Evaluating the response of a pilot dune restoration project on an urban beach to an extreme wave surge event

By

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ABSTRACT

Coastal dunes are globally recognized as natural features that can enhance coastal resilience and protection from wave events, storm surges, coastal flooding, and longer-term sea level rise. As a result, dune restoration is being increasingly used along urban and natural coasts as an adaptation option for climate change. However, information on the performance of restored dunes in response to extreme events is limited. On urban beaches where management includes grooming, dunes are often degraded or absent, leaving coastal communities more vulnerable to flooding and erosion during storms and wave events. Following an extreme wave surge event in December 2023, we compared the performance of a small (1.2 hectare) pilot dune restoration on an intensively groomed urban beach in southern California to an adjacent mechanically groomed control site. We used total water level (wave setup, tide, wave runup) as a proxy for flooding potential. The average wave runup incursion distance was extended 13.6 m farther inland on the groomed control site compared to the dune restoration site. This result demonstrates the potential for restored dunes to enhance flood protection and the potential for increasing coastal resilience using nature-based solutions on urban beaches.

KEYWORDS: Climate change, coastal dune, drone, nature-based solutions, remote sensing, resilience, sandy beach.

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Climate change and the growing frequency and intensity of extreme events associated with climatic variability are major contributors to increased risks and widespread destruction and loss of infrastructure and ecosystems. These impacts are especially pronounced in the coastal zone, where pressures from both the land and the sea, coupled with human development impacts, are stressing these ecosystems and reducing their resilience to disturbance.

Highly valued as economic, aesthetic, and cultural assets and unique ecosystems, sandy beaches are particularly threatened by climate change on a global scale (Luijendijk *et al.* 2018; Davidson-Arnott *et al.* 2019; Vousdoukas *et al.* 2020). For example, modeled sea level rise (SLR) scenarios have predicted the state of California will lose a significant fraction of its sandy beaches, in some cases up to 24%-75% by 2100 without intervention (Vitousek *et al.* 2017; Myers *et al.* 2019; Barnard *et al.* 2021; Vitousek *et al.* 2023). Along with the press impacts of SLR and the pulse impacts of extreme events (e.g., wave-driven erosion, storm surges), urbanized beaches also face "coastal squeeze" impacts from urban development, coastal armoring, and other anthropogenic impacts that limit the capacity of beaches to absorb, respond, and/or adjust to SLR. This combination of high vulnerability and value makes beaches and dunes an ideal ecosystem for conservation and restoration to increase their resilience, as well as that of inland communities and their infrastructure, to climate change and extreme events.

Resilience is the capacity of coastal ecosystems to resist, persist, adapt, recover, and thrive under a changing climate. A resilient coastal ecosystem is one that can maintain its ecological attributes and functions, from provisioning biodiversity to conferring protection from storm and wave disturbances (Arkema *et al.* 2013; Spalding *et al.* 2013; Nguyen *et al.* 2022).

Losses of beach and dune habitats from coastal squeeze are reducing coastal resilience for many communities by decreasing associated protective functions for flood control, mitigation of erosion, and buffering of longer-term SLR impacts. In urban settings, the loss of habitat zones, reduced topographic heterogeneity, declines in vegetation cover, and a general lowering of the beach landscape increases the likelihood of coastal flooding and erosion compared to beach and dune ecosystems with greater habitat heterogeneity and natural features. This in turn reduces the resilience and recovery potential of the ecosystem and adjacent low-lying communities and critical infrastructure (Hauer 2017; Forzieri *et al.* 2018).

Nature-based restoration using dunes can enhance coastal resilience of beaches to SLR and extreme events (Kabisch *et al.* 2017, Narayan *et al.* 2016). Rather than armoring coastlines with hard infrastructure, restoring dunes can provide an alternative coastal protection strategy that can preserve ecosystem function and provide more dynamically responsive protection for the coast when compared to fixed infrastructure (Morris *et al.* 2019). Dunes as a coastal protection strategy function as a buffer against waves, increased water levels, and erosion (Sigren *et al.* 2014).

