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

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Key Points:

- We present a comprehensive assessment of coastal dune habitat loss in California, spanning 165 years and 1,625 km of coastline
- Since the 1850s, more than half the coastal dunes in California have been lost due to urban development, altered land-uses, and erosion
- Our methods provide a framework for assessing large-scale habitat change that could be extended globally to inform restoration efforts

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Coastal sand dunes support unique biodiversity and buffer beaches and communities against storm impacts. However, these sensitive and dynamic ecosystems are increasingly threatened by erosion, sea-level rise (SLR), and encroaching coastal development. Restoration projects designed to re-establish the eco-geomorphic functions of degraded dunes and associated ecosystem services present a viable pathway to relieve these stressors. Yet, even for populated coasts like California, insufficient information on the location of dunes and patterns of change over time constrain regional efforts to identify suitable restoration/conservation sites, and forecast future impacts on vulnerable beach–dune systems. Here, we present a comprehensive assessment of coastal dune extent and loss, spanning 165 years and 9.5° of latitude across California. Areas and drivers of change were quantified by comparing historical and current dune extents generated using historical surveys, high-resolution aerial imagery, and LiDAR, combined with a machine-learning tool. Coastal dunes currently extend along 352 km (22%) of California's 1,625 km coastline, covering almost 300 km^2. This represents a 60% (442 km^2) decrease in area since the mid-1800s with the loss, degradation, and fragmentation of many dune ecosystems attributed to urban development, altered land-uses, and erosion. Strong regional patterns of dune loss were evident, reflecting population demographics and land uses. Densely populated areas of southern California experienced the greatest dune losses (95%, 108 km^2), although substantial reductions were also found in central California (60%, 331 km^2). Our results highlight the magnitude of coastal change in California over time and can inform future conservation, restoration, and resilience-planning efforts and priorities.

Plain Language Summary California has some of the largest and most ecologically diverse coastal sand dunes in North America. These dunes protect coastal communities from flooding and have important ecological, recreational, and cultural benefits, but are increasingly threatened by rising sea levels and coastal development. Efforts to restore these vulnerable ecosystems and forecast future climate change impacts are hindered by a lack of information regarding the location and spatial extent of coastal dunes, and reasons for their demise. Using historical maps and modern aerial photographs, we conducted a comprehensive, statewide assessment of coastal dune extent and loss. Since the mid-1800s, total dune area has decreased by 60% due to urban development, erosion, and land use changes. Dune ecosystems are significantly more isolated and fragmented than in the past, with losses concentrated in southern and central California. The magnitude of these losses over the last 165 years represents a significant challenge to California's climate resilience, SLR adaptation, and biodiversity goals. Our methods provide a framework for assessing large-scale habitat change that could be extended to coasts around the world to aid the identification and prioritization of suitable restoration sites, helping to offset past dune losses and mitigate future climate change impacts.

1. Introduction

Coastal sand dunes are important, globally distributed ecosystems (Gao et al., 2020; Martínez et al., 2008). These dynamic, sensitive, and culturally significant landforms provide a variety of co-benefits to local communities, economies, and wildlife, including flood protection, recreational space, and habitat for rare and endangered species (Barbier et al., 2011; Emery et al., 2024). Coastal urbanization, invasive species, and climate-change impacts, such as sea-level rise (SLR), increasingly threaten vulnerable dune systems (Gao et al., 2020; Jackson et al., 2019; Matsushima & Ferreira, 2022; Pickart, 2021). This includes along the West Coast of North

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America, where the impacts of recent El Niño events and damaging winter storms have amplified concerns regarding the condition and resilience of dune-backed beaches and related ecosystems (Barnard et al., 2021; Smith & Barnard, 2021; Vos et al., 2023). Many coastal dunes across this region already face significant conservation challenges related to the spread of invasive plant species (Buell et al., 1995; Pickart, 1997), including European Beachgrass (*Calamagrostis arenaria*, formerly *Ammophila arenaria*) and iceplant (*Carpobrotus* spp.), which have both played significant roles in dune habitat change and loss by reducing native biodiversity and limiting foredune recovery following erosional events (Buell et al., 1995; Galaz Garcia et al., 2024; Hilgendorf et al., 2022; Pickart, 1997, 2021).

Restoration projects that create new dunes or re-establish the ecological and geomorphic functions of degraded beach–dune systems are a viable pathway for mitigating climate-change impacts and facilitating processes that support natural recovery and coastal resilience (Hilgendorf et al., 2022; Johnston et al., 2023). However, the successful application of these approaches and associated efforts to improve coastal resilience, develop adaptation plans, and forecast future SLR impacts are currently hindered by limited information regarding the spatial distribution and condition of modern coastal dunes, the main drivers and patterns of change over time, and fundamental understanding of dune recovery and resilience to erosive events.

Lack of a spatially explicit inventory of coastal dunes is particularly evident and problematic for California, a region that supports some of the most ecologically diverse and geographically extensive coastal dune fields in North America and the largest coastal population in the United States (approximately 27 million people). Previously published coastal dune assessments are outdated, incomplete, or coarse in resolution (Cooper, 1967; Hapke et al., 2006; Orme & Tchakerian, 1986; Zeller, 1962), small or regional in scale (Clark, 2009; McDonald, 2017; Rader et al., 2018; Thornton et al., 2006; Warrick et al., 2023), or focus on coastal barriers and estuarine environments (Clark et al., 2013; Clark & O'Connor, 2019). This includes the California Aquatic Resource Inventory (CARI, version 2.2), a GIS data set of coastal and riparian ecosystems that is widely used in conservation planning, but frequently misidentifies dunes across the State (SFEI, 2025).

A comprehensive assessment of coastal dunes (both past and present) is greatly needed to help advance modeling approaches used to simulate beach–dune responses to SLR and future extreme events. This includes the U.S. Geological Survey (USGS) Coastal Storm Modeling System (CoSMoS; Vitousek et al., 2017, 2023), a state-recognised coastal change prediction model, which currently assumes static back-beach environments and does not explicitly account for the presence of dunes or their potential buffering capacity to longer-term SLR. Such an inventory would also help practitioners and policymakers monitor progress toward climate resilience and biodiversity goals (California State Sea Level Rise Collaborative, 2024), including recent investments in nature-based solutions (NbS) to improve coastal resilience, and the statewide 30 × 30 initiative (California Executive Order N-82-20, 2020) that commits to conserving 30% of California's land and coastal waters by 2030.

Recent developments in machine-learning approaches that enable quick and accurate identification of coastal features (e.g., Beuzen, 2019; Fitzpatrick et al., 2024; Muir et al., 2024; Studer et al., 2023; Vos et al., 2019), coupled with improved access to historical archives (e.g., early maps, aerial photographs, and satellite imagery), have unlocked new opportunities to accurately record and quantitatively assess coastal dunes and related ecosystems over large spatial (>1,000 km) and temporal (>40 years) scales (Garcia-Lozano et al., 2018; Lansu et al., 2025; O'Hara et al., 2024). Although long-term evaluations of shoreline change rates and land-cover types have been conducted using automated satellite-imagery based methods (Muir et al., 2024; Vos et al., 2023), these tools often necessitate substantial training data to be effective (Buscombe et al., 2023; Murry et al., 2022). To further advance these efforts, we set out to accurately delineate geographically diverse and complex ecosystems, such as coastal dunes, using human-guided machine learning and manual identification.

In this paper, we present a comprehensive assessment of coastal dune extent and loss in California since 1851. We generated an inventory of historical dunes by collecting, georeferencing, and digitizing 140 topographic survey maps (*T*-sheets) produced in the mid-to-late 1800s and early 1900s. High-resolution aerial imagery, Light Detection and Ranging (LiDAR) data sets, and Normalized Difference Vegetation Index (NDVI) maps were then used in combination with a novel machine learning tool to identify the position and elevation of key dune features (i.e., toe and crest) and generate an inventory of contemporary (2016) dunes. Areas of dune loss/change over time were then quantified by comparing the historical and contemporary dune inventories, with specific drivers of change identified using modern aerial imagery and historical archives. At two-case study sites in northern California (i.e., Gold Bluffs Beach and the Lanphere Dunes Unit), the potential impacts of invasive plants on the

Figure 1. Historical map (*T*-sheet, no. 474) from 1854 showing the extent of coastal sand dunes on the North Spit of Humboldt Bay, Humboldt County, California (U.S. Coast Survey, 1854). Aerial photographs of the same region from 1948 (Laird et al., 2007) and 2016 (NAIP 4-Band Imagery; EROS, 2023) are also shown for comparison.

geomorphic evolution of coastal dunes were examined in greater detail using historical photographs from the mid-1900s to the present-day. Habitat distribution metrics (e.g., patch number and size) were also determined across the State to compare differences in the fragmentation and isolation of historical and contemporary dune systems to help guide future conservation priorities.

