix*), resulting in smothering of the understory and increased blowdown of trees (HWR Engineering & Science 2010; Vuln. Assessment Reviewer, pers. comm., 2018).

Several wildlife species and domestic or feral animals may also be problematic in coastal dune systems, including gulls, ravens, foxes, coyotes, dogs, feral cats, skunks, and raccoons; most of these are associated with human activity, particularly within the wildland-urban interface (Campbell 2013). Although these species can impact the native plant and animal communities within coastal dune systems in a variety of ways, they have particularly large negative impacts on shorebird species, such as the western snowy plover (*Charadrius alexandrinus nivosus*) (Campbell 2013).

Roads, highways, and trails

Roads, highways, and trails have eliminated, displaced, or degraded many dune habitats across the region, causing habitat fragmentation, reduced dune mobility, and barriers to the movement and foraging activity of dune wildlife (Alpert 2016; Vuln. Assessment Workshop, pers. comm., 2017). As sea level rises, roads and road maintenance activities may also impede the sand movement necessary for inland habitat migration (Feagin et al. 2005; Schlacher et al. 2007; Alpert 2016).

Illegal off-road vehicle (ORV) use, in particular, is an ongoing threat in some northern California coastal dune systems (Vuln. Assessment Workshop, pers. comm., 2017). Intense use of ORVs can compact soils, create gullies that alter hydrologic patterns, and increase erosion, dust emissions, and noise impacts on wildlife and humans (Stokowski & LaPointe 2000). Both herbaceous and shrubby perennial vegetation in dune habitats are greatly reduced in areas where ORVs operate (Luckenbach & Bury 1983).

Residential and commercial development

Residential and commercial development has eliminated dune habitat throughout coastal California and contributed to the alteration of remnant habitat via stabilization by non-native plants (Alpert 2016). Most of remaining intact dune systems along the California coast are located in federal, state, or local preserves (Alpert 2016), and the California Coastal Act of 1976 (Cal. Stat. 16 § 1451-1464) precludes future development in these areas. However, localized development threats still exist in adjacent areas (Vuln. Assessment Workshop, pers. comm., 2017). In response to increasing development and beach erosion associated with rising sea levels, coastal armoring may become more common in northern California (Vuln. Assessment Reviewer, pers. comm., 2018). Both development and associated armoring structures (e.g., seawalls, jetties, revetments) are likely to constrain future dune migration (Titus 1986; Feagin et al. 2005; Schlacher et al. 2007; Dugan et al. 2008; Alpert 2016).

Livestock grazing, agriculture, and pollution

Coastal California has a long history of livestock grazing, much of it supporting the dairy industry (Gordon 2000; Chiniewicz 2015). In northern California, some coastal dune systems are located adjacent to active livestock operations in coastal grasslands (CDFW 2015), and there are many abandoned pastures in the transition area between semi-stabilized dunes and beach pine forests (Green 1999; Gordon 2000; Chiniewicz 2015). Livestock grazing can destabilize dune habitats, and vegetation trampling can extirpate local plant populations (EPIC 2014; Alpert 2016). Additionally, water diversions for livestock reduce in-stream flow levels, which may exacerbate declining summer flows under future climate conditions and negatively impact water supply and quality within coastal areas (CDFW 2015). Finally, abandoned livestock fencing can impede wildlife movement, as seen in Del Norte County by the presence of wild elk in a former cattle grazing area following removal of livestock (EPIC 2014).

Even where no grazing occurs in coastal dunes, livestock operations can increase sediment, nutrient, and pesticide pollution in coastal streams and wetlands, degrading water quality and potentially causing the loss of fish and wildlife (Vuln. Assessment Workshop, pers. comm., 2017). Other sources of pollution in coastal dune aquatic systems include agricultural and commercial activities within the watershed (Beman et al. 2005; Defeo et al. 2009), which can carry pollutants such as fecal bacteria into coastal dune systems through river discharges and storm drains (Dorsey 2010). However, coastal dune wetlands have shown the capacity to reduce pollution levels in coastal dune systems by filtering runoff and reducing fecal bacteria levels (Dorsey 2010).

