

Supporting Information for

Significant Coastal Dune Loss Challenges California's Climate Resilience and Biodiversity Goals

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Introduction

The supporting information provided here includes a detailed description of the workflow used to georeference the T-sheets (Text S1), flowcharts of the methods used to create the historical and contemporary dune inventories (Figure S1 and S3), and a catalogue of habitat types/ land-uses mapped in this study (Figure S2). The locations of site visits and workshops is also provided (Figure S4), as well as a list of organizations that participated in the workshops (Table S1). Table S2 provides details of the modes and drivers of 'habitat change' collectively classified in the inventory. Figure S5 shows the modern (2016) extent of coastal sand dunes across California and the elevation of key dune features. In contrast, Figure S6 shows the inland extent (width) of dunes lost and gained through different drivers of change over the last 165 years. Table S3 provides details of previous studies that have assessed coastal dune loss due to urban development from around the world, while Figure S7 compares long-term foredune migration rates to vertical land motion in Humboldt Bay. A historical photography showing coastal dunes on Santa Monica Beach in 1893 is also provided (Figure S8).

Text S1.

Beaches, dunes (vegetated and unvegetated), and coastal wetlands are distinguishable in T-sheets, allowing comparisons to other historical maps and recent aerial photographs, and interpretations of dune extent, type, and related changes over time. These same sources of information have been used to conduct statewide and regional-scale assessments of the historical condition of wetlands and coastal ecosystems (Clark et al., 2013; Engstrom, 2006; Grossinger et al., 2011), shoreline change rates (Hapke et al., 2006; Kratzmann, 2024), and the long-term evolution of beach–dune systems in northern California (Pickart & Hesp, 2019; Rader et al., 2018; Warrick et al., 2023).

Here, North American Datum (NAD) 1927 graticules spaced at one-minute intervals were used to digitally align the T-sheets, with an average of 11 control points used to georeference each map. The mean root-mean-square-error (RMSE) derived from these control points was 0.000049 ± 0.000030 decimal degrees (approximately 5 ± 3 m, mean $\pm$ SD) indicating low levels of distortion. The T-sheets were then reprojected to NAD 1983 (2011) using ArcGIS Pro software (version 3.2.2; Esri, Redlands, California, USA). Distinct corresponding features (i.e., road intersections, rocky outcrops, buildings) identified in contemporary aerial imagery (4-Band Imagery acquired by the National Agriculture Imagery Program, NAIP; Earth Resources Observation and Science Center, EROS, 2023) downloaded from the NOAA Data Access Viewer website (<https://coast.noaa.gov/dataviewer>) were then used to evaluate the positional accuracy of a representative sample of T-sheets ($n = 66$) from across California using five control points per map (RMSE = 8.16 ± 3.42 m). Unfortunately, every T-sheet could not be evaluated this way due to a lack of corresponding features, especially in rural areas of central and northern California with no urban centers. However, given the consistency of our approach and geographical spread of the maps that were evaluated, we believe the T-sheets can be considered broadly accurate to around 10–20 m.

In cases where T-sheets were unavailable, damaged, or insufficiently detailed, the historical locations and extents of coastal dunes were determined and/or reviewed using additional resources. This includes early aerial photographs obtained from the University of California Santa Barbara (UCSB) Library, oblique aerial images and terrestrial photographs obtained from public libraries and local historical societies, regional-scale maps of dune extent (Cooper, 1967; Zeller, 1962), historical topographic maps produced by the U.S. Coast Guard and U.S. Geological Survey (USGS), and geological maps produced by the USGS, California Geological Survey, and Dibblee Geology Center. While many of these resources were obtained in formats containing geospatial information (e.g., GeoTIFF), several maps and photographs required georectification using latitude/longitude graticules or fixed, physical features identifiable in contemporary imagery. Details on all the resources used to generate the historical dune inventory are provided in the Supporting Information (Dataset S1).