In addition to providing one of the most comprehensive and detailed assessments of coastal dune connectivity, morphology, and extent ever produced—spanning over 160 years and 1,625 km of coastline across 9.5° of latitude—our study provides detailed interpretations of long-term patterns and drivers of change to dune ecosystems since the mid-1800s, a period of significant socio-cultural change associated with the California Gold Rush (1848–1855) and intensive Euro-American settlement on the West Coast of North America (Clay & Jones, 2008).

2. Data and Methods

2.1. Historical Dune Extent

The United States Coast Survey (U.S. Coast and Geodetic survey after 1878) produced a series of topographic survey maps (*T*-sheets) of the California coastline during 1851–1890 and 1909–1938 (Grossinger et al., 2011). These surveys provide an early record of coastal environments in the region, including beach and dune ecosystems (Figure 1). Although the accuracy and detail of the *T*-sheets vary depending on the cartographer and dates of production, the maps were generally produced to a high standard and at an unusually large scale (1:10,000), and thus provide a detailed assessment of the coastal landscape that precedes extensive Euro-American modification.

High-resolution scans of *T*-sheets ($n = 140$) produced between 1845 and 1934 were obtained from the National Oceanic and Atmospheric Administration (NOAA) Index of Non-Georeferenced Manuscripts (https://shoreline.noaa.gov/t-sheets.html) and the National Archives Records Administration. Following a similar approach to Grossinger et al. (2011), who used *T*-sheets to map the historical extent of coastal wetlands in southern California, we generated a historical inventory of coastal sand dunes through a systematic process of georectification, vectorization, interpretation, and classification. Information on every *T*-sheet (e.g., title, date, surveyor) used to generate the historical dune inventory is provided in Data Set S1 along with a flowchart of the methods (Figure S1

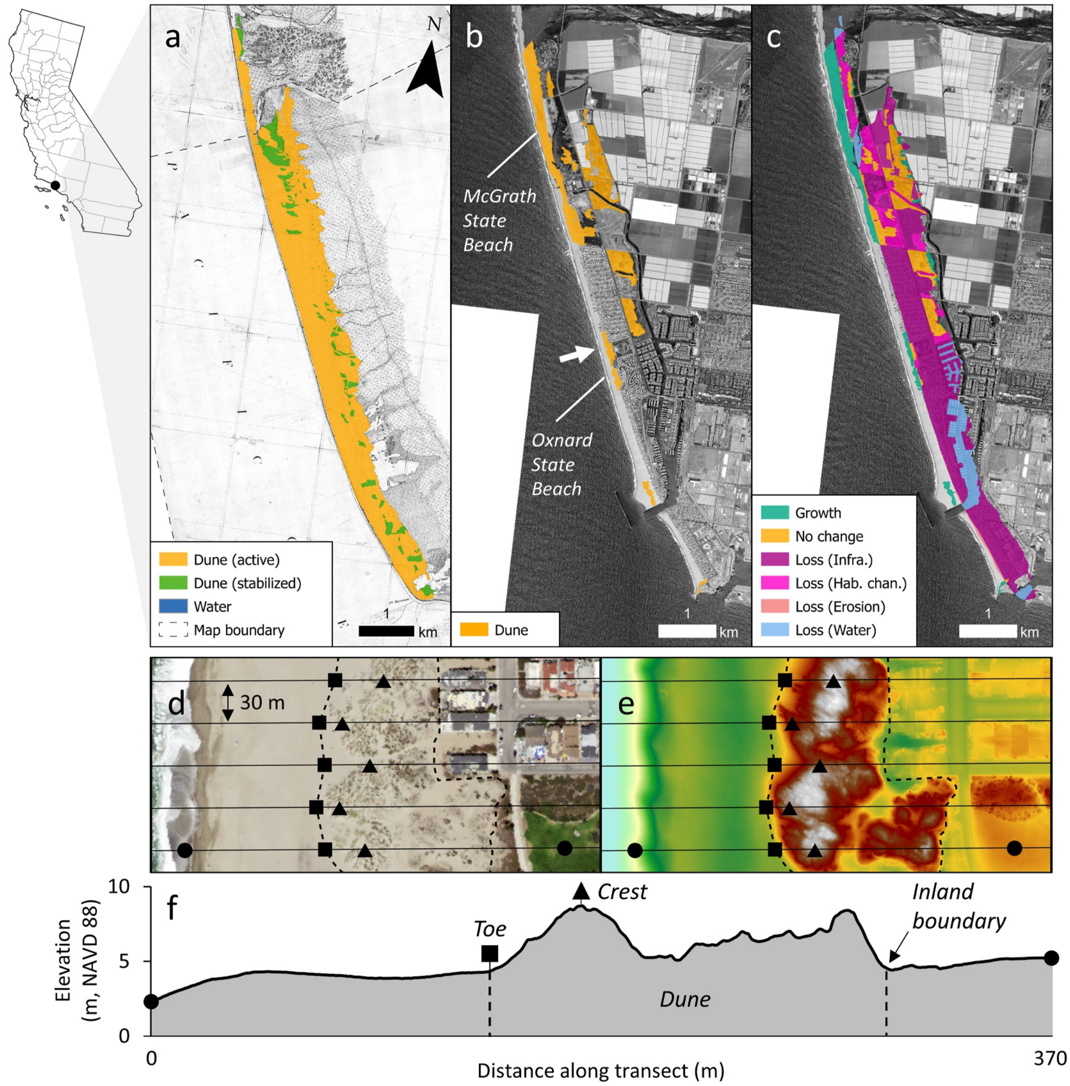

Figure 2. (a) Extent of coastal dunes shown in historical (1855) topographic surveys (*T*-sheets no. 576 and 682) along McGrath State Beach and Oxnard State Beach, Ventura County. (b) Current (2016) extent of coastal dunes, and (c) drivers of change over time at the same location. (d) High-resolution aerial imagery (NAIP 4-Band Imagery; EROS, 2023) and (e) elevation data (2016 USGS West Coast El-Nino LiDAR digital elevation model, Office for Coastal Management (OCM), 2024a) showing a small section of Oxnard State Beach with the extent of modern (2016) dunes outlined (dashed line), as well as the location of toe (black square) and crest (black triangle) features along five shoreline-perpendicular transects (black lines). (f) An elevation profile of the most southerly transect is also shown.

in Supporting Information S1) and a detailed description of the georeferencing process (Text S1 in Supporting Information S1).

Once the historical maps and photographs were georeferenced, vectors of different habitat types were created using manual (heads-up) digitization (Figure 2). In cases where *T*-sheets overlapped, earlier maps were relied on to resolve differences, except when later maps were more detailed (Grossinger et al., 2011). Although a full suite of coastal environments is shown in *T*-sheets, we focused on mapping coastal dunes and related features. In total, over 1,500 polygons were mapped, interpreted, and classified into 11 different habitat types. This includes active dunes, stable (vegetated) dunes, and relict dunes (i.e., those formed over Holocene or Late Pleistocene), wetland environments (e.g., swales), grassland and/or forested areas, and infrastructure (e.g., buildings and roads) as well as "transitional" environments which, due to their location, environmental setting, and proximity to sediment source, may have supported ephemeral dune systems. These transition zones include spits and barriers close to river mouths ("Estuary–Beach" environments), beaches supporting incipient dunes without a clearly defined foredune ("Beach–Dune" environments) or at the base of coastal bluffs ("Dune–Bluff" environments), and ephemeral wetlands located within or adjacent to dune fields ("Dune–Wetland" environments). A catalog of the different habitat types categorized in the historical inventory is provided in Figure S2 of the Supporting Information S1).

2.2. Contemporary (2016) Dune Extent

High-resolution (0.5–1 m) aerial imagery (2016 4-Band imagery acquired by the National Agriculture Imagery Program, NAIP; Earth Resources Observation and Science Center, EROS, 2023) and oblique photographs from the California Coastal Records Project (www.californiacoastline.org) were used to conduct a general reconnaissance of the entire California coast and create an initial list of potential dune sites (refer to flowchart in Supporting Information S1, Figure S3). At each location where dunes were identified, elevation data (2016 USGS West Coast El-Nino LiDAR DEM; Office for Coastal Management (OCM), 2024a) were used in combination with HAML—Human Attuned Machine Learning Tool for Dune Annotation (Studer et al., 2023)—to map the location and elevation (North American Vertical Datum 1988) of foredune toe and crest features at 30 m intervals along the coastline using a 1,625-km-long baseline created for the USGS National Shoreline Change project (Kratzmann, 2024). Foredune toe and crest elevations influence important biological interactions (Ruiz de Alegría-Arzaburu et al., 2025), including the nest placement and breeding success of federally protected species, such as least terns (*Sternula antillarum*) and Western snowy plovers (*Charadrius nivosus nivosus*), and are valuable indicators of erosion and flood protection thresholds. The dune toe is also regularly used in geomorphology to denote the seaward limit of coastal dune systems (Smith et al., 2020), a necessary boundary for determining total dune extent.