Sediment and nonpoint source runoff from nearby wildfire-impacted areas can also impact coastal dune systems (Morrison & Kolden 2015). For example, in freshwater streams that flow through coastal areas, severe wildfire can increase the amount of sediment (e.g., total suspended solids) and nutrients (e.g., phosphorus, nitrogen; (Spencer & Hauer 1991; Hauer & Spencer 1998; Stein et al. 2012; Warrick et al. 2012; Coombs & Melack 2013; Morrison & Kolden 2015). Finally, atmospheric nitrogen pollution may play a role in altering growing conditions for native dune plants (Jones et al. 2004). Higher levels of atmospheric nitrogen deposition can impact dune vegetation by raising nitrogen loads in soil, increasing vegetative growth and accumulation of organic matter, and accelerating soil development, which may lead to a decline in foredune plant species richness (Jones et al. 2004).



Adaptive Capacity

Coastal dune systems were evaluated by regional experts as having low-moderate overall adaptive capacity (high confidence in evaluation).

### Habitat extent, integrity, continuity, and permeability

Regional experts evaluated mobile/semi-stable coastal dunes as having a moderate-high geographic extent (moderate confidence in evaluation), low-moderate structural and functional integrity (high confidence), and low-moderate continuity (high confidence). By contrast, stabilized forested dunes were evaluated as having a low geographic extent (high confidence in evaluation), low structural and functional integrity (moderate confidence), and low continuity (high confidence).

Landscape permeability for coastal dune systems overall was evaluated as low-moderate (high confidence). Land-use conversion, roads/highways/trails, invasive species, agriculture, geologic features (tectonic), and coastal armoring (e.g., seawalls, jetties, dikes, older riprap structures) were identified as the primary barriers to habitat continuity and dispersal across the study region.[[6]](#footnote-6)

The extent of coastal dune systems is limited by their location between the dynamic beach and more stable landward habitats that are less affected by coastal dynamics (Wiedemann 1984; Alpert 2016). Changes in the areal extent and connectivity of semi-stable dunes under climate change will be driven by sea level rise, storm surge flooding, and seasonal erosion/accretion patterns as well as sand availability, plant species composition (including the presence of invasive species), and management activities (Seabloom et al. 2013; Alpert 2016). Altered dune morphology, in particular, can hinder the dunes’ ability to buffer against extreme high tides and storm surge, especially where the foredune is overstabilized by invasive plant species or coastal armoring (Vuln. Assessment Workshop, pers. comm., 2017).

Dune areas that are blocked by development or infrastructure may be lost to rising sea levels (Titus 1986; Feagin et al. 2005; Schlacher et al. 2007; Alpert 2016). Stabilized dunes that support coastal dune forests are not likely to migrate landward in response to sea level rise, and these forests are vulnerable to substrate erosion or sand burial with changes in storm frequency or severity, flooding, and sea level rise (Vuln. Assessment Reviewer, pers. comm., 2018). Some of the component species (e.g., Sitka spruce) are likely to populate habitat areas farther inland (Vuln. Assessment Reviewer, pers. comm., 2018; CNPS 2019).

### Habitat diversity

Regional experts evaluated coastal dune systems as having moderate-high physical and topographical diversity (moderate confidence in evaluation), moderate-high component species diversity (moderate confidence), and moderate functional diversity (moderate confidence).

Coastal dune systems comprise a heterogeneous landscape of sand- or herbaceous-dominated dunes, swales with wetland vegetation or small water bodies, and forests (Wiedemann 1984; Gordon 2000; Alpert 2016). The foredune areas are vegetated with native and introduced dune grasses and/or herbaceous dune mats composed of a variety of species, including sand verbena, silver beachweed, coastal sage-wort (*Artemisia pycnocephala*), seashore bluegrass (*Poa douglasii*), and beach pea (*Lathyrus littoralis*), among others (Wiedemann 1984; Pickart & Barbour 2007; CNPS 2019). Dune mats transition through multiple phases depending on successional stage; for example, two distinct associations of dune mat are distinguished according to the presence of coastal sage-wort or seashore bluegrass and beach pea (Pickart & Barbour 2007).

Several federally endangered or threatened plant species are limited to coastal dunes in California (Alpert 2016; CDFW 2018; CNPS 2019), including Menzies’ wallflower (*Erysimum menziesii)*, beach layia (*Layia carnosa)*, Howell’s spineflower (*Chorizanthe howellii*),and Tidestrom’s lupine (*Lupinus tidestromii*;U.S. Fish and Wildlife Service 1998). Semi-stable coastal dunes in northern California have also been extensively invaded by European beach grass, iceplant, yellow bush lupine, and annual grasses (e.g., European hairgrass and squirreltail fescue; Pickart & Sawyer 1998).