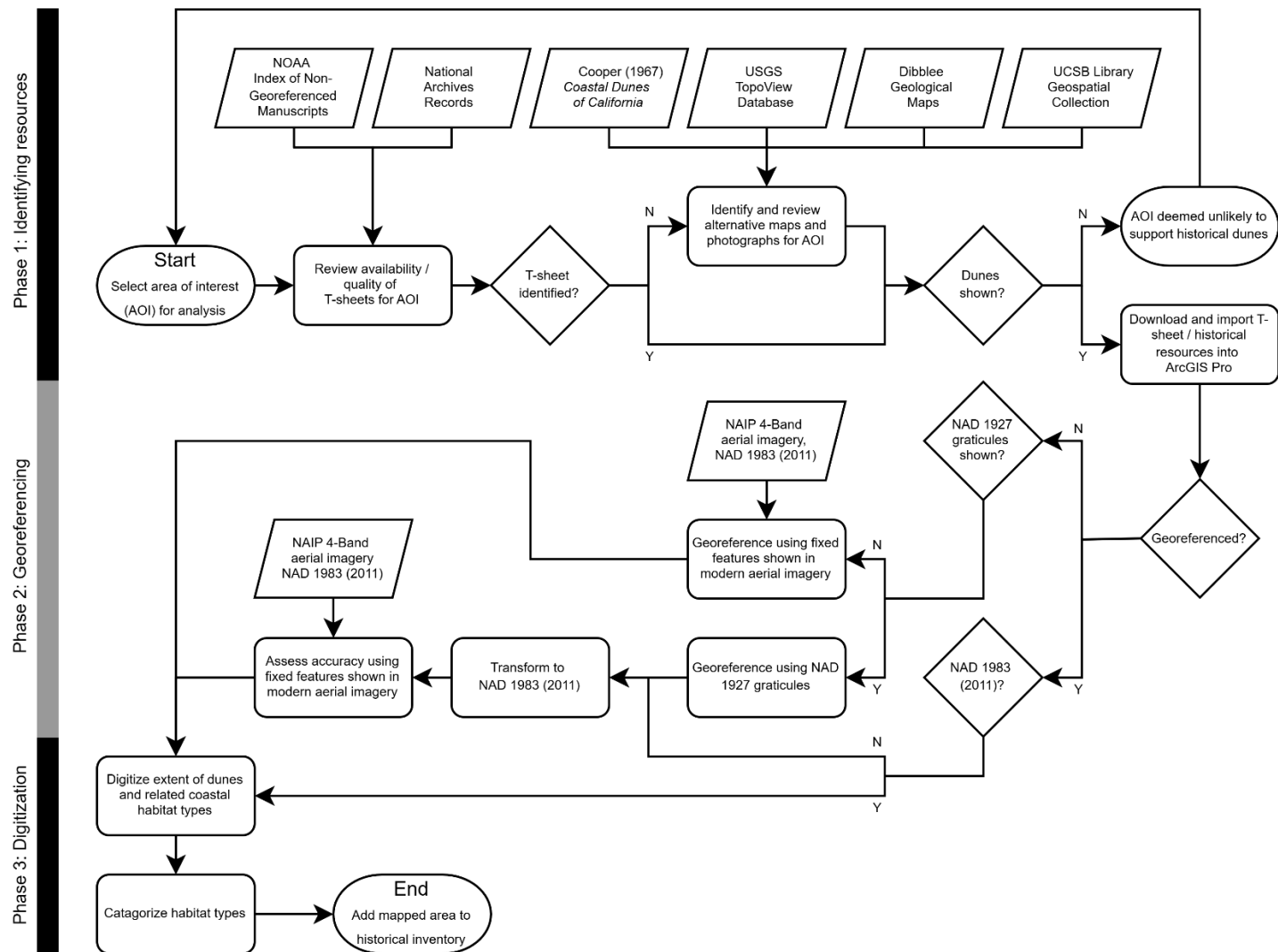


Figure S1. Workflow used to determine the historical extent of coastal dunes in California. Y = Yes, N = No.

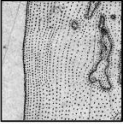
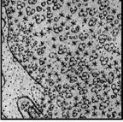
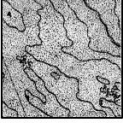
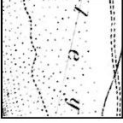
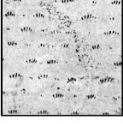
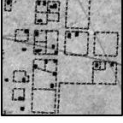
Historical Maps	Aerial Imagery	
		Beach → Dune Transitional region between beach and dune environments. Susceptible to the development of incipient dunes.
		Dune (stabilized) Dunes stabilized by vegetation growth. In the modern inventory, active, stabilized and relict dunes are collectively defined as 'Dune'.
		Dune (active) Active dunes with limited or no vegetation. In the modern inventory, active, stabilized and relict dunes are collectively defined as 'Dune'.
		Dune (relict) Dunes that formed and stabilized over 11,700 years ago during the Pleistocene. In the modern inventory, active, stabilized and relict dunes are collectively defined as 'Dune'.
		Estuary → Beach Transitional region between estuarine and beach environments. Susceptible to the development of ephemeral dunes.
		Dune → Bluff Transitional region between coastal dunes and bluffs. Susceptible to the development of climbing dunes.
		Dune → Grassland Transitional region between coastal dunes and relatively flat grassland or shrubland.
		Dune → Wetland Transitional region between coastal dunes and wetlands. Susceptible to the development of ephemeral dunes during dry periods.
		Grassland-Woodland Relatively flat grassland, shrubland and/or woodland.
		Infrastructure Developed land (i.e. roads, buildings, industry, agriculture).
		Water Bodies of water, including lakes, ponds and wetlands.

Figure S2. The eleven different habitat types that were mapped in the historical and contemporary inventories of dune extent. In the modern inventory, active, stabilized, and relict dunes were collectively categorized as 'dune'.