The Human Attuned Machine Learning Tool for Dune Annotation (HAML) is a custom ArcGIS plugin developed by the U.S. Naval Research Laboratory (Studer et al., 2023) that facilitates the quick and accurate identification and annotation of key dune features through the creation of elevation profiles derived from a user-provided digital elevation model (DEM). When first initialized, the tool uses algorithmic annotation to place features along shore-perpendicular profiles: the dune crest and toe are defined as the highest point of elevation and location of maximum change in downslope curvature, respectively. Users can adjust annotated features on newly generated profiles through a simple click-and-drag interface. Once the tool has accumulated a reasonable amount of training data (achieved after approximately 30 profiles), the machine-learning backend initiates, providing updated suggestions for crest and toe placement, while still allowing user edits (Studer et al., 2023).

The positional accuracy of toe and crest features mapped using HAML depends on the horizontal and vertical accuracy of the DEM used to generate the elevation profiles and the amount of human input to adjust or verify the placement of features initially located by the tool. In this study, we used HAML to help identify the location and height of nearly 20,000 dune toe and crest features using elevation data (2016 USGS West Coast El-Nino LiDAR DEM; Office for Coastal Management (OCM), 2024a) with a horizontal accuracy of 0.21 m, vertical accuracy of 0.12 m, and resolution of 0.5 m. The position of each feature was individually reviewed on at least two occasions: once following its initial placement by HAML and again following the creation of the entire data set for a region/dune system (Supporting Information S1, Figure S3). In most cases, only small adjustments (i.e., 1–2 m) were necessary. However, on occasion, more substantial changes (i.e., 10–20 m) were required when features were incorrectly placed by HAML. This includes, for example, instances where the tool incorrectly placed the dune toe at the base of a berm or crest on top of a cliff. Given the accuracy and resolution of the 2016 DEM used for selection and the two-step review process, we believe the toe and crest features mapped in this study can be considered accurate to approximately 1 m. Toe and crest features were not mapped for isolated dune systems, including clifftop dunes and those disconnected from beaches and other coastal processes due to infrastructure.

Following the review process, toe features were connected and used to define the seaward dune boundary. In contrast, the inland dune boundary was manually identified using elevation data downloaded from the NOAA Data Access Viewer website. For smaller dune systems, the inland boundary was determined using the same DEM used to identify toe and crest features (i.e., 2016 USGS West Coast El-Nino LiDAR DEM; Office for Coastal Management (OCM), 2024a). However, as the 2016 data set only extends for approximately 500 m inland, alternative DEMs were used to determine the inland extent of larger dune systems. The horizontal and vertical accuracy of the DEMs used to map these larger systems ranged between 0.12–1.00 m and 0.05–0.20 m, respectively. However, in some locations with limited data availability (e.g., Vandenberg Space Force Base), older and less accurate (i.e., >2 m) DEMs were used (e.g., 2002–2003 IfSAR data for southern California DEM;

Office for Coastal Management (OCM), 2024b). Details of all the DEMs used to map the inland dune boundary are provided in Supporting Information (Data Set S1).

Line vectors of the inland dune boundary were created using manual (heads-up) digitization in ArcGIS Pro (version 3.2.2; Esri, Redlands, California, USA) based on changes in slope and elevation shown in the DEMs (i.e., at the base of the lee slope of the backdune). In some cases, high-resolution aerial imagery (NAIP 4-Band Imagery; EROS, 2023) and NDVI data were also used, especially in low-lying areas where changes in land cover and/or plant communities provided a better indication of dune and non-dune areas (e.g., dune to wetland ecosystems). The accuracy of the inland dune boundary varies by region depending on the accuracy and resolution of the DEM referenced, quality and availability of supporting data sets (e.g., aerial images), and type of boundary assessed, with those defined by clear changes in elevation and/or land-use (e.g., dune to infrastructure) generally considered more accurate (<2 m error) than those produced for gently sloping, transitional environments (e.g., dune to wetlands, 5–15 m error). Given these uncertainties, the inland dune boundary should be considered broadly accurate to approximately 5–20 m across the State.

To create polygons of contemporary (2016) dune extent, the inland dune boundary and seaward dune boundary were connected in ArcGIS Pro. In total, over 1,400 polygons were generated. These polygons were then classified into 10 different habitat types (Figure S2 in Supporting Information S1). Most of these habitat types correspond directly to those identified in the historical inventory, including infrastructure, wetland, and transitional environments (e.g., Dune–Bluff, Dune–Wetland, and Dune–Grassland transition zones). However, due to challenges associated with accurately differentiating between active and stable (vegetated) dunes using aerial imagery, these habitats were combined into a single "dune" category in the contemporary inventory. In general, habitat type was classified using aerial imagery from 2016 (i.e., 2016 NAIP 4-Band Imagery; EROS, 2023) as this year was the most comprehensive in terms of data coverage, accuracy (i.e., 6 m), and resolution (i.e., 1 m). However, in a few isolated cases, imagery from 2002 to 2022 was also used in areas not covered by the 2016 data set, such as at Vandenberg Space Force Base (Data Set S1).

Site visits ($n = 29$) conducted throughout 2024 and 2025 were used to visually assess the location of dune systems using fixed landmarks, such as roads and buildings (Figure S4 in Supporting Information S1). These surveys were particularly beneficial in helping to identify and record the presence/absence of smaller dune sites that may have been missed during our initial reconnaissance of the coastline using aerial imagery (e.g., dunes on Casper Headlands State Beach, Mendocino County). Feedback on the contemporary dune inventory was also gathered from local managers, practitioners, and members of the California Dune Science Network (www.resilientcoastlines.com) who were engaged through a series ($n = 10$) of targeted workshops held across California (Figure S4 and Table S1 in Supporting Information S1). During these workshops, participants were provided with an opportunity to comment on our preliminary findings and suggest additional sites for analysis. Feedback from these workshops was then used, in combination with the site visits, to produce a more exhaustive list of dune systems across the State and gather site specific information on potential drivers of change.

2.3. Identifying Drivers of Change

Difference maps showing areas of dune loss and/or change over time were created by comparing the historical (1800s) and contemporary (2016) dune inventories (Figure 2), with specific drivers of change determined by identifying the dominant land-use and/or habitat type shown in modern aerial imagery (NAIP 4-Band Imagery; EROS, 2023). For example, infrastructure development was considered to be the main driver of change in areas where historical dunes had been replaced by residential buildings or roadways. In some cases, historical archives (e.g., aerial photographs, maps, and environmental reports) were also used to provide additional context (Data Set S1). This includes, for example, historical aerial photographs from the California Coastal Records Project and University of California Santa Barbara (UCSB) Geospatial Collection (mil.library.ucsb.edu/ap_indexes/FrameFinder) that were used to qualitatively assess the impacts of dune-stabilizing invasive plant species on the geomorphic evolution of two dune systems in northern California, Gold Bluffs Beach (Mendocino County) and the Lanphere Dunes Unit (Humboldt County).

Drivers of change were classified into the following categories: (a) loss through coastal erosion, (b) loss through river erosion or the redirection of waterways, (c) loss through processes that facilitated the transformation of historical dunes to wetland, grassland, or forested environments, (d) growth through the seaward progradation of foredunes, and (e) growth through the landward migration of dune systems due to aeolian transport. Changes in vegetation did not result in the classification of historical dunes as "lost" in isolation. Loss was only considered for areas deemed to be both ecologically and geomorphologically distinct from adjacent dune ecosystems. This includes, for example, wetland environments and low-lying grassland and/or forested areas with little or no topography. As it was generally difficult to determine a single, causal mechanism that may have facilitated the transformation of historical dunes to wetland, grassland, or forested areas—whether through environmental, geomorphic, or anthropogenic drivers—these transitions where collectively classified as "habitat change" in the inventory (Table S2 in Supporting Information S1). This contrasts to historical dunes lost through human development and land-use change (e.g., industry, residential communities, transport links, agricultural land), that were more readily identifiable using high-resolution (1 m) aerial imagery and land cover data (i.e., Impervious Cover) from the NOAA Coastal Change Analysis Program.

All the research data generated in this study, including the historical and contemporary dune inventories, difference maps, and location and elevation of key dune features (i.e., toe and crest) are available to download as ArcGIS shapefiles from the California Coastal Dune Inventory (CCDI), an online data set stored on DRYAD (Baxter et al., 2026) and available in Supporting Information (Data Set S2).

2.4. Isolation and Fragmentation

To determine the proportion of coastal dunes isolated from beaches and other coastal processes, we used ArcGIS Pro and modern aerial imagery (i.e., 2016 NAIP 4-Band Imagery; EROS, 2023) to manually identify and select every "dune" polygon in the contemporary inventory directly fronted by infrastructure. The total area of these "isolated" dunes was then compared to the total area of dunes mapped across the State.