At a minimum, restoring dunes can provide an option in coastal adaptation

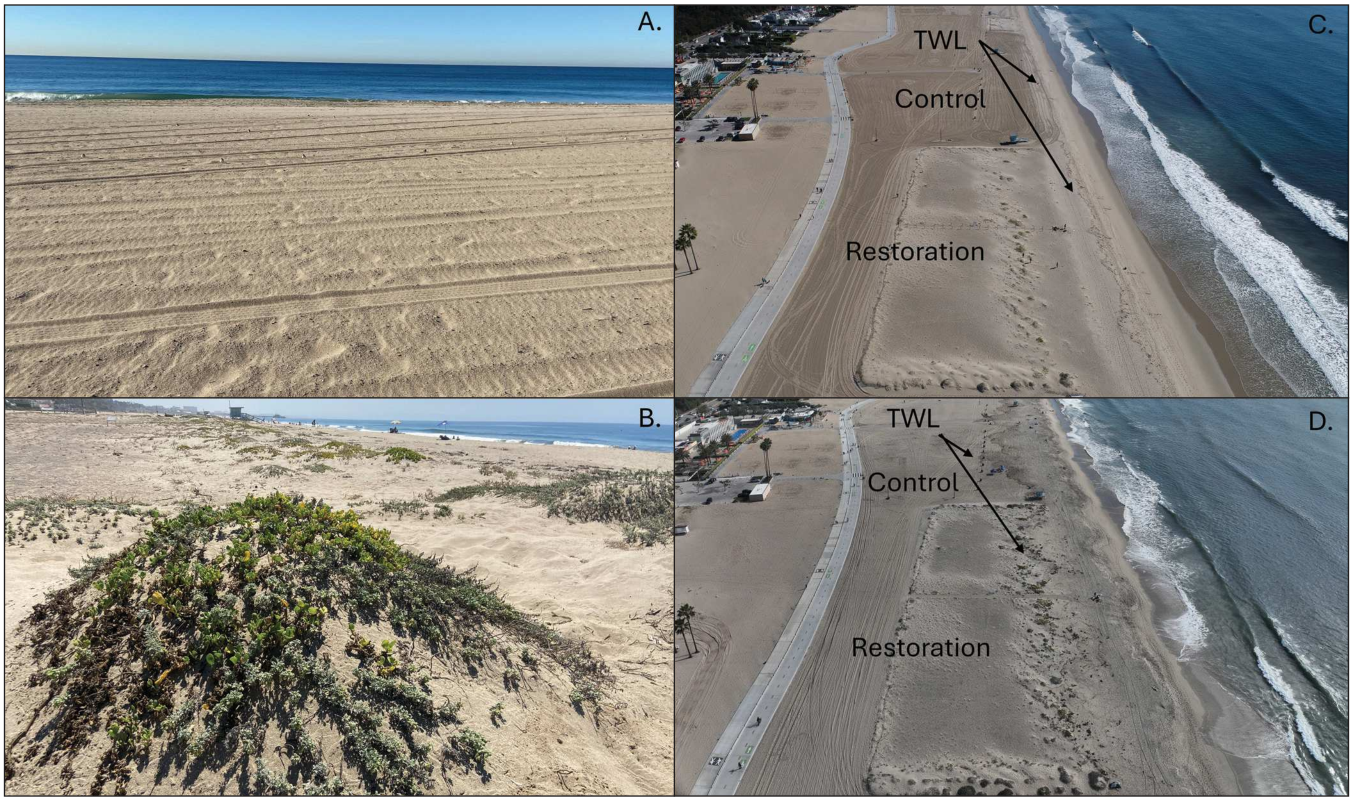

Figure 1: (A) The mechanically groomed control site and (B) the vegetated foredune ridge inside of the restoration site. An oblique aerial view of the eastern portion of the Santa Monica Beach Restoration Pilot Project site and the adjacent control site, showing (C) the position of the total water level line at equivalent locations low on the beach face under average summer conditions in August 2023, and (D) the total water level line extending further inland on the beach outside of the restoration site in January 2024. (Photo for Figure 1(A) and Figure 1(B) by Karina Johnston. Photo for Figure 1(C) and Figure 1(D) by Kyle Emery.)

