Coastal Dunes

Climate Change Vulnerability Assessment for the Golden Gate Biosphere Region

This document represents an evaluation of climate change vulnerability for coastal dunes in the Golden Gate Biosphere (GGB) region of California. The following information is based on stakeholder input provided during and following a winter 2022 vulnerability workshop as well as sources from the scientific literature.

Ecosystem Description

Coastal dune ecosystems within the Golden Gate Biosphere (GGB) region extend from San Mateo County northwards through Sonoma County, with notable sites occurring at Gazos Creek Beach, Pescadero State Beach, Dunes Beach at Half Moon Bay, Fort Funston, Ocean Beach, the Presidio, Golden Gate Heights in San Francisco, Limantour Beach and Abbotts Lagoon at Point Reyes National Seashore, Dillon Beach, and Bodega Dunes (Vuln. Assessment Worksheets, pers. comm., 2022). Dunes are formed from unconsolidated sand from coastal bluffs and watersheds, and are strongly impacted by wind and waves that move sand inland from the beach, as well as land-use change, management activities, and other marine and terrestrial processes that impact sand movement and vegetation development (Pickart & Barbour 2007; Wiedemann & Pickart 2008; Alpert 2016; Pickart & Hesp 2019). Coastal dune systems range from mobile foredunes to semi- or fully-stabilized dunes dominated by dune grasses and, eventually, later-successional coastal scrub vegetation (Alpert 2016) and oak woodlands (Vuln. Assessment Worksheets, pers. comm., 2022). Vegetation is characterized by species tolerant of harsh conditions, including low nutrient availability, high water drainage, salt spray, wind desiccation, and periodic erosion and burial by windblown sand (Pickart & Barbour 2007; Wiedemann & Pickart 2008; Alpert 2016). Foredune plant communities include native dune grasses such as American dunegrass (*Elymus mollis*), though many have been extensively colonized by non-native species, including European beach grass (*Ammophila arenaria*; Pickart & Sawyer 1998; Alpert 2016). Notable threatened and endangered plants include beach layia (*Layia carnosa*), San Francisco lessingia (*Lessingia germanorum*), and Tidestrom's lupine (*Lupinus tidestromii*), which are disturbance-dependent species that have been significantly impacted by habitat loss and competition with invasive species (USFWS 1991, 2003, 2009). Coastal dune systems also provide habitat for a variety of wildlife species, including shorebirds, mammals, and pollinators (Wiedemann 1984; Hutto et al. 2015; Alpert 2016).

Fine-scale vegetation maps for San Mateo, Marin, and Sonoma Counties were used to identify seven vegetation classes that generally represent coastal dunes within the GGB region (Tukman Geospatial et al. 2018), which occupy a combined total of 5,780 acres (Figure 1, Table 1). Of that, 84% (4,858 acres) is protected, with the largest area of protected lands managed by the National Park Service at Point Reyes National Seashore (3,896 acres; Table 2).