In both the historical and contemporary inventories, areas of dune within 100 m of one another were also identified and grouped into distinct "patches" of dune. The total number and mean area of these patches, as well as the average distance between them, was then determined for each inventory (i.e., historical and contemporary) and used as simple metrics for habitat connectivity and fragmentation. To reduce the influence of local-scale fragmentation on connectivity values, these metrics were also determined for patches of dune in the contemporary inventory that were grouped and amalgamated if they were within historically contiguous dune areas.

3. Results

3.1. Historical and Contemporary (2016) Dune Extent

In the mid-to-late 1800s, coastal dunes extended along at least 27% (434 km) of the California coast, covering an area of approximately 739 km^2 (Figure 3). Transitional environments (i.e., those with the potential to support ephemeral dune systems, such as spits or barrier beaches) extended for an additional 101 km (6%) alongshore. Considered together, approximately 33% of the coastline may have supported established and/or ephemeral dune systems at that time. In contrast, only 22% (352 km) of the modern (2016) coastline is dune-backed, covering an area of approximately 300 km^2. This represents a 19% (82 km) decrease in the linear (shoreline) length of coastal dunes and 60% (442 km^2) decrease in area since the mid-1800s. The magnitude of loss varied strongly by region, with dunes in southern, central, and northern California decreasing in area by 95% (108 km^2), 60% (331 km^2), and 3% (2 km^2), respectively. While decreases in linear extent were observed in southern (56%, 84 km) and central California (9%, 14 km), dune-backed shorelines increased in length by 11% (16 km) in northern California.

In both the historical and contemporary inventories, large dune fields were typically located: (a) close to major sediment sources (e.g., rivers or coastal bluffs), (b) on shorelines with northern or northwestern orientations, and (c) proximal to structural highs (e.g., headlands) or stretches of low relief. This includes the Santa Maria dune system (San Luis Obispo and Santa Barbara Counties), the largest recorded in both the historical and contemporary inventories, with an estimated area of 263 and 85 km^2, respectively. Geological maps indicate that many of the largest dune systems, including Santa Maria, Vandenberg, Morro Bay, and Monterey Bay, consist of active and stabilized dunes from the Quaternary as well as relict dune sheets from the Late Pleistocene (Orme & Tchakerian, 1986).

The historical extent of coastal dunes varied by region, with dunes covering 113, 555, and 71 km^2 in southern, central, and northern California, respectively (Table 1). Five of the 10 largest dune systems were observed in central California, including Vandenberg (52 km^2), Morro Bay (29 km^2), Monterey Bay (145 km^2), and San Francisco (42 km^2), in addition to Santa Maria. In southern California, the largest dune field was found in Santa

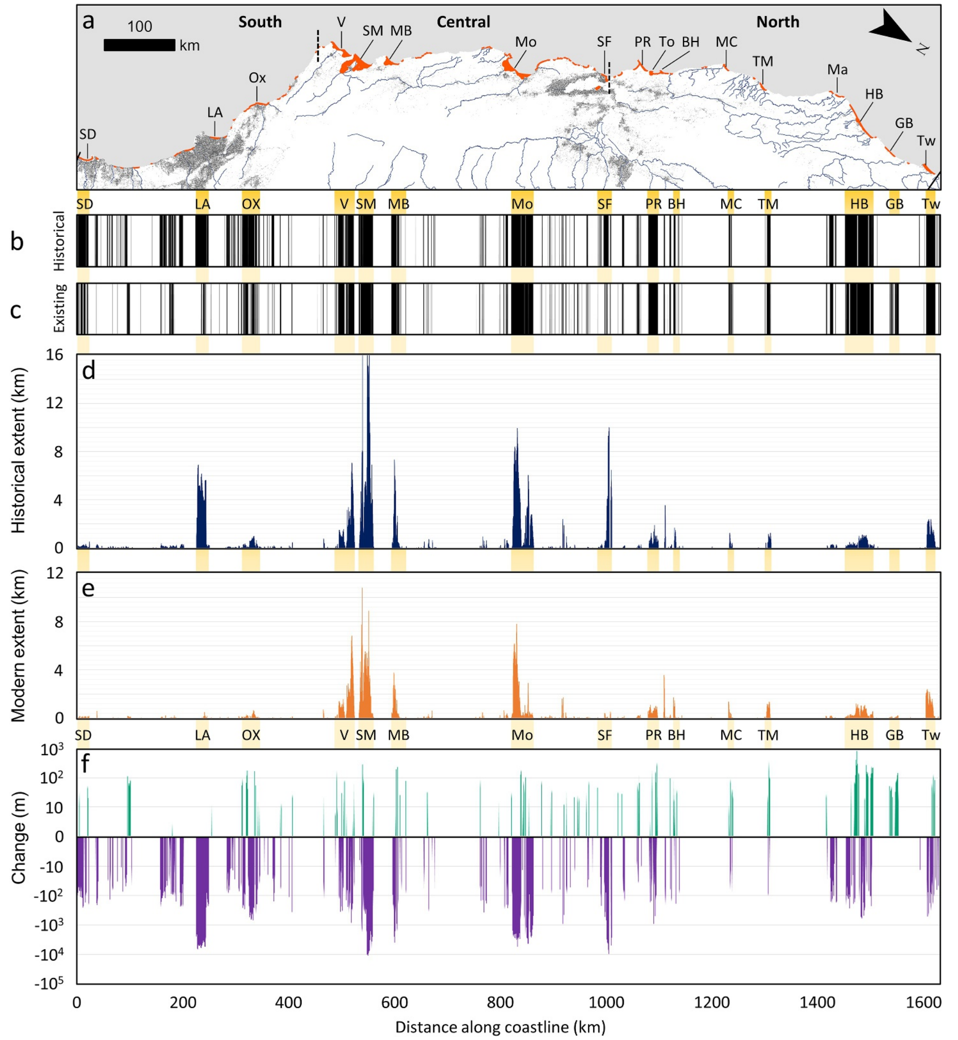

Figure 3. (a) Locations of contemporary (2016) coastal dunes in California (orange) with major dune fields labeled (refer to Table 1 for corresponding IDs). The map is oriented from south to north (left to right). Urban centers (gray), major rivers (blue) and regional boundaries (dashed lines) are shown. An enlarged version of this figure is provided in Supporting Information S1 (S5a). (b and c) Presence/absence plots showing the location of historical (mid-to-late 1800s) and contemporary coastal dunes recorded at 30-m intervals along the coastline of California. (d and e) Historical (dark blue) and contemporary (orange) inland extent (width, km) of coastal dunes recorded at 30-m intervals. (f) Change in inland extent (width, m, logarithmic scale) of coastal dunes between the mid-to-late 1800s and 2016.

Monica Bay (Los Angeles County), with an estimated area of 96 km^2, although significant dune systems were also recorded in San Diego and Ventura Counties (Figure 2). In northern California, three dune systems had historical areas equal to or greater than 10 km^2, including Point Reyes (10 km^2), Humboldt Bay (20 km^2), and Tolowa Dunes State Park (22 km^2).

Strong regional variations persisted in the contemporary dune inventory with some notable differences. Dune fields were considerably smaller in southern California with no dune fields larger than 3 km^2 recorded. The proportion of dunes within the State found in northern California was also much higher in the contemporary inventory (23%) than the historical inventory (10%), indicating that a higher share of the State's dunes is now located in northern California than in the past. Regional variations in long-term population dynamics characterized by the development of densely populated urban centers in central and southern California explains these observed patterns of change, along with increases in post-gold-rush sand supply in northern California.