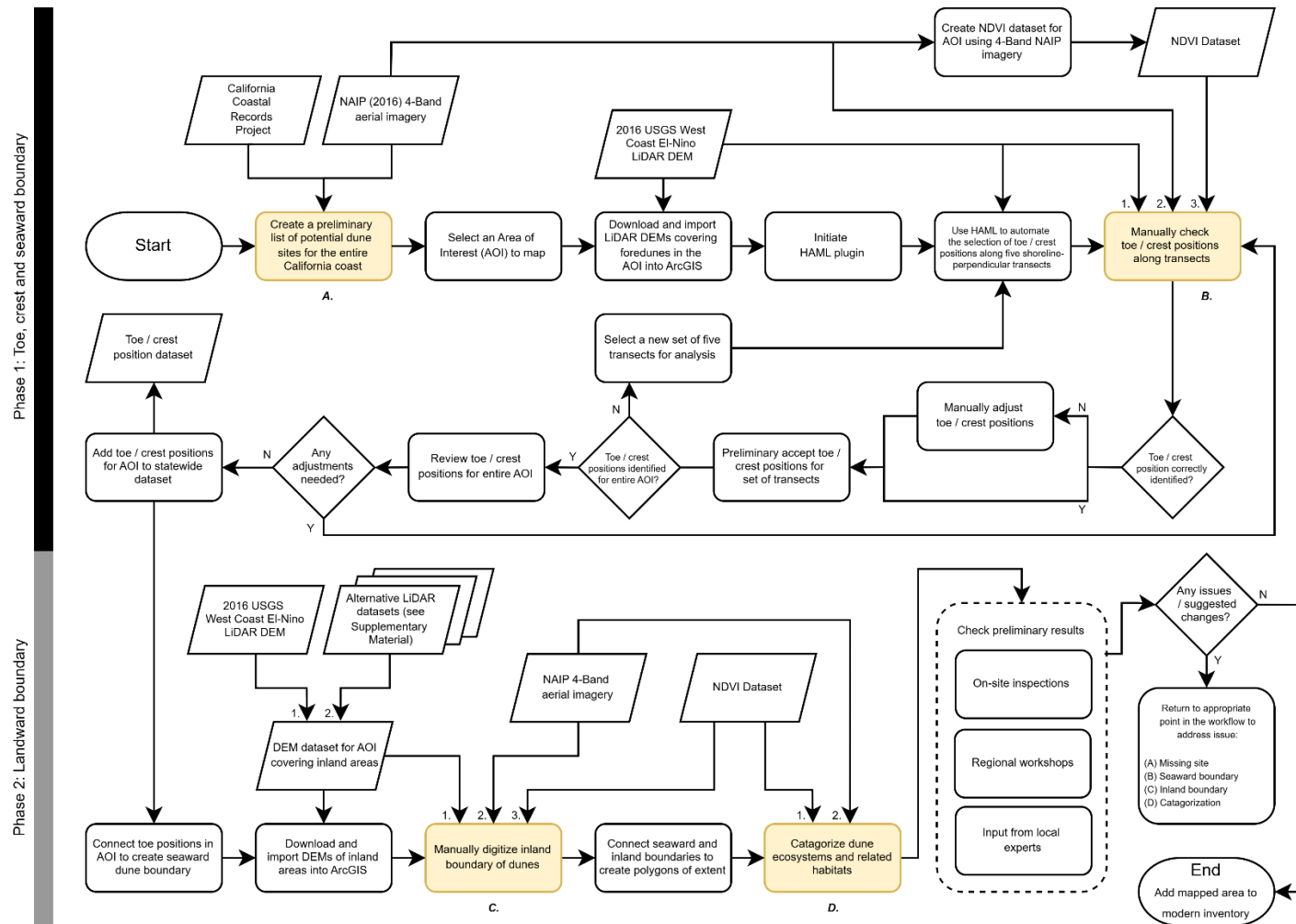


Figure S3. Workflow used to determine the modern (2016) extent of dunes. Y = Yes, N = No. Numbers indicate the order/ priority in which datasets were used to conduct a specific task. Highlighted sections (A, B, C, and D) indicate stages where edits were made in response to information gained during site-visits and workshops.