pathways that offers a broader range of positive ecosystem services to enhance coastal values and resilience (Drius *et al.* 2019). Large-scale constructed sand berms and dunes have been utilized as coastal protection strategies but require intensive manipulation of the beach (Matias *et al.* 2005; Magliocca *et al.* 2011; Gesing 2019). Nature-based solutions, as an alternative approach, can include highly passive restoration strategies and be significantly more cost-effective (Acosta *et al.* 2013; Lithgow *et al.* 2013; Johnston *et al.* 2023). Urbanized coasts with wide groomed beaches are particularly suitable for nature-based adaptation using dune restoration.

The cessation of intensive management practices, like grooming or raking, can promote the recovery of dunes with minimal human intervention. For example, such practices can promote the formation of features like foredunes, which can potentially enhance the resistance and resilience of the overall ecosystem (Johnston *et al.* 2023). Results of a pilot dune restoration project in Santa Monica, California, USA (34° 01' 27.4" N, 118° 30' 57.8" W), demonstrated that, through the growth and expansion of native dune vegetation (primarily *Abronia maritima* (red sand verbena), *Ambrosia chamissonis* (beach bur), *Atriplex leucophylla* (beach salt bush), and *Camissoniopsis cheiranthifolia* (beach evening primrose)) and subsequent trapping of sand, a foredune ridge accreted by natural aeolian processes to a height of approximately 0.9 m above the adjacent unrestored beach over the course of six years (Johnston *et al.* 2023).

While evidence exists demonstrating the response of beach and dune ecosystems to extreme events (Feagin *et al.* 2019; Castelle and Harley 2020; Garzon *et al.* 2021), including in experimental settings (Feagin *et al.* 2023), there is a paucity of information about the response or performance of restored sites during and after extreme events (Zabin *et al.* 2022), as compared to overall restoration performance (Walker *et al.* 2022; Johnston *et al.* 2023). This is an important knowledge gap in determining the coastal resilience potential of dune restoration efforts.

Here, we assess seawater incursion distance and wave runup in the dune restoration site to runup in an adjacent mechanically groomed control site during an extreme storm–driven wave surge event by comparing the position and elevation of the resulting total water levels (TWL, predicted tide + wave setup + wave runup), a proxy for flooding potential.

METHODS

The Santa Monica Beach Restoration Pilot Project was implemented in two phases over the course of two weeks in December 2016. This pilot restoration project (1.2 hectares) has developed features characteristic of a natural southern California foredune system (Figure 1; see Johnston *et al.* 2023 for monitoring results).

Following an extreme large wave event on 31 December 2023, we conducted a survey to evaluate the performance of this dune restoration to a wave-driven disturbance event. On 2 January 2024 we flew a mapping mission at 25 m above ground level using an uncrewed aircraft system (UAS, DJI Mavic 3M) to fully image the restoration site and the control site to the east.