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Table 1
Historical (Mid-to-Late 1800s) and Contemporary (2016) Dune Extent, and Change Over Time (km² and Percentage Change) for Select Dune Sites and Regional Totals in Southern, Central, and Northern California

		Dune extent (km²)		Difference		Drivers of change (km²)					
Region	ID	Historical	Contemp.	Area (km²)	% Change	No change	Growth	Loss–erosion	Loss–hab. ch.	Loss–water	Loss–infra.
South. California		113.4	5.3	−108.1	−95.3	2.2	3.1	1.6	2.2	1.5	105.9
San Diego Bay	SD	2.6	1.0	−1.6	−61.5	0.5	0.5	0.4	0.3	0.1	1.3
Santa Monica Bay	LA	96.2	0.6	−95.6	−99.4	0.4	0.1	0.1	<0.1	<0.1	95.5
Point Hueneme	Ox	8.6	2.7	−5.9	−68.6	1.1	1.7	0.3	1.4	1.0	4.8
Central California		554.6	112.5 [111.1]	−331	−59.7	105.7	6.7	3.1	7.8	0.6	326.2
Vandenberg	V	51.9	42.3 [6.1]	−3.5	−6.7	47.1	1.2	0.1	2.2	<0.1	2.1
Santa Maria	SM	263.4	53.5 [31.2]	−178.7	−67.8	82.8	2.0	0.2	1.7	0.2	178.5
Morro Bay	MB	28.9	4.5 [10.2]	−14.2	−49.1	13.9	0.7	0.1	0.4	0.2	14.3
Monterey	Mo	144.8	6.7 [63.6]	−74.5	−51.5	69.3	1.2	1.2	0.2	0.1	73.9
San Francisco	SF	42.1	0.9	−41.2	−97.9	0.8	0.2	0.1	0.6	<0.1	40.5
Northern California		71.0	68.6	−2.4	−3.4	54.8	13.7	2.3	8.5	1.3	4.1
Point Reyes	PR	9.5	8.4	−1.1	−11.6	7.2	1.2	0.4	1.7	<0.1	<0.1
Tomales	To	4.8	4.6	−0.2	−5.0	4.6	0.5	<0.1	0.5	<0.1	0.3
Bodega Head	BH	4.3	4.0	−0.3	−7.0	3.7	0.3	<0.1	<0.1	<0.1	0.3
Manchester	MC	2.6	2.5	−0.1	−3.8	2.2	0.3	<0.1	0.3	<0.1	<0.1
Ten Mile	TM	4.7	5.3	**+ 0.6**	**+ 12.8**	4.5	0.8	<0.1	0.1	<0.1	<0.1
Mattole	Ma	1.5	0.9	0.5	−34.4	0.8	0.1	0.2	0.5	<0.1	<0.1
Humboldt Bay	HB	19.6	18.4	−1.2	−6.1	12.6	5.8	1.1	2.7	0.9	2.5
Gold Bluffs Beach	GB	<0.1	2.8	**+ 2.8**	*NA*	<0.1	2.8	<0.1	<0.1	<0.1	<0.1
Tolowa	Tw	22.5	20.9	−1.6	−7.1	19.5	1.4	<0.1	2.0	0.2	0.6
California		739.0	186.4 [111.1]	−441.5	−59.7	162.7	23.5	7.0	18.5	4	436.2

Note. For the contemporary dune extents (column four), values in brackets refer to relict dunes formed in the Late Pleistocene. Bold values highlight regions that have experienced a net growth in dune area.

3.2. Contemporary (2016) Foredune Toe and Crest Height Elevations

The location and elevation of foredune toe and crest features ($n = 20{,}000$) was determined at 30-m intervals along the entire California coast (Figure S5 in Supporting Information S1). Mean dune toe (z_{toe}) and crest (z_{crest}) heights were estimated at 3.86 ± 1.27 and 8.79 ± 4.36 m (North American Vertical Datum 1988), respectively. Values of z_{toe} ranged between 1.63 and 11.36 m, while z_{crest} values ranged between 2.43 and 49.03 m. The greatest values for z_{toe} and z_{crest} were recorded toward the south of the Monterey Bay, Point Reyes, Morro Bay, and Santa Maria dune systems, and north of Vandenberg. In contrast the lowest mean values were recorded in San Diego, Oxnard–Ventura, and Gold Bluffs, as well as some isolated systems scattered along the coast. On heavily populated beaches, such as Ocean Beach (San Francisco) and Playa Del Rey Beach (Los Angeles), z_{toe} values were found to exceed 9 m in some areas. Heavy foot traffic at these sites likely limits the development of incipient dunes on the lower beach, causing foredunes to develop much higher on the beach than would normally be expected. High z_{toe} values may also be linked to artificial beach nourishment at these sites, which typically facilitates the development of wide beaches and/or steep beach gradients.

3.3. Drivers of Change

Overall, the main drivers of dune loss by area were human development (436 km²), habitat change (19 km²), and coastal (7 km²) and riverine erosion (4 km², Figure 4). However, changes in dune extent and drivers of loss varied regionally (Figure S6 in Supporting Information S1). For instance, the spatial distribution of coastal dunes remained relatively unchanged for large areas of northern (55 km²) and central California (106 km²). In contrast, only a small portion of contemporary dunes in southern California (2.2 km²) were recorded in locations that

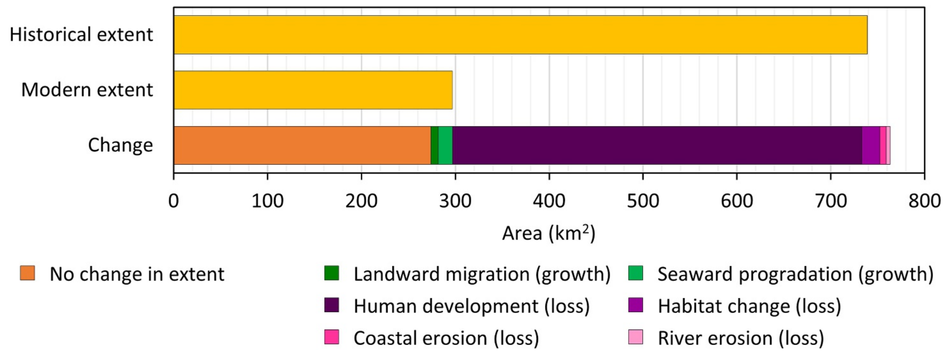

Figure 4. The historical and contemporary extent of dunes in California and the main drivers of change.

historically supported dune systems (Table 1). Observed increases in dune area due to the seaward progradation of foredunes (15 km^2) and (wind-driven) landward migration of dune fields (8 km^2) were comparatively small (Figure 4) and generally confined to sites in central and northern California.

3.3.1. Human Development

Human development represents the single largest cause of dune loss in California (Figure 4). We estimated that at least 436 km^2 (60%) of historical dune ecosystems and 5 km^2 of transitional environments have been lost due to human development associated with the expansion of residential communities, industry, and transportation networks, and conversion of historical dune areas to agricultural land (Figure 4; Figure S6 in Supporting Information S1). Dune loss from human development and land-use change is concentrated in central (326 km^2 or 97% of total regional loss) and southern California (106 km^2 or 95% of total regional loss), with a comparatively small area of dunes impacted in northern California (4 km^2 or 25% of total regional loss). In southern California, dune loss is primarily attributed to urban development in the Los Angeles area (Table 1). In contrast, loss due to urbanization and land-use change, including agriculture, is distributed across several areas of central California, including San Francisco, Monterey Bay, Morro Bay, and Santa Maria Valley.

3.3.2. Habitat Change

Processes that facilitated the transformation of historical dunes into wetland, forested, or grassland environments, were the most significant driver of dune loss in northern California (8.5 km^2 or 52% of total regional loss) and the second most significant driver in southern (2.2 km^2 or 2% of total regional loss) and central California (7.8 km^2 or 2% of total regional loss). Statewide, however, overall losses due to habitat change were marginal (<5%) relative to those attributed to coastal urbanization and infrastructure development (Figure 4). Analysis of historical aerial photographs and NDVI data revealed that in many locations vegetation cover has increased on coastal dunes over time, including locations that have experienced limited change in area since the mid-1800s.

3.3.3. Coastal and River Erosion

In total, an estimated 7 km^2 of coastal dunes have been lost due to coastal erosion since the mid-1800s (Figure 4). Foredune retreat was observed along more than 185 km (11%) of California's coastline, but was most significant in Año Nuevo State Park in San Mateo County (retreat of up to 520 m), Border Field State Park in San Diego County (retreat of up to 90 m), south of the Eel River in Humboldt County (retreat of up to 220 m), and the southern portions of Point Reyes (retreat of up to 120 m) and Monterey Bay (retreat of up to 80 m). At several locations, river erosion was also identified as a significant driver of dune loss. For instance, it is estimated that the Garcia River in Mendocino County caused the erosion of approximately 0.09 km^2 of the Manchester State Park dunes system. Even greater losses were recorded in other dune systems bordering large rivers in northern California, such as backdune areas of Tolowa Dunes State Park that border the Smith River (loss of ~0.50 km^2) and dunes in Humboldt County that border the Mad River (loss of ~0.77 km^2).

To a lesser extent, dune loss was also caused by the creation of water bodies associated with maritime infrastructure (e.g., ports, harbors, marinas, entrance channels), agriculture (e.g., irrigation channels), and the

Table 2
Coastal Dune Habitat Distribution and Connectivity Metrics Recorded in the Historical and Contemporary Inventories

		Patch size (km^2)			Distance to nearest patch (m)		
Period	No. of patches	Mean	Median	Range	Mean	Median	Range
Historical	232	3.10	0.05	<0.01 to 123.41	1405	414	106 to 26,046
Contemporary							
- With fragmentation	339	0.88	0.02	<0.01 to 64.84	948	302	100 to 19,375
- Without fragmentation[a]	193	1.54	0.02	<0.01 to 65.47	1703	721	106 to 19,375

Note. For each period, the total number of distinct patches of dune is presented, alongside the range, mean, and median patch size (km^2) and distance between neighboring patches (m). [a]Patches amalgamated based on overlap with historical dune patches.

redirection of river systems. Although examples exist across the State, dunes in southern California were found to be disproportionately impacted by the artificial creation/modification of aquatic systems, with an estimated 1.5 km^2 lost in this region as a result. This includes, for example, historical dune systems at the mouth of the Santa Clara River delta (Ventura County), that have been negatively impacted by the creation of harbors that service communities in Oxnard and Ventura, such as the Channel Islands Harbor, Ventura Harbor, and Ventura Keys.