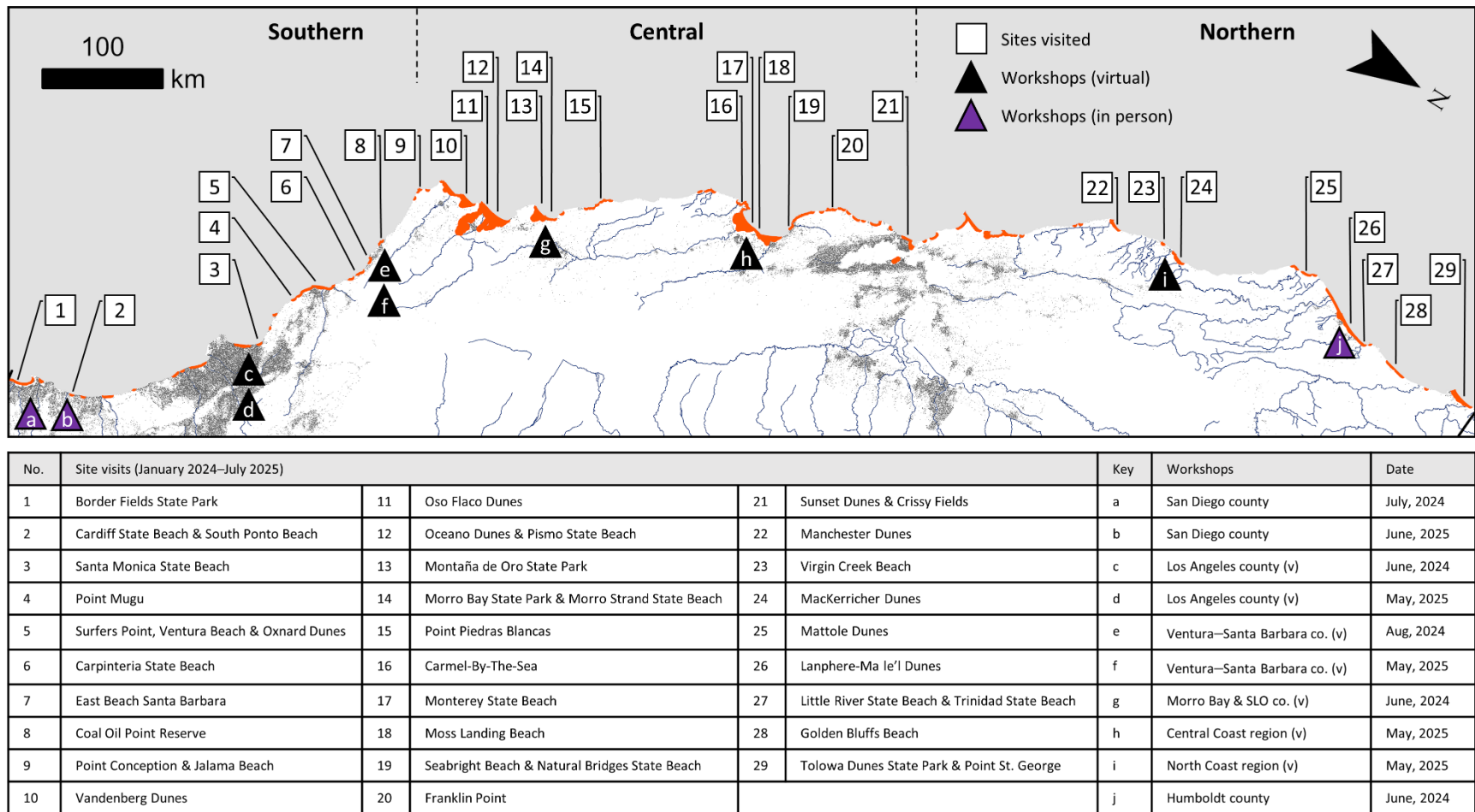


Figure S4. Preliminary results of the contemporary dune inventory were qualitatively assessed during a series of site visits conducted across the California (1–29) between January 2024 and July 2025. Feedback from practitioners and regional experts engaged in a series of in-person and online workshops (a–j) was also used to refine the inventory. The mapped extent of modern (2016) coastal dunes is shown in orange. The map is oriented from south to north (left to right). Urban centers (grey), major rivers (blue) and regional boundaries (dotted lines) are also shown.

Table S1. Location, date, and participants of regional workshops.

Workshop	Location	Date	Participants
San Diego County (1)	Scripps Institute of Oceanography & Virtual	July 18 th , 2024	California Department of Parks and Recreation Cities of Oceanside Climate Science Alliance City of Encinitas City of Imperial Beach City of San Diego San Diego Natural History Museum Rincon and GHD (consultants) Tijuana National Estuarine Research Reserve US Fish and Wildlife Service
San Diego County (2)	San Diego Natural History Museum & Virtual	June 24 th , 2025	California Department of Parks and Recreation Cities of Oceanside Climate Science Alliance City of Encinitas City of Imperial Beach City of San Diego San Diego Natural History Museum Rincon and GHD (consultants) Tijuana National Estuarine Research Reserve US Fish and Wildlife Service
Los Angeles County (1)	Virtual	June 12 th , 2024	Beach Ecology Coalition California Department of Parks and Recreation City of Malibu City of Manhattan Beach City of Santa Monica Environmental Protection Agency Region 9 Heal the Bay LA County Department of Beaches and Harbors Loyola Marymount University Santa Monica Resources Conservation District University of California Santa Barbara University of Southern California Sea Grant
Los Angeles County (2)	Virtual	May 22 nd , 2025	Beach Ecology Coalition California State Parks California State Coastal Conservancy California Coastal Commission City of Malibu City of Santa Monica Environmental Protection Agency EcoKai Environmental Friends of Ballona Wetlands Heal the Bay Los Angeles City Los Angeles World Airports Pepperdine University Resource Conservation District (Santa Monica) Sacred Places Institute for Indigenous Peoples Santa Monica Bay Restoration Commission Surfrider Foundation Selva International The Bay Foundation Tidal Influence LLC University of Southern California Sea Grant University of California Santa Barbara

Ventura–Santa Barbara co. (1)	Virtual	Aug. 22 nd , 2024	Beach Erosion Authority for Clean Oceans and Nourishment (BEACON) California State University Channel Islands California State Parks City of Carpinteria City of Oxnard City of Santa Barbara Dudek Santa Barbara County Flood Control State Coastal Conservancy Surfrider Foundation The Nature Conservancy Ventura Audubon Society
Ventura–Santa Barbara co. (2)	Virtual	May 19 th , 2025	BEACON California Coastal Commission California State Parks California State University Channel Islands Ceto Consulting City of Goleta City of Oxnard City of Santa Barbara Coastal Chumash Foundation Coastal Futures LLC County of Ventura Harbor Department Heal the Ocean Naval Base Ventura County Santa Barbara Airport Santa Barbara County Flood Control State Coastal Conservancy Surfrider Foundation U.S. Geological Survey University of California Santa Cruz University of California Santa Barbara US Fish and Wildlife Service
Morro Bay and SLO county	Virtual	June 6 th , 2024	California Conservation Corps Coastal San Luis Resource Conservation District Guadalupe-Nipomo Dunes Center Morro Bay National Estuary Program State Parks Oceano and Morro Bay
Central Coast region	Virtual	May 27 th , 2025	California Coastal Commission California Central Coast Joint Venture California Department of Parks and Recreation California Department of Fish and Wildlife California Marine Sanctuary Foundation California State Parks - Monterey District California State Parks - Oceano Dunes District Caltrans Central Coast Wetlands Group Coastal Conservancy Coastal San Luis Resource Conservation District County of San Luis Obispo Public Works Groundswell Ecology Harris Environmental Group Humboldt Bay Harbor District Integral Consulting Middlebury Institute of International Studies Monterey Peninsula Regional Park District Morro Bay National Estuary Program