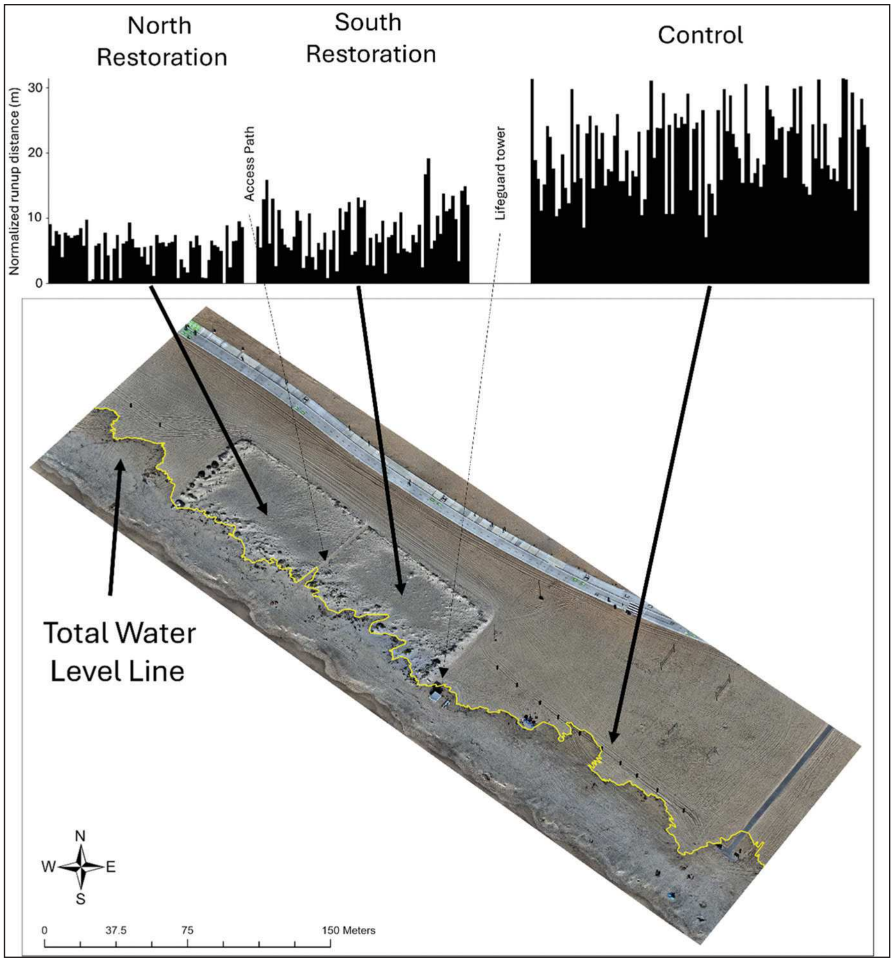

Figure 2: An orthomosaic of the Santa Monica Beach Restoration Pilot Project dune restoration site with an inset of normalized wave runup incursion distance showing the greater inland distance of the total water level line on the beach in the control site outside of the dune restoration site. Excluded regions (access path and lifeguard tower) are indicated with dashed lines.

Image alignment and generation of an orthomosaic and digital elevation model were conducted in Agisoft Metashape (Agisoft LLC) using position and elevation data from 15 ground control points surveyed with an Eos Arrow Gold+ (Eos Positioning Systems). Horizontal accuracy for the resulting orthomosaic was 1.3 cm and vertical accuracy was 2.5 cm.

The maximum total water level line was delineated in ArcGIS Pro and compared to a shore-parallel reference line in order to measure the seawater incursion distance for cross-shore transects placed at 1-m intervals across the study area. The elevation at total water level line was also extracted in 1-m increments across the study area.

We did not include data from the pedestrian path in the center of the restoration site or from the area of the lifeguard tower southeast of the restoration site. We compared the wave runup incursion distance and runup elevations inside the restoration site to values from the control site using one-way ANOVA in R (R Core Team 2021). The delta value of wave runup incursion distances was calculated by subtracting the mean seawater incursion distance between the control and the restoration areas.

Wave buoy data was downloaded from the Coastal Data Information Program for Santa Monica Bay (https://cdip.ucsd.edu/m/products/?stn=028p1) (Krisnamurthy 2024). Significant wave height was averaged by day for the 24-year period from March 2000 through May 2024 and the December 2023 wave event was compared to other observations in the series.

RESULTS

The wave disturbance event evaluated in this study peaked in Santa Monica Bay on 31 December 2023. The mean significant wave height for that date was 2.9 ± 0.4 m and the maximum observation in the series was 3.8 m. This wave event was in the top 15, or 0.17%, of daily wave events for the period March 2000 through May 2024. No erosion was observed in the foredunes at the restoration site, but there was minor scarping on the beachface. The position of the highest total water level, or slope runup distance, normalized to the minimum observation across the study area, was on average 6.7 m ± 3.7 m in the restoration site and 20.4 m ± 6.1 m in the control site (Figure 2A).