3.3.4. Dune Expansion

Although most dune systems decreased in area over time, a few increased in size (Figures 3 and 4). This includes some smaller dune systems (<0.1 km^2) located close to river mouths, and larger complexes, such as those at Gold Bluffs Beach (Humboldt County) and Ten Mile Beach (Mendocino County), which increased in size by 2.8 and 0.6 km^2, respectively. Dune expansion varied by region and along latitudinal gradients (Table 1), with northern and southern California experiencing the largest (13.7 km^2) and smallest (3.1 km^2) increases, respectively.

In most locations, the seaward progradation of foredunes was the main driver of dune expansion. Since the mid-1800s, it is estimated that foredune progradation has created approximately 15.2 km^2 of new habitat, distributed along roughly 202 km of the coast. Significant areas of dune expansion due to the progradation of foredunes were recorded at Tolowa Dunes State Park (Del Norte County), Gold Bluffs Beach (Humboldt County), Little River State Beach (Humboldt County), close to the entrance channel of Humboldt Bay (Humboldt County), Ten Mile Beach (Mendocino County), Tomales Beach (Marin County), Salinas River State Beach (Monterey County), McGrath State Beach (Ventura County), and along the outer edge of San Diego Bay (San Diego County).

To a lesser extent, dune expansion was also caused by the landward migration of dune lobes or sheets, which resulted in the creation of approximately 8.3 km^2 of dune habitat across California. Significant areas of dune expansion due to the landward transgression of dune fields were recorded in Manchester State Park (Mendocino County), Ten Mile Beach (Mendocino County), Tomales Beach (Marin County), Point Reyes (Marin County), Morro Bay (San Luis Obispo County), and Ormond Beach (Ventura County), as well as isolated portions of Humboldt Bay (Humboldt County) and Santa Maria Valley (San Luis Obispo and Santa Barbara Counties).

Other notable areas of dune expansion include restoration sites in locations where dunes were narrowly distributed, ephemeral, or completely non-existent in the past. This includes, for example, dune restoration projects in Santa Monica (Los Angeles County) and within the San Francisco Bay Area (Alameda County), which cover a total estimated area of 0.04 and 0.06 km^2, respectively. In these areas, the artificial widening of beaches through sand nourishment has enabled dune development in locations previously underwater or heavily impacted by tidal processes.

3.4. Habitat Fragmentation and Isolation

Our findings for habitat fragmentation show a loss of larger contiguous areas of coastal dunes and a major decline in average patch size. In total, 232 distinct patches of dune were identified in the historical inventory, with a mean area of 3.10 km^2 (Table 2). In contrast, 339 patches were recorded in the contemporary inventory, with a mean area of 0.88 km^2. More than half the dune patches in the contemporary inventory are isolated from the shoreline and coastal processes by infrastructure and transportation networks, such as railroads and highways.

The average distance between patches (i.e., distance to nearest edge of nearest neighbor) was found to be 1,405 m in the historical inventory and 948 m in the contemporary inventory. However, for contemporary dunes this value increased to 1,703 m when local-scale fragmentation was eliminated through the amalgamation of patches that fell within historically contiguous dune areas (Table 2).

4. Discussion

4.1. Significant Losses in Critical Coastal Habitat Challenge Conservation Goals

Concern over the degradation and loss of coastal dunes is growing globally (Gao et al., 2020; Jackson et al., 2019). Our detailed analysis of dune ecosystems spanning 1,625 km of coastline over a 165-year period provides the most comprehensive assessments of dune habitat loss to date. Our results highlight a significant reduction in coastal dunes in California over the last 165 years, with dunes now existing at only 40% of the coverage compared to the mid-to-late 1800s. This mirrors similar losses reported for other coastal ecosystems in California over corresponding time periods, including estuarine and coastal wetlands (Dahl, 1990; Grossinger et al., 2011) and kelp forests (Scarborough et al., 2022), as well as dune systems in other parts of the world (Table S3 in Supporting Information S1).

Despite these significant losses, coastal dunes currently exist along 22% (352 km) of California's coast, covering an area of almost 300 km^2. In comparison, dune-backed beaches occupy nearly 45% of the coastline in the U.S. Pacific Northwest (i.e., Oregon and Washington) and only 7% in the United Kingdom (Doody, 2008; Ruggiero et al., 2018).

The estimated total dune area reported here is significantly greater (by up to 60%) than that provided in previous assessments of modern dune extent in California, such as CARI (SFEI, 2025), largely due to the misidentification of dunes as coastal bluffs or wetland environments in the past. This discrepancy emphasizes the importance of accurate measurements and the necessity for an improved methodology for assessing the extent of dune systems. An updated assessment of modern dune extent can help monitor progress toward achieving conservation goals, such as the statewide 30 × 30 initiative to conserve 30% of the State's lands and oceans by 2030 (California Executive Order N-82-20, 2020), and advance the refinement of modeling approaches used to simulate beach–dune responses to SLR and future extreme events. Our finding that almost one-fourth of the California coast is backed by dunes further highlights their ongoing importance as a critical ecosystem of interest in the region. For instance, when considered against past evaluations of beach and wetland environments (Dahl, 1990; Swirad & Young, 2022), our findings suggest that approximately one-third of beaches in mainland California are dune-backed and that coastal dunes cover an area almost half the size of all remaining coastal wetlands in the State.

Given the scale of dune loss identified here, it is vitally important that information on the location and extent of existing dunes is made available to practitioners, land managers, urban planners, and policy developers to help guide decision-making, resource allocation, and the identification of future restoration/conservation priorities. In addition to impacting native biodiversity (Grewe et al., 2021), widespread coastal dune loss has undoubtedly caused an appreciable reduction in the ecosystem services provided by these landforms, including flood protection. With coastal communities and ecosystems increasingly threatened by storm impacts and SLR, the loss of these services is likely to become increasingly problematic if not adequately addressed through nature-based adaptation strategies that promote the re-establishment of sustainable dune ecosystems.

4.2. Transient Dunes and Shifting Shorelines

Beach–dune systems are highly dynamic and, in unconstrained settings, will move via seaward progradation, landward translation, erosion, and accretion in response to variability and trends in wave and water level forcing, relative sea-level, sand supply, and vegetation cover (Woodroffe, 2002). Statewide, the total increase in dune area attributed to the seaward progradation of foredunes (approximately 15 km^2) was found to be more than double the area lost due to coastal erosion (7 km^2) indicating that in some locations long-term foredune evolution has been dominated by accretional, dune-building processes. Significant areas of foredune expansion, such as Little River State Beach in Humboldt County (up to 240 m of progradation) and northern Tolowa Dunes State Park in Del Norte County (up to 160 m of progradation), were recorded close to the mouths of major rivers in watersheds with a legacy of industrial logging, underlining the potential impacts of anthropogenic activities on sediment supply and dune development. Changing sediment loads and beach debris caused by deforestation, hydraulic mining, and excessive livestock grazing have been linked to similar changes in shoreline and dune dynamics across the Pacific Northwest and globally (Grilliot et al., 2019a, Grilliot et al., 2019b; Heathfield & Walker, 2011; Sampath et al., 2024). In a changing climate, dune ecosystems in California will be increasingly impacted by fluctuations in sediment supply caused by post-wildfire hillslope erosion (Warrick et al., 2022), dam construction and removal related to energy production and watershed restoration (e.g., Klamath River Dam removal project), and the gradual disappearance and/or displacement of beaches due to SLR and coastal squeeze (East & Grant, 2023; Slagel & Griggs, 2008; Vitousek et al., 2023). Historical changes in sediment supply and associated impacts on dune development, such as those identified here, could help guide future conservation and restoration efforts to aid the long-term survival of dune systems that remain. Self-sustaining dunes (re)introduced along stretches of the coastline experiencing stable or net increases in sediment supply may, for example, be easier and less costly to maintain than those located in sediment-starved areas, whose long-term survival may depend on more frequent and intensive human intervention (e.g., nourishment).