			Ocean Protection Council San Francisco Estuary Institute State Coastal Conservancy The Land Conservancy of San Luis Obispo Co. US Fish and Wildlife Service Virtual Planet yak tityu tityu yak tifhini Northern Chumash Tribe
North Coast region	Virtual	June 24 th , 2025	Bureau of Land Management California Coastal Commission CA State Parks North Coast Redwoods District County of Humboldt Public Works Department Humboldt Bay Harbor District Ocean Protection Council Restoration Specialist San Francisco Estuary Institute State Coastal Conservancy Surfrider Foundation The Wildlands Conservancy Tolowa Dunes Stewards
Humboldt Bay	Cal Poly State University & Virtual	June 2 nd , 2024	Blue Lake Rancheria Bureau of Land Management California Department of Parks and Recreation Coastal Ecosystem Institute Friends of the Dunes Humboldt County Parks Humboldt Sea Level Rise Initiative US Fish and Wildlife Service

Table S2. Modes of habitat change recorded in the inventory and possible drivers. In general, it was difficult to attribute a single causal mechanism to the transformation of historical dune ecosystems to other habitat types. As such, these transitions were collectively classified as ‘habitat change’ in the inventory.

Mode of change	Characterization and interpretation	Possible drivers of change	
		Geomorphological or Environmental	Anthropogenic
Dune → Wetland	Coastal dunes identified in T-sheets replaced by wetland environments, such as saltwater marshes, estuaries, mudflats, and sloughs. Habitat transformation determined through the identification of water and estuarine habitats using modern (2016) high-resolution aerial imagery and NDVI data.	- Natural migration of river channels resulting in the erosion of coastal dunes and creation of wetlands. E.g., mudflats bordering the Garcia River, south of the Manchester dune system (Mendocino County). - Natural variations in water levels resulting in the submergence/erosion of coastal dunes bordering lakes and creation of wetlands. E.g., marshes bordering Lake Tolowa (Del Norte County). - Reduction in sediment supply to backdune areas bordering wetlands (e.g., due to vegetation growth, reduced aeolian activity or sediment input from beaches)	- Redirection of river channels resulting in the erosion of coastal dunes and creation of wetlands. E.g., south of the Eel River Estuary (Humboldt County), and south of the Santa Clara River mouth.
Dune → Grassland	Coastal dunes identified in T-sheets replaced by low-lying grassland or shrubland with little or no topography. Primarily identified using modern (2016) high-resolution aerial imagery and LiDAR data showing areas of relatively flat, vegetated grassland.	- Natural migration of river channel resulting in the erosion of coastal dunes and transformation of habitat into a floodplain. E.g., grassland bordering the Garcia River, south of the Manchester dune system (Mendocino County). - Reduction in sand supply to backdune areas (e.g., due to vegetation growth, reduced aeolian activity or sediment input to beaches) facilitating the natural succession of hinterland areas into grassland or shrubland ecosystems.	- Levelling of coastal dunes for farmland, construction or other land uses that have since been abandoned. E.g., former log yards on the North Spit of Humboldt Bay (Humboldt County). - Reduction in sediment supply to backdune areas due to the construction of hard barriers (e.g., highway, railroad) and/or vegetation growth. E.g., regions inland of Highway 101 near Little River State Beach (Humboldt County), and Highway 1 near Virgin Creek State Beach (Mendocino County).
Dune → Forested	Coastal dunes identified in T-sheets replaced by dense forested areas with little or no topography. Primarily identified using modern (2016) high-resolution aerial imagery and LiDAR data.	- Reduction in sand supply to backdune areas (e.g., due to vegetation growth, reduced aeolian activity or sediment input from beaches) facilitating the natural succession of hinterland areas into forest ecosystems. - Natural migration of river channels resulting in the erosion of coastal dunes and transformation of habitat into a forest. E.g., forest/shrubland bordering the Santa Maria River (Santa Barbara County).	- Levelling of coastal dunes for farmland, construction or other land uses that have since been abandoned and transformed into forested areas. - Planting of trees and other woody vegetation that has fundamentally altered the ecosystem. E.g., Presidio of San Francisco (San Francisco).