The oldest, most stabilized dunes in the region support small patches of forest dominated primarily by beach pine, and are usually located near river mouths and bays or on broad sea-cut terraces (Wiedemann 1984). Other species associated with beach pine forests include grand fir, Sitka spruce, bishop pine, Douglas-fir, western hemlock, and Pacific madrone (Green 1999; Alpert 2016; CNPS 2019). The understory of these forests includes lichens, mosses, and shrubs such as salal, evergreen huckleberry, and silk tassel (Green 1999). Dense pockets of moss and lichens also occur (HWR Engineering & Science 2010; Villella & Carlberg 2012), and may include two rare lichens, *Bryoria spiralifera* and *B. pseudocapillaris* (Glavich 2003). Dune forests in northern California may serve as refugia for more cold-acclimated plant species as highlighted by the recent discovery of little prince’s pine (*Chimaphila menziesii*) at Mal-l’el, Lanphere, and Tolowa Dunes, a plant that is usually found at higher elevations (Canter 2012; EPIC 2014). The Port Arena area marks a transition point for coastal dune communities; to the south, stabilized dunes are generally dominated by coastal scrub vegetation rather than forest (Vuln. Assessment Reviewer, pers. comm., 2018).

Coastal dune systems also support diverse fauna, including mammals, birds, and pollinators (Wiedemann 1984). Approximately 40 species of bees occur in the Humboldt Bay area, some of which are unique to the dunes (Gordon 2000; Nyoka 2004). Many birds utilize coastal dune systems, including northern harrier (*Circus cyaneus*), white-tailed kite (*Elanus leucurus*), and Swainson’s thrush (*Catharus ustulaus*) as well as the federally and state-listed western snowy plover (Wiedemann 1984; HWR Engineering & Science 2010; Alpert 2016). Flying mammals in the area may include the big brown bat (*Eptesicus fuscus*), California myotis (*Myotis californicus*), and Yuma myotis (*Myotis yumanensis*; (HWR Engineering & Science 2010). In addition, northern elephant seals (*Mirounga angustirostris*) reproduce and molt in coastal dune systems (Hückstädt 2015).

### Resistance and recovery

Regional experts evaluated mobile/semi-stable coastal dunes as having low-moderate resistance to climate stressors and natural disturbance regimes (high confidence in evaluation), while recovery potential was evaluated as low (high confidence). For stabilized forested dunes, resistance and recovery were both evaluated as low (high confidence).

In general, coastal dune species evolve in a high-disturbance environment (Wiedemann 1984; Alpert 2016). Semi-stable dune species face exposure to multiple stressors and disturbances in daily and yearly cycles, including desiccating winds, salt spray, sand burial, and/or water table fluctuations (Wiedemann 1984; Alpert 2016). However, climate change will likely bring more extreme conditions than these species have currently evolved to withstand (Cayan et al. 2009; Alpert 2016). Small habitat patches, in particular, may be more vulnerable to high-intensity disturbances compared to larger, more continuous areas (Forman 1995). In addition, the range of niches available for vegetation establishment has been reduced by invasive plants, which build and anchor the foredunes by trapping sand, reducing habitat heterogeneity, and hindering wetland creation (Pickart 1997; Alpert 2016). In some areas, European searocket appears to quickly recolonize following erosion events and then support the establishment of native species, which could become increasingly important in maintaining habitat quality (Vuln. Assessment Reviewer, pers. comm., 2018). However, in other areas searocket establishment may lead to overstablization of dunes (McGraw et al. 2017).

Coastal dune systems have low resistance to the impacts of sea level rise, and many areas will likely be inundated or lost due to dune armoring by invasive species and/or development (NHE 2015; Alpert 2016; Laird 2018). Since many dune plant species have drought-resistant characteristics and wind-dispersed seeds, there is the potential for them to migrate across the landscape as conditions such as soil texture, nutrient and water availability, and wind exposure change (Green 1999; Alpert 2016). However, migration could be slowed or eliminated if flooding becomes too frequent or development blocks landward movement (NHE 2015; Alpert 2016; Laird 2018). Plant species on the edge of their existing ecological range are particularly likely to be impacted by these factors (Vuln. Assessment Reviewer, pers. comm., 2018). Additionally, stabilized dune forests are unlikely to migrate because this habitat develops *in situ* on dune systems (Pickart & Sholars 2016; Vuln. Assessment Reviewer, pers. comm., 2018; CNPS 2019). For instance, beach pines are characteristic of sandy substrates and would likely not establish inland of dunes (CNPS 2019).