On average, the event generated a wave runup incursion distance that was 13.6 m farther inland (as horizontal distance) in the groomed control site than in the dune site (Figures 1D and 2). The incursion distance was significantly farther inland in the control site than in the restoration site (one-way ANOVA, $F = 459.3$, $p << 0.0001$) while the runup elevation was comparable at 4.3 m ± 0.1 m (NAVD 88) inside the restoration site and 4.25 ± 0.1 m in the control site (Figure 3). While elevation values differed significantly between the restoration site and the control site (one-way ANOVA, $F = 25.6$, $p < 0.0001$), the mean difference was only 5 cm (Figure 3).

DISCUSSION

A number of beaches in California experienced significant erosion during the December 2023-January 2024 extreme wave event. We detected a significant effect of the Santa Monica Beach pilot dune restoration site on the effect of wave runup during this event on the horizontal distance of seawater incursion on the beach.

Generally, wave runup at the site generated a 13.6 m greater incursion over the beachface in the unrestored and mechanically groomed control site (Figure 2), which appears to be related to the steeper beachface and higher elevation provided by the development of a low foredune ridge in the restoration site that is roughly 0.9 m higher than the same zone of the unrestored beach (Johnston *et al.* 2023). TWL reached similar elevations inside and outside of the restoration site (4.30 m and 4.25 m, respectively) but the distance inland was notably less in the dune restoration site due to its higher elevation and steeper beach-face slope, thereby providing more protection from waves and flooding (Figure 3).