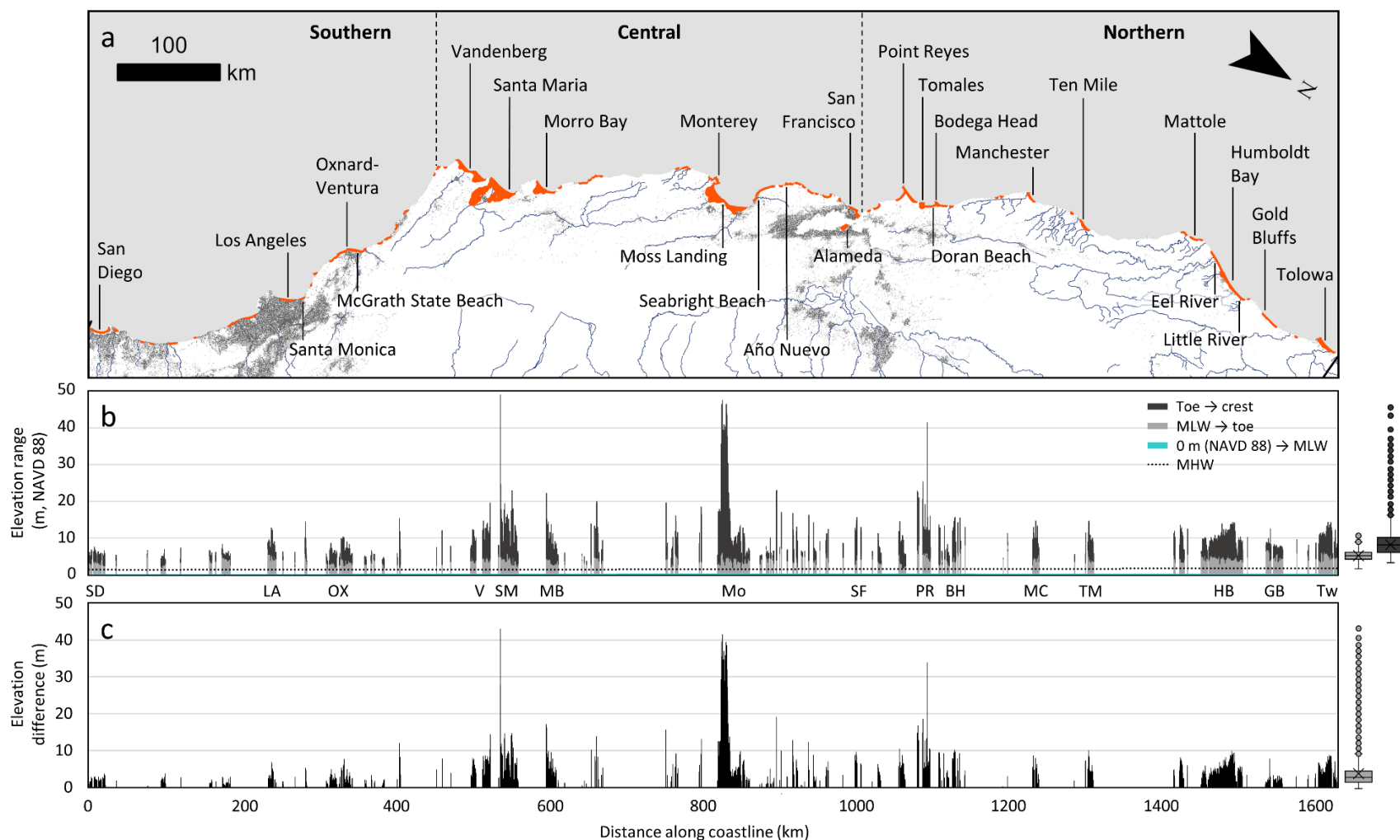


Figure S5. (a) Locations of existing (2016) coastal dunes in California (orange) with major dune fields labelled. The map is oriented from south to north (left to right). Urban centers (grey), major rivers (blue) and regional boundaries (dashed lines) are shown. (b) Elevation range (m, NAVD 88) between mean low water (MLW, 1983-2001), and foredune toe and crest recorded at 30 m intervals at existing (2016) dune complexes. Mean high water (MHW, 1983-2001) is also shown (dotted line). (c) Difference in height between the dune toe and crest.