### Management potential

#### Public and societal value

Regional experts evaluated coastal dune systems as having moderate public and societal value (moderate confidence in evaluation).

Although the general public appreciates coastal dune systems for recreation and nature viewing, they may not be aware of the many other benefits provided by dune systems (Alpert 2016; Vuln. Assessment Workshop, pers. comm., 2017). For example, coastal dune systems provide important benefits such as protection from flooding and inundation, habitat for pollinators and wetland species, and connectivity for terrestrial and aquatic species moving across the landscape (Alpert 2016; Vuln. Assessment Workshop, pers. comm., 2017).

Coastal dune systems contain important ecocultural areas for northern California tribes (HWR Engineering & Science 2010; Chiniewicz 2015; Long et al. 2018), including access to riverine and beach areas to harvest fish, mollusks, and seaweed (Sloan & Hostler 2014; Chiniewicz 2015; Alpert 2016; Vuln. Assessment, pers. comm., 2017). Coastal tribes also use a broad array of natural resources from this habitat, including many types of berries, mushrooms, roots, fibers, medicines, and waterfowl (Loud 1918; Sloan & Hostler 2014; Vuln. Assessment Workshop, pers. comm., 2017; Vuln. Assessment Reviewer, pers. comm. 2018).

Management capacity and ability to alleviate impacts[[7]](#footnote-7)

Regional experts evaluated the potential for reducing climate impacts on coastal dune systems through management as low-moderate (high confidence in evaluation). Off-road recreation was identified as a possible use conflict and/or competing interest for coastal dune systems (Vuln. Assessment Workshop, pers. comm., 2017).

Because coastal dune systems face multiple threats, addressing anthropogenic stressors is an important component of building the adaptive capacity of this habitat in the face of climate change (Alpert 2016). Actions that address non-climate stressors may include removing invasive species to protect remaining dunes (Pickart & Sawyer 1998), mitigating the impacts of livestock and legacy fencing, and managing development on adjacent land (Alpert 2016; Vuln. Assessment, pers. comm. 2017). Generally, focusing eradication and management efforts on intact native dune plant and wildlife communities is likely to allow the most efficient use of limited resources (Alpert 2016).

Significant efforts have been made in the last few decades to restore native vegetation and natural dune processes in northern California dune systems, focusing primarily on the removal of invasive plants, especially European beach grass, iceplant, and yellow bush lupine (Pickart & Sawyer 1998; Pickart 2013). Revegetation is not required following the removal of invasive species, as native dune species are quickly recruited from nearby sources (Pickart & Sawyer 1998). In fact, the physical disruption associated with manual or mechanical removal can increase the abundance of early successional species such as the endangered beach layia (Pickart & Sawyer 1998). Currently, a 5-year study is underway to determine the planting composition that best optimizes sand transport and facilitates landward and upward migration of an intact foredune (Pickart 2018).

Managing livestock impacts both within and adjacent to coastal dune systems is another strategy to maintain habitat quality (Wolf et al. 2017; Vuln. Assessment Workshop, pers. comm., 2017). However, conflict between livestock grazers, recreational users, and land management agencies may perpetuate poor livestock management practices and increase development pressure due to conflicts over land use (Wolf et al. 2017). Land managers and livestock grazers in California have started to collaborate on public education efforts designed to reduce conflict between livestock management practices and recreational users (Resnik et al. 2006; Plieninger et al. 2012; Wolf et al. 2017).

Managing development activities on adjacent lands will help maximize the connectivity and areal extent of coastal dune systems, potentially allowing dune migration as sea level rises (Alpert 2016; Vuln. Assessment Workshop, pers. comm., 2017). Understanding where development, roads, infrastructure, and coastal armoring reduce dune extent or constrain migration on adjacent properties will be important in setting priorities to prevent future losses (Feagin et al. 2005; Schlacher et al. 2007). It is also critical to understand how large-scale sedimentation processes will alter coastal dune habitat as sea level rises (Vitousek et al. 2017b; Heady et al. 2018; Laird 2018). Unlike other areas of the state, beach nourishment is not regularly used to protect dune communities in northern California (Pendleton et al. 2012), and there are adverse ecological impacts on flora and fauna attributed to this practice (Speybroeck et al. 2006).