This difference in wave runup response reflects the influence of the de-

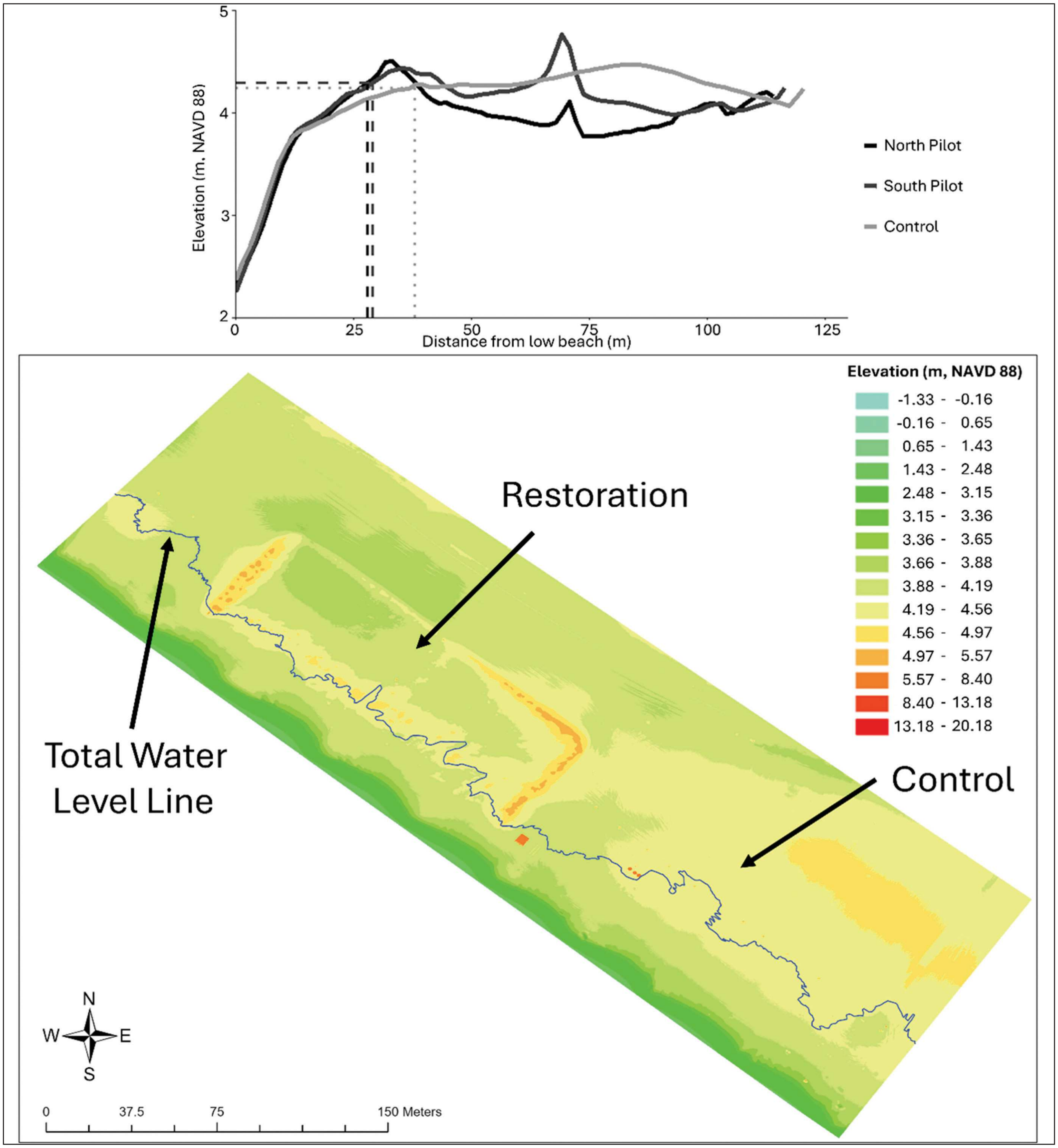

Figure 3: A digital elevation model of the Santa Monica Beach Restoration Pilot Project dune restoration site and adjacent control site with an inset displaying cross-shore transects of the north and south sections of the restoration site and the control site with dashed lines indicating the mean positions and elevations of the total water level (north restoration = black, south restoration = dark grey, control site = light grey).

veloping foredune on beach slope wave runup, which was slightly higher and had significantly less inland incursion than on the flatter, groomed control site. As such, the increased elevation on the backshore offered by the foredune provided greater protection against inland seawater incursion from this extreme wave event to 66% of that experienced at the control site (Figure 2). However, a depression landward of the foredune in the pilot restoration site, possibly due to aeolian deflation (Ruz and Allard 1994, Hesp *et al.* 2022), may affect responses to more extreme high-water events (Figure 3). The differences in cross-shore profiles between the restoration and the control sites highlight how the buffering capacities and resilience to extreme events vary with management and restoration practices (Figure 3).

Our findings demonstrate how nature-based dune restoration on an urban beach can increase buffering capacity against extreme wave events as well as the more gradual impacts of SLR (Fernández-

Montblanc *et al.* 2020) and, potentially, enhance coastal resilience. Results from this small pilot dune restoration area highlight the potential for enhancement of coastal resilience through dune restoration. However, research on larger scales is needed to more fully evaluate the performance of dune restoration on urban beaches.

Compared to hard engineering approaches, nature-based solutions can be more effective and less costly for enhancing resilience and coastal protection (Narayan *et al.* 2016). In coastal dunes, nature-based restoration efforts that require minimal interventions (i.e., sand fencing, broadcast seeding, etc.) can quickly result in the development of an ecologically functional dune ecosystem (Johnston *et al.* 2023; Walker *et al.* 2023). Natural processes, including sand transport and colonization by dune plants, facilitate the development of coastal dunes when connectivity between the beach and the nearshore is high and human-mediated disturbance (armoring, grooming, etc.) is minimized (Costas *et al.* 2024). Vegetated dunes are significantly more resilient to storm and wave erosion, highlighting their important role as a natural protective structure for sandy coastlines and adjacent infrastructure (Sigren *et al.* 2014; Bryant *et al.* 2019; Hilgendorf *et al.* 2022). Restoration of dune ecosystems has also demonstrably enhanced their ecological structure and functioning (Nordstrom *et al.* 2000; Lithgow *et al.* 2013).

It is imperative to evaluate restoration projects after major disturbance events — not only to determine the resilience of the restoration, but to determine the extent of the resilience of the broader ecosystem and/or community (DeAngelis *et al.* 2020; Kurth *et al.* 2020; Bacopoulos and Clark 2021; Musumeci *et al.* 2022). Quantifying the coastal resilience conferred by restoration projects will inform future projects and demonstrate their importance to managers and stakeholders.

Our results for a pilot project highlight the potential enhancement of coastal resilience through dune restoration, but more research on scaled-up comparisons is needed to address these important questions.

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