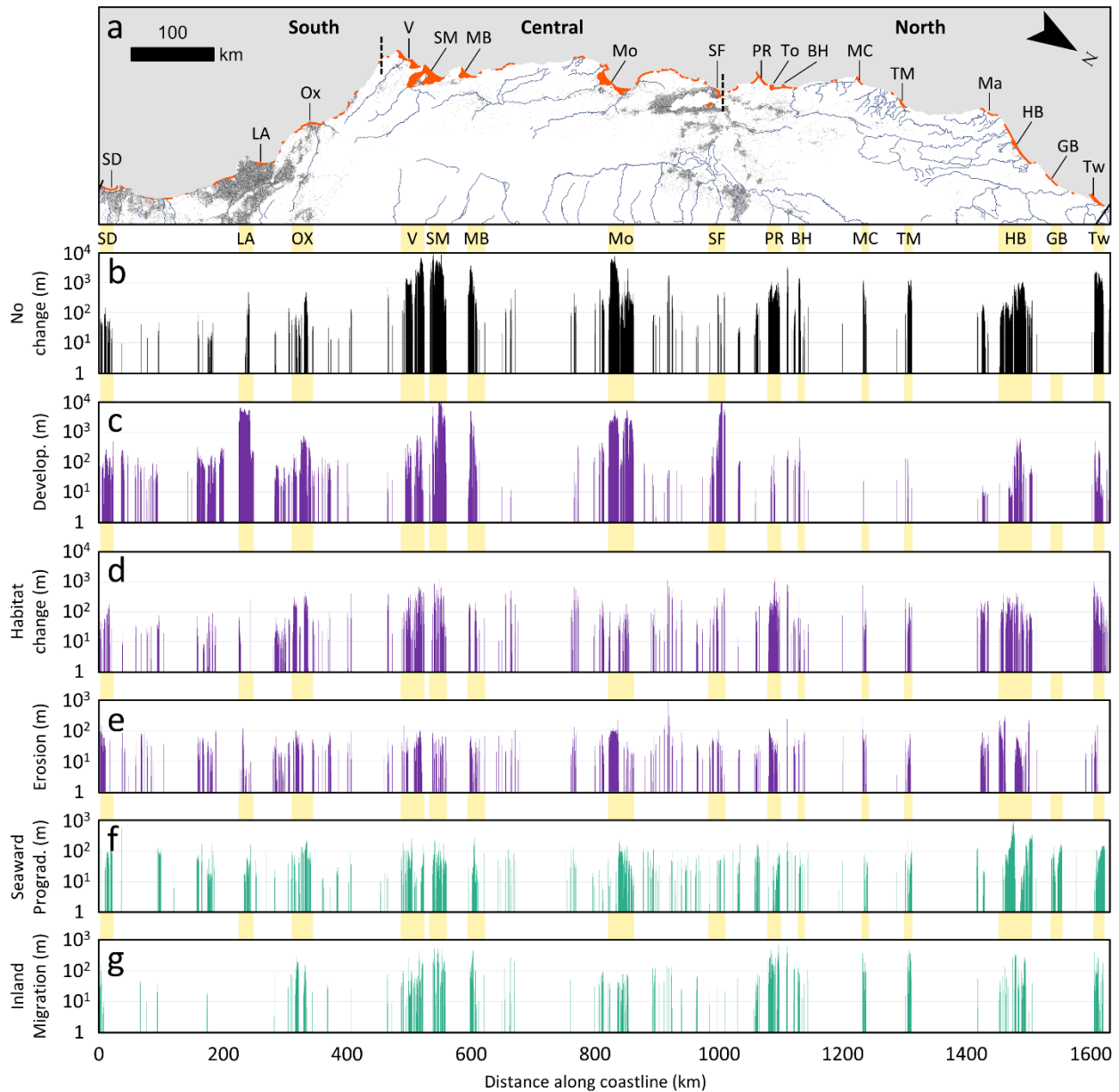


Figure S6. (a) The location of contemporary dune systems in California (orange) with major dune fields labelled (refer to Table 1 in main text for corresponding IDs). The map is oriented from south to north (left to right). Urban centers (grey), major rivers (blue) and regional boundaries (dashed lines) are shown. (b) The inland extent (width, m) of dunes that have experienced no change in extent since the mid-1800s recorded at 30-m intervals along the coastline of California. (c-e) The inland extent (width, m) of dunes lost and (f-g) gained (width, m) through different drivers of change over the last 165 years. Note the use of logarithmic scales on rows b-g. Rows b-g are proportionally scaled.

Table S3. Area (km²) and percentage of coastal dunes lost due to urban development in California and other locations around the world between the 1800s and present-day. Studies ordered by length of coastline analyzed.

Location	Timeframe		Coastline length (km)	Loss		Reference
	Period	Yrs.		(km ²)	(%)	
California, U.S.	1851-2016	165	1650	436	60	<i>This study</i>
Spain, France, Italy (<i>Med.</i>)	1960s-1990s	30	-	-	75	Van der Meulen & Salman (1996)
Catalonia, Spain	1890-2015	125	600	-	> 60	Garcia-Lozano et al. (2018)
Netherlands	1850-1990	140	451	30	~ 7	Janssen (1992) in Doody (2012)
Black Sea Coast, Bulgaria	2007-2022	15	378	0.1	1	Prodanov et al. (2023)
Israeli Coastal Plain, Israel	1944-1990s	50	190	-	> 50	Kutiel & Sharon (1996)
Veneto, Italy	-	-	169	-	24 ^a	Bezzi et al. (2018)
Abruzzo, Italy	1811-1999	188	125	70 ^b	80	Miccadei et al. (2011)
Flemish Coast, Belgium	1948-1988	40	65	3.8	50	Provoost & Van Landuyt (2001)
Kemer, Turkey	1981-2004	23	53	0.9	37	Kemal Sönmez et al. (2009)
Tetouan, Morocco	1969-2007	38	35	-	95	El Mrini et al. (2012)
Molise, Italy	1954-1984	30	30	1.5 ^c	~ 40	Malavasi et al. (2013)
Sefton, UK	1850s-2000s	150	~ 25 ^d	-	40	Doody (2012)
Sunny Beach, Bulgaria	1970-2005	35	10	1.0	46	Stancheva et al. (2011)
Maspalomas, Gran Canaria	1961-2003	42	~ 4.7 ^d	1.3	27	Hernandez-Cordero et al. (2018)
Ravenna, Italy	1954-2011	57	3.5	0.2	75	Sytnik & Stecchi (2015)
Võsu, Estonia	1900-2009	109	~ 3.4 ^d	0.2	~ 20	Stancheva et al. (2011)
Kangneung, South Korea	1910s-2000s	90	2	0.3	61	Choi et al. (2007)
Chachalacas, Mexico	1995-2006	11	-	1.0	4	Martínez et al. (2014)

^a Percentage of coastal dunes that are 'human-altered'. ^b Length in km (coastline). ^c Determined from a graph.

^d Estimated from satellite imagery.