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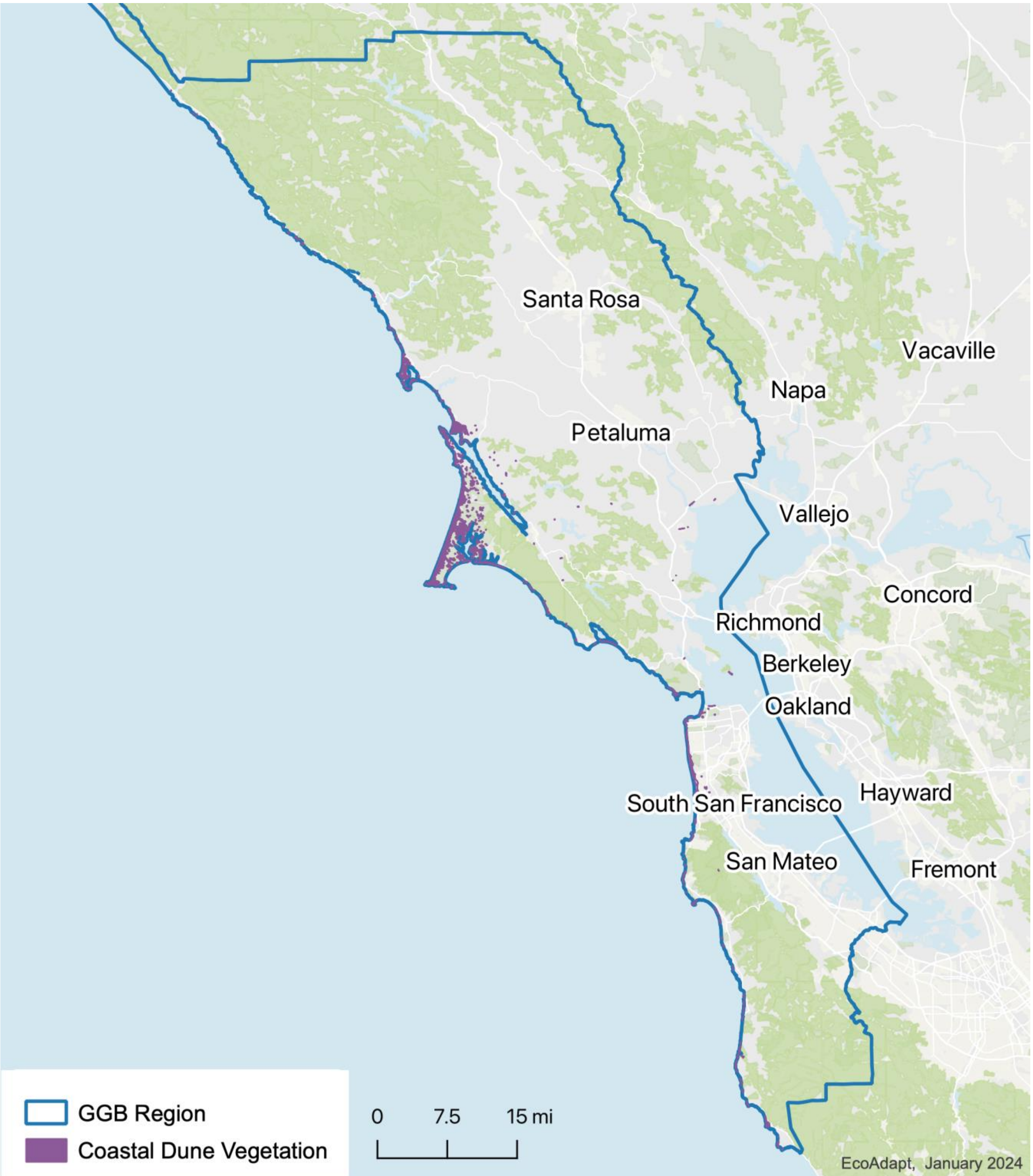

Figure 1. Distribution of vegetation map classes that likely represent coastal dune communities within the GGB region, derived from fine scale vegetation maps for San Mateo, Marin, and Sonoma Counties (Tukman Geospatial et al. 2018).

Table 1. Vegetation map classes likely to represent coastal dune communities within the GGB region, derived from fine scale vegetation maps for San Mateo, Marin, and Sonoma Counties (Tukman Geospatial et al. 2018).

Vegetation Map Class
Ammophila arenaria Semi-Natural Alliance
Artemisia pycnocephala Association
Cakile (*edentula*, *maritima*) Provisional Semi-Natural Alliance
Lupinus arboreus Alliance
Lupinus chamissonis – Ericameria ericoides Alliance
Mesembryanthemum spp. – *Carpobrotus* spp. Semi-Natural Alliance
Pacific Coastal Beach & Dune Mapping Unit

Table 2. Total protected acres in the GGB region by land management agency, derived from fine scale vegetation maps for San Mateo, Marin, and Sonoma Counties (Tukman Geospatial et al. 2018).

Land Management Agency	Protected Acres
National Park Service – Point Reyes National Seashore	3,896
California Department of Parks and Recreation	562
Other protected lands	177
National Park Service – Golden Gate National Recreation Area	153
Sonoma County Regional Parks Department	44
San Mateo County Parks and Recreation Department	10
Audubon Canyon Ranch	8
California State Lands Commission	4
Peninsula Open Space Trust	2
United States Fish and Wildlife Service	2
San Francisco – Public Utilities Commission	1
California Department of Fish and Wildlife	1
TOTAL	**4,858**

Ecosystem Vulnerability → Moderate *(moderate confidence)*

Vulnerability is evaluated by considering the ecosystem's sensitivity and exposure to various climate and non-climate stressors as well as the ecosystem's adaptive capacity (i.e., ability to cope with these stressors), and is *given a ranking of low, moderate, or high. The confidence ranking represents confidence in the accuracy of the ranking based on available scientific knowledge, and is similarly ranked on a scale from low to high.*