In addition to fluctuations in sediment supply, tectonic activity and related vertical land motion may also be an important driver of dune expansion and loss in California (Goff et al., 2008; Orme, 1992). In Humboldt Bay, for example, long-term foredune migration rates were found to broadly correspond to rates of relative SLR and vertical land motion over the last 165 years (Blackwell et al., 2020; Govorcin et al., 2025; Patton et al., 2017; Shinsato et al., 2025). Erosion (up to -0.5 m yr^{-1}) was concentrated toward the south of Humboldt Bay in regions influenced by tectonic subsidence. In contrast, foredune progradation (up to 1.25 m yr^{-1}) was greatest toward the north in regions experiencing relatively high rates of uplift (Figure S7 in Supporting Information S1). These findings contradict anecdotal evidence of dunes persisting in coastal areas of California that have experienced net tectonic subsidence or limited uplift (Orme, 1992). Establishing connections between foredune evolution, vertical land motion, and relative SLR, as well as catastrophic seismic-related events (e.g., tsunami, earthquakes), represents an important avenue of future research in California and other regions around the world with highly-populated, tectonically active coastlines (Goff et al., 2008). Detailed inventories, such as those presented in this study (Baxter et al., 2026; Data Set S2), enable these associations to be explored in greater detail and across larger spatial scales.

4.3. The Legacy of Invasive Species

The introduction of invasive plant species, such as European Beachgrass (*C. arenaria*) and iceplant (*Carpobrotus* spp.) has also played a significant role in coastal dune habitat change and loss in California. Initially introduced in the early 1900s for erosion control (Buell et al., 1995; Pickart, 1997), these species have since spread to most dune ecosystems in the State (Galaz Garcia et al., 2024; Pickart, 2021). Invasive species compete for resources with native plants and create monospecific zones that fundamentally alter the ecogeomorphic functioning of dune ecosystems (Hilgendorf et al., 2022; Pickart, 2021; Sarmati et al., 2019). Under certain conditions, *C. arenaria* and *Carpobrotus* spp. can facilitate dune development by enhancing sand accumulation and the stabilization of mobile sediment (Wiedemann & Pickart, 1996). However, on large established foredunes on the West Coast of North America, these species have also been shown to alter dune morphodynamics (Pickart, 2021; Ruggiero et al., 2018) and stunt foredune recovery from erosive events (Hilgendorf et al., 2022). The complex relationship between invasive species and the geomorphic evolution of coastal dunes is highlighted by two case studies in northern California, where *C. arenaria* is linked to both the expansion and contraction of different dune systems over time.

At Gold Bluffs Beach (Mendocino County), for example, analysis of historical aerial photographs from 1972 to the present-day (Data Set S1) suggest that the spread of *C. arenaria* may have contributed to the formation and expansion of the dune system throughout the second half of the 20th century. In support of previous assessments of this region (Warrick et al., 2023), we estimate that the foredune prograded seaward by up to 490 m and increased in area by at least 2.8 km^2 between 1873 and 2016. Dune development here is attributed to the spread of *C. arenaria* and other sand-stabilizing species, in combination with the southward migration of a coastal "sediment accretion wave" caused by industrial-scale logging, hydraulic mining, and extreme climatic events and associated fluctuations in local sediment supply from the nearby Klamath River (Warrick et al., 2023).

Further north, the introduction of *C. arenaria* has been linked to foredune erosion and the persistence of erosive scarps at the Lanphere Dunes Unit in Humboldt Bay (Hilgendorf et al., 2022). Consistent with past assessments of shoreline and foredune change rates along this stretch of coast (Hapke et al., 2006; McDonald, 2017; Rader et al., 2018), our findings indicate that the Lanphere Dunes have retreated by up to -0.31 m yr^{-1} since the 1870s. Field experiments and long-term observations previously conducted at Humboldt Bay suggest that *C. arenaria* alters airflow and sand transport dynamics over foredunes compared to native vegetation (Bauer et al., 2022), reducing the capacity of foredunes to recover from erosional events by maintaining steep dune profiles that limit the landward transfer of windblown sediment from the beach (Hilgendorf et al., 2022; McDonald, 2020; Pickart, 2021).

Over the last 120 years, the spread of invasive plants and woody vegetation has significantly altered the eco-geomorphology of coastal dunes in California, negatively impacting native biodiversity and, in some cases, the resilience of beach-dune systems to erosive events. The gradual "greening" of coastal dunes across California mirrors similar trends observed around the world (Jackson et al., 2019). Recent studies conducted in southern California and across the U.S. highlight the utility of using high-resolution aerial imagery (NAIP 4-Band Imagery; EROS, 2023) and NDVI data to monitor the extent and spread of invasive plants, including dune species (e.g., Galaz García et al., 2024; Meerdink et al., 2024; Villalobos Perna et al., 2023). By providing researchers and coastal managers with a comprehensive catalog of dune sites, detailed inventories of dune extent through time can aid the identification and prioritization of monitoring efforts, including those making use of remote sensing techniques, as well as more traditional field-based approaches. Long- and short-term changes in dune extent derived from these inventories may also help conservation managers evaluate the effectiveness of restoration projects designed to re-activate stabilized dunes through the removal of invasive (dune-stabilizing) plant species, with gains in dune area potentially indicating some level of success.

4.4. Past Human Impacts and Future Opportunities

Human development and land-use change were the most significant drivers of dune loss, causing estimated losses of approximately 436 km^2 (or 59% of the historical dune extent). This is primarily attributed to the growth of large urbanized centers and expansion of agriculture in central and southern California, such as in San Francisco (40.5 km^2), Los Angeles (95.5 km^2), Monterey Bay (73.9 km^2), and Santa Maria Valley (178.5 km^2). Infrastructure development has contributed to the loss of coastal dunes along approximately 98 km of the shoreline, significantly outweighing gains due to progradation of foredunes recorded along 39 km of the coast. Transportation networks (e.g., railroads and highways) now intersect dune ecosystems along vast stretches of the coastline, isolating them from beaches and making them more vulnerable to degradation, stabilization, and biological invasions (Galaz Garcia et al., 2024). These impacts are compounded by increased public access/use and the related trampling of dune plants, as well as mechanical grooming operations and reductions in sediment supply caused by the damming of rivers, mining of sand, and construction of coastal barriers (Clark, 2009; Dugan & Hubbard, 2010; Patsch & Griggs, 2006; Slagel & Griggs, 2008; Thornton et al., 2006). This includes along heavily urbanized beaches in southern California (e.g., Oxnard, Zuma, Santa Monica, Manhattan, and Huntington Beaches), where widespread public use, foot traffic, and beach grooming practices have limited contemporary dune development, including in areas that historically supported dunes (Figure S8 in Supporting Information S1). Hard engineered boundaries, such as breakwalls or roadways, also limit the natural capacity of beaches and dunes to migrate inland in response to storm events or SLR, reducing their resilience and adaptive capacity to future climate change impacts (Lansu et al., 2024). Dunes in heavily urbanized regions of southern and central California may be particularly vulnerable to SLR, as many were observed to be directly backed by infrastructure during the mapping process.

In addition to being more isolated, dune patches are now, on average, nearly one-fourth of the size they were in the mid-to-late 1800s (Table 2). Reduced patch size, habitat loss, and fragmentation significantly impacts species richness, community composition, and ecosystem functioning (Salgado et al., 2022; Sperandii et al., 2021). Fragmented habitats also support smaller populations of native taxa, increasing vulnerability to invasive plants and the probability of extinction/extirpation caused by demographic and environmental stochasticity (Fahrig, 2003; With, 2004). Reduced ocean and land connectivity further impacts native dune wildlife and flora by reducing species interactions and the dispersal of seeds by wind, ocean currents, or animals moving between adjacent beach, dune, and hinterland ecosystems. Detailed inventories of past and present dune extent can help inform the identification and prioritization of dune restoration sites that increase the connectivity of fragmented ecosystems, in addition to total dune area.

In small, localized areas, human development was also found to facilitate increases in dune extent. For instance, the construction of jetties at the entrance channel of Humboldt Bay in 1889 contributed to the seaward progradation of adjacent foredunes by up to 870 m (also refer to Hapke et al., 2006; Pickart & Hesp, 2019). Other notable cases of dune expansion resulting from jetty construction include Doran Beach in Sonoma County (up to 170 m), Morro Bay in San Luis Obispo County (up to 290 m), Moss Landing in Monterey County (up to 50 m), and Seabright Beach in Santa Cruz County (up to 80 m).

Other anthropogenic activities that facilitate beach widening, such as beach nourishment, have also facilitated the development and expansion of dunes in locations where they were historically scarce or narrowly distributed. This includes several areas of restored dunes located on beaches that have been artificially widened following decades of beach nourishment, such as Santa Monica Beach (Los Angeles County) and Hollywood Beach (Ventura County). At these sites, dunes exist in areas protected from public use and/or other anthropogenic pressures, such as mechanical beach grooming (Johnston et al., 2023). Our findings indicate that many beaches in southern and central California, including some of the most iconic and heavily managed in the world (e.g., Santa Monica), have supported dune systems in the past (Figure S8 in Supporting Information S1). Beaches widened by decades of nourishment with a history of dune development and competent wind regimes may provide potential opportunities for future dune restoration projects. The historical inventory presented here (Baxter et al., 2026; Data Set S2) provides coastal managers with a valuable tool for identifying the locations of historical dune systems, one of many factors, along with sand supply, foreshore width, and trends in relative SLR, that could be used to help prioritize sites suitable for restoration.