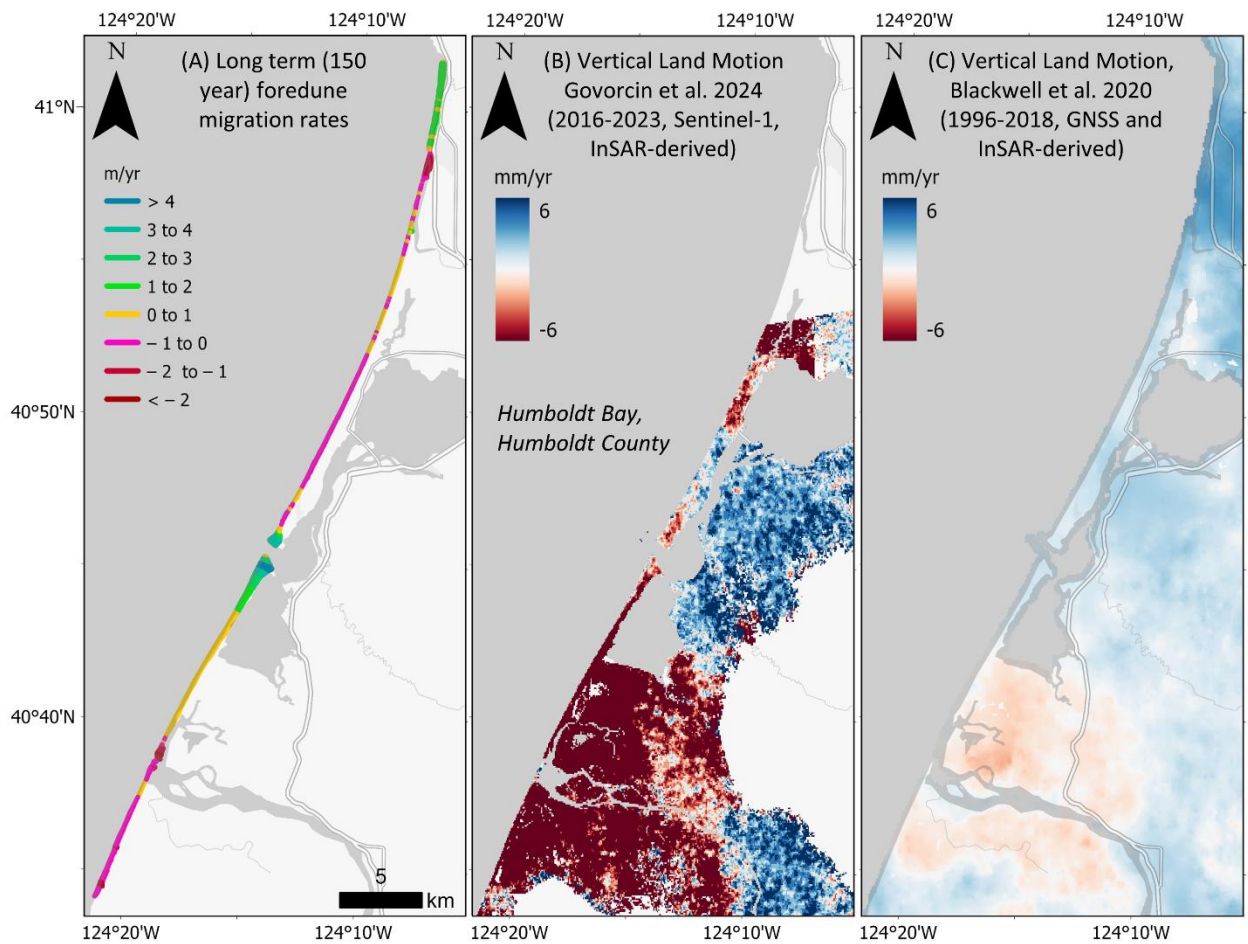


Figure S7. (a) Long-term (150-year) foredune migration rates (m/yr) in Humboldt Bay, Humboldt County, and rates of vertical land motion (VLM, mm/yr) derived from interferometric synthetic aperture radar (InSAR) analysis by (b) Govorcin et al. (2025), and (c) Blackwell et al. (2020).



Figure S8. Historical photograph (1893) showing dunes on the northern end of Santa Monica Beach, Los Angeles County. Taken by Charles. C. Pierce. North Beach and Railroad, Santa Monica, photCL_555_01_1224, the Huntington Library, San Marino, California.

Data Set S1. Excel spreadsheet with information on the following: (a) T-sheets used to map the historical extent of coastal sand dune in California, (b) T-sheets used as a reference (i.e., to confirm information shown in other maps), but not digitized, (c) resources other than T-sheets that were used to determine historical dune extent, (d) aerial imagery and DEM datasets used to determine modern dune extent, and (e) additional resources used to determine drivers of change over time.

Data Set S2. Shapefiles of historical dune extent, contemporary dune extent, change and loss in dune extent over time, and modern (2016) toe and crest positions. This dataset is available to download from: Baxter, T.I., Walker, I.J., Dugan, J.E., Hubbard, D.M., Engeman, L., Emery, K.A., Vitousek, S., Johnston, K.K., Pickart, A.J., Smith, S., Fee, D.R., Willet, D., Wisniewski, J., 2025. California coastal dune inventory [Dataset]. Dryad. DOI: <https://doi.org/10.5061/dryad.hqbzkh1w7>