Summary of ecosystem vulnerability

Coastal dunes are sensitive to climate stressors and disturbance regimes that alter seasonal water availability (e.g., changes in precipitation patterns) and reduce habitat extent (e.g., sea level rise, storm surge). Many of these factors also impact sediment transport and supply (e.g., altered stream flows, wind and wave action), and can have direct effects on native plant growth and survival (e.g., air temperature). Non-climate stressors such as invasive plants, land-use conversion, recreation, dredging, and sand mining have already degraded most coastal dune systems in the region by altering sediment supplies and geomorphic processes, shifting species composition, and fragmenting or eliminating habitat areas.

Coastal dune systems in the region are often limited in extent due to their position between the dynamic beach and more stable inland systems and/or developed landscapes. Intact ecosystems are well-adapted to natural disturbances and have the potential to shift inland where not backed by infrastructure. However, habitat degradation and altered natural geomorphic processes have reduced the ability of most coastal dunes to respond to rising sea levels and other climate impacts. 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.

Sensitivity and Exposure → High *(moderate confidence)*

***Sensitivity** is a measure of whether and how an ecosystem is likely to be affected by a given change in climate factors, climate-driven changes in disturbance regimes, and non-climate stressors. By contrast, **exposure** is a measure of how much change in these factors an ecosystem is likely to experience. Sensitivity and exposure are combined here into one score representing both components of vulnerability, with high scores corresponding to increased vulnerability and low scores suggesting an ecosystem is less vulnerable.*

Sensitivity and future exposure to climate factors → High *(high confidence)*

- **Sea level rise** is likely to increase rates of shoreline erosion and may inundate lower-elevation dunes, especially in conjunction with storms and strong El Niño seasons (Feagin et al. 2005; Barnard et al. 2015; Alpert 2016). Over longer time scales, erosion and flooding are likely to result in reduced areal extent and/or elimination of dune systems, though inland migration could occur where the movement of dynamic foredunes is unconstrained (Feagin et al. 2005; Largier et al. 2010; Alpert 2016; Heady et al. 2018). As erosion occurs, remaining coastal dunes are likely to become increasingly fragmented and shift towards narrower and steeper pocket beaches (Largier et al. 2010), though in some areas erosion of coastal cliffs may increase sediment deposition and help dunes keep pace with sea level rise (Hutto et al. 2015). Sea level

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rise may also impact dune vegetation by increasing saltwater inundation and salt spray impacts (Feagin et al. 2005; Russell & Griggs 2012; Alpert 2016).

- **Changes in precipitation patterns** are likely to alter the amount and timing of available water for coastal vegetation. Although dune plants are adapted to moisture stress associated with rapid soil drainage and evaporation from coarsely-textured soils (Maun 1994; Pickart & Barbour 2007; Alpert 2016), increased late-summer water stress may reduce overall growth and recruitment of native dune vegetation (Alpert 2016), particularly in combination with potential continued declines in the frequency of coastal fog (Johnstone & Dawson 2010). Drier conditions are particularly likely to limit seedling establishment and growth of plants with shallow roots (Alpert 2016). However, projected increases in winter precipitation (Flint et al. 2023) have the potential to stimulate early growth of both native and non-native plants in semi-stable dunes (Maun 1994; Sims et al. 2019). Invasive species such as European beach grass and iceplant (*Carpobrotus edulis*) are also generally better-adapted to dry conditions than native species (e.g., American dune grass; Pickart 1997; Pickart & Sawyer 1998). As a result, it is likely that future precipitation conditions may encourage increased recruitment and spread of these plants due to a combination of their competitive advantage during the summer months and tendency to spread during winters with above-average precipitation (Sims et al. 2019).
- **Altered stream flows** as a result of changes in patterns of runoff from upland areas have the potential to alter sediment delivery to coastal dune systems, particularly following heavy precipitation events (Largier et al. 2010). Trends towards more severe drought may also increase pressure for water storage projects, and dams associated with these projects can significantly impact the supply and transport of replenishing sediments carried by streams to dune ecosystems (Slagel & Griggs 2008; Vuln. Assessment Worksheets, pers. comm., 2022).
- I**ncreasing air temperatures** have the potential to impact coastal dune vegetation, which experiences low variation in annual temperatures (Compagnoni et al. 2021). A modeling study of the endangered clover lupine at Point Reyes National Seashore found that average annual temperature increases of 1°C (1.8°F) would result in a 90% reduction in the number of individuals, largely as a result of reduced survival (Compagnoni et al. 2021). Studies in Mediterranean dune systems in the European Union have also found shifts in foredune plant community composition towards increased thermophilic species as well as higher plant cover, likely as a result of increases in average annual temperatures (Del Vecchio et al. 2015).