Finally, incorporating traditional ecological knowledge into coastal management activities through collaborations with tribal and non-tribal partners can allow land managers to better address multiple priorities (Sloan & Hostler 2014; Chiniewicz 2015; Norgaard et al. 2016). In a recent survey given at the Wiyot Table Bluff Reservation, 100% of respondents thought that sea level rise and climate change are threats that the Wiyot Tribe should address through adaptation and mitigation planning and action (Vuln. Assessment Reviewer, pers. comm., 2018; WNRD 2018). Currently, the Wiyot Tribe is co-managing a relic geophyte garden at the Humboldt Bay National Wildlife Refuge Ma-l’el Dunes Unit, where non-native annual grasses and woody vegetation encroachment are threatening to exclude important ecocultural food bulbs (Vuln. Assessment Reviewer, pers. comm., 2018).

#### Ecosystem services

Coastal dune systems provide a variety of ecosystem services, including:

* Provisioning of food/fiber (cultural), genetic resources (rare plants), and natural medicines;
* Regulation of air quality and climate/microenvironments, flood/erosion control, water purification, pollination, natural hazard regulation, and carbon sequestration;
* Support of insect production, oxygen production, and soil formation/retention;
* Wildlife habitat, including grazing areas and habitat for migrating species; and
* Cultural/tribal uses for spiritual/religious purposes, knowledge systems, educational values, aesthetic values, social relations, sense of place, cultural heritage, inspiration, and recreation (e.g., day use, camping, nature viewing, etc.; Sloan & Hostler 2014; Chiniewicz 2015; Alpert 2016; Vuln. Assessment Workshop, pers. comm., 2017).

Some ecosystem services are also provided by particular habitat niches within coastal dune systems (i.e., dunes, wetlands, forests). For example, foredune areas protect inland habitat components from the impacts of storm surge, flooding, high wind events, and, to some extent, sea level rise, and wetlands provide ornamental resources, water cycling, and nutrient cycling (Sloan & Hostler 2014; Chiniewicz 2015; Alpert 2016; Vuln. Assessment Workshop, pers. comm., 2017).



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Further information on the Northern California Climate Adaptation Project is available on the project website (<https://tinyurl.com/NorCalAdaptation>).



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***Northern California Climate Adaptation 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 (EcoAdapt 2014a; EcoAdapt 2014b; Kershner 2014; Hutto et al. 2015; Gregg 2018),[[8]](#footnote-8) and includes evaluations of relative vulnerability by local and regional stakeholders who have detailed knowledge about and/or expertise in the ecology, management, and threats to focal habitats, species groups, individual species, and the ecosystem services that these resources provide. Stakeholders evaluated vulnerability for each resource by discussing and answering a series of questions for sensitivity and adaptive capacity. Exposure was evaluated by EcoAdapt using projected future climate changes from the scientific literature. 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 six elements for adaptive capacity. Elements for each vulnerability component are described in more detail below.

In-person workshops were held in Eureka, Redding, and Upper Lake between May and October 2017. Participants self-selected habitat and species group/species breakout groups and evaluated the vulnerability of each resource. Participants were first asked to describe the habitat and/or to list the species to be considered in the evaluation of an overarching species group. Due to limitations in workshop time and participant expertise, multiple resources were not assessed during these engagements. Evaluations for remaining habitats, species groups, and species were completed by contacting resource experts.[[9]](#footnote-9)

Stakeholders assigned one of five rankings (High, Moderate-High, Moderate, Low-Moderate, or Low) for sensitivity and adaptive capacity. EcoAdapt assigned rankings for projected future climate exposure. 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 were 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 because the uncertainty about the magnitude and rate of future change is greater. Sensitivity, adaptive capacity, and exposure scores were combined into an overall vulnerability score calculated as:

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

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 (2012) 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, from these rankings, estimates the overall level of confidence for each component of vulnerability and then for overall vulnerability.

Stakeholders and decision-makers can consider the rankings and scores presented as measures of relative vulnerability and confidence to compare the level of vulnerability among the focal resources evaluated in this project. Elements that received lower confidence rankings indicate knowledge gaps that applied scientific research could help address.