4.5. Global Insight for Coastal Dune Habitat Loss, Conservation, and Costal Resilience to SLR

California is among the most climatically and biologically diverse regions in North America (Burge et al., 2016; Cowling et al., 1996; Myers et al., 2000). The California coast encompasses a variety of climatic and biogeographic regions, and supports a range of land uses, from densely populated urban centers, intensive agriculture, and military bases, to extensive parks and wildlands. Given the geographical scope of our analysis—spanning 1,650 km in length and 9.5° of latitude—our methodology and findings may have global implications for identifying and describing critical habitat loss, and understanding the drivers and implications of change. Detailed inventories, such as those produced here, could be extended to other regions across the U.S. by taking advantage of *T*-sheets that are available for the entire U.S. coastline and high-resolution geospatial data (i.e., LiDAR, NAIP aerial imagery, satellite imagery) accessed through the NOAA Data Access Viewer website and similar repositories. Updates to existing inventories from around the world (Arens & Wiersma, 1994; Bezzi et al., 2018; Doody, 2008; Farrell & Connolly, 2019; Hilton et al., 2000; Prodanov et al., 2023) may also be possible using an integrated approach that combines historical maps, aerial imagery, and machine learning tools where comparable resources are available. The utility of these inventories is often proportional to their scale, geographic scope, and the range of ecological and geomorphic attributes characterized. Combined, high-resolution inventories that document eco-geomorphic changes and anthropogenic impacts over time can provide substantial utility for interpreting and managing critical habitats (Bezzi et al., 2018; Hilton et al., 2000). In turn, this information is vital for informing ecosystem restoration and coastal adaptation planning efforts to help mitigate the impacts of climate change and SLR.

In addition to providing detailed interpretations of dune extent, condition, and change over time, this study presents an updated assessment of contemporary dune morphology, with significant improvements in detail and coverage compared to previous assessments. Produced using high-resolution DEMs (1 m), our data set of modern (2016) dune extent includes information on the position and elevation of key dune features (i.e., dune toe and crest) at 30-m intervals along the entire California coast (Baxter et al., 2026; Data Set S2). Although aided by machine-learning tools, the identification of these features involved significant human input, setting our data set apart from those produced using automatic detection alone (e.g., Shope et al., 2022), especially for stretches of the coast where complex and/or variable dune morphologies (e.g., hummocky dunes, scarped dunes, blowouts, parabolic dunes) hinders the effectiveness of models relying on universal selection criteria. The inventories presented here also represent a significant improvement in terms of geographical coverage compared to previous assessments of coastal dunes in California (Clark, 2009; McDonald, 2017; Rader et al., 2018; Thornton et al., 2006; Warrick et al., 2023). Indeed, having exhaustively reviewed the literature, we believe our assessment of coastal dune extent and loss represents one of the most comprehensive ever produced globally (Table S3 in Supporting Information S1).

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Updated information on the position and elevation of foredune features and the location and extent of contemporary dune systems can inform coastal vulnerability assessments, efforts to restore habitat for federally protected species (e.g., C. *n. nivosus*), and the refinement of modeling approaches used to simulate and project beach–dune responses to future extreme events and SLR. This includes, for example, state-recognised modeling systems, such as CoSMoS (Vitousek et al., 2017, 2023), that are used to make detailed predictions of storm-induced coastal flooding, erosion, and cliff failures under future SLR scenarios in California. Although many processes that govern coastal change are already integrated into the model (e.g., beach erosion, cliff retreat, wave physics), CoSMoS does not currently account for the presence of dunes or sediment transport across dynamic, coupled beach–dune systems. In combination with site-specific topographic monitoring data sets (e.g., Emery et al., 2024; Winters et al., 2020), our inventory of modern (2016) dune extent could be used to aid the development of updated coastal change models by highlighting regions of the coastline where coastal dunes are more likely to influence sediment/shoreline dynamics.

More broadly, this study demonstrates the benefits of using an interdisciplinary, multi-methods approach to evaluate coastal dune morphology and ecosystem change over time. The data sets produced here were generated using a combination of techniques (i.e., historical archive analysis, human-supervised machine learning, workshops, and site visits) that enabled the identification and integration of information gathered from a diverse range of data sources. When analyzed together, this information allowed for detailed, holistic interpretations of landscape change not possible in isolation. While time-consuming, the systematic analysis of historical archives (e.g., early maps, aerial photographs, and reports) can provide information on past landscape conditions unattainable from other modern data sources or those prone to error in unsupervised methods. Although the future of coastal monitoring will increasingly rely on machine-learning approaches and satellite imagery (Vitousek et al., 2023), inventories like those developed here (incorporating manual digitization and labeling) can be used as training data (Buscombe et al., 2023; Murray et al., 2022) for automatic satellite-based machine-learning methods for land-cover classification. When combined, base inventories and automatic machine-learning approaches can be used to greatly enhance the temporal resolution and/or spatial extent of change detection, possibly even to national and global scales. Similar methods could also be explored to improve understanding of other types of coastal ecosystems shown in historical maps in California and around the world, including beaches, cliffs, rocky intertidal zones, kelp forests, and wetland environments.

5. Conclusions

The extent of coastal dunes in California has decreased significantly (i.e., 60%, 442 km^2) since the mid-1800s, due to coastal development, altered land-uses, and erosion. Although regional variations persist between northern, central, and southern California, modern dunes are typically more degraded and fragmented than in the past, and are smaller in size and less well connected. The construction of highways, railroad networks, and other forms of infrastructure have isolated more than half the remaining dune systems from beaches and coastal processes.

Given the importance of dunes in providing flood protection for communities and critical infrastructure, habitat for migratory, rare, and endangered species, and a multitude of other ecosystem services and co-benefits, the magnitude of losses identified here represents a significant challenge to California's shoreline protection, climate resilience, and biodiversity goals (California State Sea Level Rise Collaborative, 2024). Infrastructure development has contributed to the disappearance of foredunes along more than 95 km of the coastline, increasing the vulnerability of many coastal communities to storm-induced flooding, erosion, and SLR. Although large-scale coastal habitat loss and associated reductions in ecosystem services will be irreversible in some situations, restoration projects that promote the development of dynamic coastal dune ecosystems offer a viable adaptation pathway for mitigating climate change impacts and biodiversity loss. By helping to inform future conservation priorities and sites suitable for dune ecosystem (re)introduction and restoration, detailed assessments of coastal dunes, both past and present, can support these efforts and other NbS that promote the development of sustainable, climate-resilient, coastlines in the future. Although developed in the context of California, the methods presented here are widely applicable and could be scaled and adapted to support restoration prioritization, resource allocation, and resilience-building efforts around the world. As coastal dunes face increasing pressure from climate change impacts and anthropogenic activities, the wider application of these approaches is of global importance for safeguarding dynamic dune ecosystems and the crucial services they provide.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All the research data generated in this study, including the historical and contemporary dune inventories, difference maps, and location and elevation of toe and crest features are available to download as shapefiles from the CCDI (Baxter et al., 2026) available at https://doi.org/10.5061/dryad.hqbzkh1w7. These data are also provided in Data Set S2 as a .tar.gz file. If you are unable to access this data set, please download the file, rename its extension to .tar.gz and extract the archive. The historical dune inventory was produced using *T*-sheets downloaded from the NOAA Index of Non-Georeferenced Manuscripts (https://shoreline.noaa.gov/t-sheets.html). Historical aerial photographs downloaded from the California Coastal Records Project (Copyright © 2002–2026 Kenneth and Gabrielle Adelman, California Coastal Records Project, https://californiacoastline.org/) and UCSB Geospatial Collection (https://mil.library.ucsb.edu/ap_indexes/FrameFinder) were also used, in addition to historical maps downloaded from the U.S. Geological Survey TopoView Database (https://ngmdb.usgs.gov/topoview). The contemporary dune inventory was produced using aerial imagery and LiDAR DEMs downloaded from the NOAA Data Access Viewer website (https://coast.noaa.gov/dataviewer). Further details of all the data sets used in this study are provided in a Microsoft Excel spreadsheet in Data Set S1. The location and height of toe and crest features were determined using the HAML Dune Annotation Tool. Full algorithmic details of the tool are provided in the Appendix of Studer et al. (2023), with further details of the general framework underpinning the iterative process described in Michael et al. (2019). For further information, please contact the corresponding author, Timothy Baxter (timothy.baxter@prm.ox.ac.uk). Figures were made using ArcGIS Pro version 3.2.2, available under the ArcGIS Pro license at https://esri.com.

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