Sensitivity and future exposure to climate-driven changes in disturbances → High *(high confidence)*

- **Changes in the frequency and/or severity of storms and associated wind and waves** are likely to accelerate dune erosion and inundation, in conjunction with rising sea levels (Hutto et al. 2015; Alpert 2016). This is particularly likely during severe El Niño years such as occurred in the winter of 2015–16, when storms in the Bay Area increased wave action by 50% and resulted in significant coastal erosion (Barnard et al. 2017). Extreme storms that coincide with king tides can also cause severe erosion to dune systems (Russell & Griggs 2012; Alpert 2016), as can "bomb cyclones" (large storms associated with very rapid intensification as atmospheric pressure drops) such as occurred in California in March 2023 (S. Hutto, pers. comm., 2023). Large waves associated with events such as these significantly increase coastal flooding, accelerating erosion and weakening of foredunes (Feagin et al. 2005; Russell & Griggs 2012; 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; Pickart & Hesp 2019). Higher storm surge is also likely to increase the intensity of salt spray in both foredune communities and farther inland in areas usually more protected from storms (Oosting 1945; Barbour & DeJong 1977).

Sensitivity and current exposure to non-climate stressors → High *(moderate confidence)*

Non-climate stressors can exacerbate ecosystem sensitivity to changes in climate factors and disturbance regimes, and/or can be exacerbated by these changes.

- **Land-use conversion** (i.e., to **residential/commercial development** and **agriculture**) and **roads** have degraded, fragmented, and eliminated coastal dune systems across the region (Reed et al. 2011; Alpert 2016). Both development and associated infrastructure (e.g., roads, coastal armoring) also increase erosion rates and limit dune mobility, playing a major role in reducing the extent of beaches and dunes and constraining inland dune migration in response to sea level rise (Feagin et al. 2005; Schlacher et al. 2007; Dugan et al. 2008; Alpert 2016). In some areas, managed retreat is already occurring (i.e., moving or abandoning infrastructure rather than continuing efforts to prevent inevitable erosion and inundation; Bragg et al. 2021). This has the potential to allow restoration of coastal dune systems, particularly in areas where they have the potential to provide significant storm protection to inland communities (Vuln. Assessment Worksheets, pers. comm., 2022; Wedding et al. 2022).
- **Invasive and/or problematic species** have significantly altered the structure and functioning of coastal dunes, inhibiting sand movement and displacing native species (Pickart & Sawyer 1998; Alpert 2016). Across the GGB region and the state, invasive plants such as European beachgrass and iceplant are widespread within coastal dune systems, particularly in the foredunes where they were originally introduced for stabilization (Pickart 1997; Pickart & Sawyer 1998; Alpert 2016). The growth pattern of these species results in dense mats of vegetation held in place by deep root systems, excluding native vegetation (Pickart & Sawyer 1998; Zarnetske et al. 2012; Alpert 2016) and contributing to the decline or extirpation of disturbance-dependent annuals (e.g., beach layia, San Francisco lessingia) and other rare plants (USFWS 1991, 2003). Invasive dune plants also anchor sand and reduce foredune mobility in response to wind and waves, causing the development of steep, peaked foredunes and limiting inland migration of the system (Pickart & Sawyer 1998; Zarnetske et al. 2012; Alpert 2016; Pickart & Hesp 2019).

Invasive plants may also have secondary effects beyond dune stabilization. For instance, European beachgrass is known to provide cover for native rats near endangered Tidestrom's lupines, which allows more successful foraging on lupine seed pods and contributes to population declines (Dangremond et al. 2010). Although bush lupine (*Lupinus arboreus*) is considered native to San Francisco Bay and points south (Cal-IPC 2022; Sholars & Riggins 2022), north of that area its nitrogen fixation and shade promotes the invasion of non-native annual grasses that exclude native species (Pickart et al. 1998).

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).