**Vulnerability Assessment Model Elements**

*Sensitivity & Exposure (Applies to Habitats, Species Groups, Species)*

* **Climate and Climate-Driven Factors:** e.g., air temperature, precipitation, freshwater temperature, soil moisture, snowpack, extreme events: drought, altered streamflows, etc.
* **Disturbance Regimes:** e.g., wildfire, flooding, drought, insect and disease outbreaks, wind
* **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 water flow regimes, shifts in vegetation types)
* **Stressors Not Related to Climate:** e.g., tectonic and volcanic events; residential or commercial development; agriculture and/or aquaculture; roads, highways, trails; dams and water diversions; invasive and other problematic species; livestock grazing; fire suppression; timber harvest; mining; etc.

*Sensitivity & Exposure (Applies to Species Groups and Species)*

* **Dependencies:** e.g., dependencies on sensitive habitats, specific prey or forage species, and the timing of the appearance of these prey and forage species (concern for mismatch)

*Sensitivity & Exposure (Applies to Species ONLY)*

* **Life History:** e.g., species reproductive strategy, average length of time to reproductive maturity

*Adaptive Capacity (Applies to Habitats, Species Groups, Species)*

* **Extent, Integrity, and Continuity/Connectivity:** e.g., resources that are widespread vs. limited, structural and functional integrity (e.g., degraded or pristine) of a habitat or health and functional integrity of species (e.g., endangered), isolated vs. continuous distribution
* **Landscape Permeability:** e.g., barriers to dispersal and/or continuity (e.g., land-use conversion, energy production, roads, timber harvest, etc.)
* **Resistance and Recovery:** e.g., *resistance* refers to the stasis of a resource in the face of change, *recovery* refers to the ability to “bounce back” more quickly from the impact of stressors once they occur
* **Management Potential:** e.g., ability to alter the adaptive capacity and resilience of a resource to climatic and non-climate stressors (societal value, ability to alleviate impacts, capacity to cope with impacts)
* **Ecosystem Services:** e.g., provisioning, regulating, supporting, and/or cultural services that a resource produces for human well-being

*Adaptive Capacity (Applies to Habitats ONLY)*

* **Habitat Diversity:** e.g., diversity of physical/topographical characteristics, component native species and functional groups

*Adaptive Capacity (Applies to Species Groups, Species)*

* **Dispersal Ability**: i.e., ability of a species to shift its distribution across the landscape as the climate changes
* **Intraspecific/Life History Diversity:** e.g., life history diversity, genetic diversity, phenotypic and behavioral plasticity



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1. All climate and climate-driven factors presented were ranked as having a moderate or higher impact on this habitat type. [↑](#footnote-ref-1)
2. Trends in climate factors and natural disturbance regimes presented in this and subsequent summary tables are not habitat-specific; rather, they represent broad trends and future projections for the study region. The precipitation, temperature, climatic water deficit, and snowpack projections for this project are derived from the Basin Characterization Model, which uses modified Jepson ecoregions (Flint et al. 2013; Flint & Flint 2014). Projections for all other factors are based on a review of relevant studies in the scientific literature. For this project, exposure was evaluated by calculating the magnitude and direction of projected change within the modified Jepson ecoregions that include habitat distribution within the study geography. [↑](#footnote-ref-2)
3. Projections for changes in seasonal precipitation can be found at in the full climate impacts table (<https://bit.ly/2LHgZaG>). [↑](#footnote-ref-3)
4. All disturbance regimes presented were ranked as having a moderate or higher impact on this habitat type. [↑](#footnote-ref-4)
5. `Non-climate stressors presented are those ranked as having a moderate or higher impact on this habitat type; additional non-climate stressors that may influence the habitat to a lesser degree include fire suppression, recreation, and homeless populations. [↑](#footnote-ref-5)
6. All barriers presented were ranked as having a moderate or higher impact on this habitat type. [↑](#footnote-ref-6)
7. Further information on climate adaptation strategies and actions for northern California can be found on the project page (<https://bit.ly/31AUGs5>). [↑](#footnote-ref-7)
8. Sensitivity and adaptive capacity elements were informed by Lawler 2010, Glick et al. 2011, and Manomet Center for Conservation Sciences 2012. [↑](#footnote-ref-8)
9. Resources evaluated by experts included: coastal bluff/scrub habitats, coastal conifer hardwood forest, true fir forest, lakes/ponds, freshwater marshes, vernal pools, seeps/springs, native insect pollinators, native ungulates, salamanders, frogs, native mussels, marbled murrelet, and northwestern pond turtle. [↑](#footnote-ref-9)