- **Recreational activity** (e.g., foot traffic, off-road vehicles) contribute to vegetation loss and increased erosion via trampling in coastal dunes (Schlacher et al. 2007; Largier et al. 2010). Off-road vehicles, in particular, are known to reduce herbaceous and shrubby perennial vegetation in dunes (Luckenbach & Bury 1983). Recreational activity can also disturb or reduce habitat quality for wildlife (Hutto et al. 2015), and has been documented as a contributing factor in reduced shorebird nesting success due to direct disturbance of nesting birds as well as increased populations of nest predators (e.g., corvids) that are attracted to garbage and other food sources (Hardy & Colwell 2012; Schlacher et al. 2013). Trash accumulating within and around dune habitats as a result of recreational use can impact wildlife through entanglement, ingestion, or smothering (Hutto et al. 2015). Although there is some concern that growing populations and increased inland air temperatures may result in greater recreational pressure on dune ecosystems, recreational opportunities in these areas are also a critical factor in maintaining stewardship support (Vuln. Assessment Worksheets, pers. comm., 2022).
- **Dredging** and **sand mining** alter ecosystem sediment dynamics, and have a long history within the urbanized San Francisco Bay area. Over the past century, at least 200 million square meters of sediment has been removed from the San Francisco Bay Coastal System through dredging and mining, with much of that transported outside of the littoral cell (Barnard et al. 2013). For instance, the majority of dredged material in the region is disposed of in deep water in the Pacific Ocean (Barnard et al. 2013). Sediment removal through dredging and sand mining result in direct reductions in material available to replenish eroding dunes, and, more broadly, is associated with altered patterns of sediment transport, erosion, and accretion within the region (Barnard et al. 2013). These activities can also mobilize buried contaminants (e.g., heavy metals; Torres et al. 2009), which then impact plants and wildlife within affected systems (Hutto et al. 2015). Dredged materials can be used for beach nourishment projects, which have

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the potential to offset sediment losses due to erosion; however, these also have negative impacts on invertebrate communities (Hutto et al. 2015).

Adaptive Capacity → Moderate *(moderate confidence)*

***Adaptive capacity** is the ability of an ecosystem to respond to or cope with climate change impacts with minimal disruption. High adaptive capacity corresponds to lower overall climate change vulnerability, while low adaptive capacity means that the ecosystem will be less likely to cope with the adverse effects of climate change, thus increasing the vulnerability of the ecosystem.*

Ecosystem extent, integrity, and continuity → Low (moderate confidence)

Coastal dunes are naturally geographically-isolated systems, with relatively limited extent within the GGB region (Vuln. Assessment Worksheets, pers. comm., 2022). Extensive human development in coastal zones have isolated them further, creating barriers to sand movement and plant dispersal for species that do not rely on birds or ocean currents (Alpert 2016). The presence of invasive species has also degraded dune integrity through stabilization that further inhibits sand movement (Pickart & Sawyer 1998; Alpert 2016), as have other factors that alter sediment dynamics (Hutto et al. 2015). Over longer time scales, overstabilization and the presence of development adjacent to dunes may result in continued narrowing and the possible loss of dunes unable to move in response to sea level rise (Feagin et al. 2005; Alpert 2016; Heady et al. 2018).

Ecosystem diversity → Moderate (moderate confidence)

Coastal dune systems comprise a heterogeneous landscape, with relatively high physical and topographical diversity across sand- or herbaceous plant-dominated dunes, swales, and scrub or oak woodland vegetation on stabilized backdunes (Alpert 2016). They also support many specialized plant species that are adapted to a high-disturbance environment, including several federally-endangered or threatened plant species limited to coastal dunes in California (USFWS 1991, 2003; Alpert 2016). Populations of these species are often very limited due to habitat loss and dune stabilization (USFWS 1991, 2003), increasing their vulnerability to climate changes such as sea level rise and increasing temperatures (Garner et al. 2015; Compagnoni et al. 2021). For example, seven of 15 remaining populations of clover lupine are found at Point Reyes National Seashore, and a modeling study projected that all are likely to decline and four may be extirpated due to future increases in average annual temperature (Compagnoni et al. 2021). Coastal dunes also support diverse wildlife communities, including mammals, birds, and pollinators (Wiedemann 1984; Hutto et al. 2015; Alpert 2016). Shorebirds, in particular, depend on this habitat for nesting and are highly vulnerable to climate-driven habitat loss (Galbraith et al. 2014).

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Resistance and recovery → Moderate (low confidence)

Coastal dunes are naturally dynamic environments characterized by constant exposure to wind and waves, and recovery from disturbances is typically rapid for intact dunes (Hesp & Martínez 2007; Alpert 2016; Pickart & Hesp 2019; Delgado-Fernandez et al. 2019). Dune vegetation is also well-adapted to harsh conditions, including a low-nutrient substrate, airborne salt spray, strong winds and winter storms, fluctuating water tables, and erosion or burial by windblown sand (Pickart & Sawyer 1998; Wiedemann & Pickart 2008). This suggests that, with sufficient space to migrate, dune systems have the capacity to be relatively resilient to the impacts of sea level rise and other climate stressors (Vuln. Assessment Worksheets, pers. comm., 2022). However, coastal development (e.g., structures, roads) and overstabilization by invasive species reduce the ability of these systems to adapt to rising sea levels and increased coastal erosion, and are likely to result in the narrowing and eventual inundation and loss of many dune systems (Feagin et al. 2005; Alpert 2016; Heady et al. 2018). Restoration of dune ecosystems has been very successful when conducted, but in many areas endemic species on small dune parcels may be extirpated sufficient conservation actions occur (Vuln. Assessment Worksheets, pers. comm., 2022).

Management potential → Moderate (moderate confidence)

Coastal dunes are highly valued by the public for their aesthetic value and the recreational opportunities they provide, such as surfing, fishing, sunbathing, walking, and driving off-road vehicles (Alpert 2016). In the GGB region, over 84% of remaining dune systems are protected (Table 2), and public and societal support for dune conservation and restoration is likely bolstered by the critical role they play in protecting developed inland communities from storm surge and flooding (Vuln. Assessment Worksheets, pers. comm., 2022; Wedding et al. 2022). Regulatory support for these coastal dune systems comes from the Federal Coastal Zone Management Act of 1972 (16 U.S.C. § 1451) and California Coastal Act of 1976 (Division 20 of the California Public Resources Code), which limit shoreline development.

Because coastal dune systems face multiple threats, addressing anthropogenic stressors is an important component of building the adaptive capacity of these ecosystems in the face of climate change (Alpert 2016). Actions that address non-climate stressors to restore natural dune processes include removing invasive species (Pickart & Sawyer 1998) and managing development on adjacent land to allow space for inland dune migration as sea level rises (Alpert 2016). Significant efforts have been made in the last few decades to restore native vegetation and dune mobility in systems in and around the GGB region, focusing primarily on the removal of invasive plants (Pickart & Sawyer 1998; Pickart 2018; Hilgendorf et al. 2022; Parsons et al. 2023). Studies have demonstrated recovery of landward sand transport across the foredune in restored dunes (Hilgendorf et al. 2022), and the physical disruption associated with manual or mechanical removal of invasives can also increase the abundance of early-successional species, such as the endangered beach layia (Pickart & Sawyer 1998; Parsons et al. 2023). However, revegetation results following invasives removal have been somewhat mixed, with some projects finding rapid recruitment of native vegetation from nearby sources (Pickart & Sawyer 1998) and others finding continuing low levels of native plant cover and species richness even after multiple years of successful annual retreatment of invasives (Parsons et al. 2023).

Ultimately the success of these efforts is highly dependent on whether dune systems are backed by development or natural barriers (i.e., cliffs) that prevent migration or limit sediment deposition (Vuln. Assessment Worksheets, pers. comm., 2022). Managed retreat is likely to become an increasingly important adaptation strategy as rising sea levels make protecting and/or repairing infrastructure prohibitively expensive (Bragg et al. 2021), which could allow more opportunities for dune restoration and potential migration (Vuln. Assessment Worksheets, pers. comm., 2022). Beach nourishment or near-shore disposal sites for dredged materials may also bolster the adaptive capacity of beach and dune systems, and areas that are of high recreational or ecological value are likely to be prioritized for beach nourishment (Vuln. Assessment Worksheets, pers. comm., 2022). But for many of these threatened locations, there is little economic justification for intensive intervention based on their perceived level of use (Vuln. Assessment Worksheets, pers. comm., 2022).

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Further information on the Golden Gate Biosphere Region Climate Adaptation Project is available on the project page (www.ecoadapt.org/goto/GGBRClimateProject).

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