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Dynamic restoration and the impact of native versus invasive vegetation on coastal foredune morphodynamics, Lanphere Dunes, California, USA

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Abstract

The Lanphere Dunes, part of the Humboldt Bay National Wildlife Refuge, has been the focus of foredune restoration efforts since the 1980s. Efforts have centred around removal of an invasive European beach grass species, *Ammophila arenaria*, introduced in the early 1900s to stabilize the dunes to protect landward communities from coastal flooding and storm surges. Despite effectively stabilizing the foredune, *A. arenaria* forms monotypic vegetation stands, with highly dense roots, rhizomes, and above-ground biomass that can lead to pronounced scarping of the seaward slope, alongshore steering of wind and sediment, a lack of landward transfer of sand, and a steeper, more peaked profile.

Effective foredune restoration must consider the coupled interactions between dominant plant type and the geomorphic processes that influence dune form. A 5 ha reach of recently restored foredune was monitored biannually with terrestrial laser scanner and uncrewed aerial systems platforms between 2015 and 2021 to characterize the impacts of dynamic restoration on foredune form and resiliency. This reach included two control plots: (1) native, non-restored and (2) invasive, and three restored plots revegetated with native species: (3) a native grass (*Elymus mollis*), (4) a low-lying herb and subshrub assemblage, and (5) a mixture of the native grass, herbs, and subshrubs.

After five growing seasons, restored plots exhibited distinct geomorphic and sediment budget differences. Natively vegetated plots recovered from extensive scarping 2 years faster than the invasive plot. Restored plots saw foredune height (0.5–0.7 m) and width increase, landward extension (1 m) while maintaining a similar seaward position, and positive lee-slope sediment budgets that exceeded both control plots (up to 0.015 m^3 m^{-2} $month^{-1}$). These results suggest that the native vegetation plots allowed increased landward sand transport across the foredune, and increased the capacity of the foredune to recover more quickly following dune scarping.

KEYWORDS
aeolian, coastal erosion, ecomorphodynamics, foredune morphodynamics, foredune restoration, geomorphic change detection (GCD), terrestrial laser scanning (TLS)

1 | INTRODUCTION

Sandy coastal environments are under increasing pressure from the impacts of rising sea levels, coastal flooding, and erosion. Recent studies estimate that 24% of the world's sandy beaches are eroding at a rate exceeding 0.5 m yr^{-1}, putting many coastal communities and protected marine habitats directly at risk (Luijendijk et al., 2018). Currently, 75% of global megacities (>10 million people) are situated in coastal regions (Luijendijk et al., 2018) and an estimated 146 million people along the coast are within 1 m of mean high tide (National

Academies of Sciences, Engineering, and Medicine, 2018). Studies from the Pacific basin (Barnard et al., 2015, 2017) found that El Niño Southern Oscillation (ENSO) events drive coastal erosion and will continue to impact coastal communities throughout the Pacific. Estimated trends and modelled sea level rise (between 0.9 and 1.8 m) have shown that 4.2–13.1 million US citizens could be at risk of inundation (Hauer et al., 2016). Recent assessments (Barnard et al., 2019, 2021) suggest that many coastal regions could be reaching a 'tipping point' with regard to coastal flooding hazard, biodiversity, and ecosystem function if current trends in sea level rise hold constant or accelerate and steps to mitigate these trends are not taken.

Coastal foredunes can serve as a buffer to protect coastal communities from the impacts of coastal erosion, flooding, and sea level rise. They also serve an important role as an ecosystem service, providing opportunities for recreation (off-highway vehicles, hiking, tourism) and habitat for native and endemic biota. However, species introduction and the ability of introduced (often exotic) species to overwhelm native biota and modify coastal dune form (Buell et al., 1995; Cooper, 1958; Hacker et al., 2019, 2012; Hart et al., 2012; Hesp, 2002; Maun, 2009; Ruggiero et al., 2018; Wiedemann, 1998; Wiedemann & Pickart, 1996; Zarnetske et al., 2012, 2015) is being experienced at a global scale (Maun, 2009; Seebens et al., 2017). It is expected that the encroachment of invasives into new regions will only increase with further anthropogenic influence and climate change projections (Mainka & Howard, 2010; Pyke et al., 2008; Seebens et al., 2017).

Dune management and restoration is often employed to mitigate some of the aforementioned pressures. Some restoration methods, including dune stabilization, have been widely criticized for reducing ecological and geomorphic complexity (Arens et al., 2020, 2013; Austin & Walker-Springett, 2021; Creer et al., 2020; Jackson & Nordstrom, 2011; Jackson et al., 2013; Martínez et al., 2008; Nordstrom, 1994; Nordstrom et al., 2011; Rhind et al., 2013; Walker et al., 2013). Species-driven approaches to restoration and management, which typically focus on increasing the biodiversity of plant species or maintaining a status quo with regard to the number of species present (Cooper & Jackson, 2020; Delgado-Fernandez et al., 2019; Everard et al., 2010; Lithgow et al., 2013; Westhoff, 1989), have also been criticized as being too 'interventionist' (Delgado-Fernandez et al., 2019) and akin to 'dune gardening' without regard for active geomorphic processes (Cooper & Jackson, 2020).

We note a distinct difference in management and restoration goals, differentiating species-driven practices from contemporary 'dynamic' restoration practices. Dynamic restoration aims to restore the form and function of a geomorphic system and improve landform resilience to external pressures by employing complementary native plant species (Arens et al., 2013; Cooper & Jackson, 2020; Darke et al., 2013, 2016; Delgado-Fernandez et al., 2019; Eamer et al., 2013; Pickart, 2013; Walker et al., 2013). We regard landform resilience as an ability to maintain, regain, or translate form, in response to sea level rise or erosion. This type of approach places emphasis on the ecological and geomorphic interactions within a landscape to improve the overall function and resiliency of the system to external pressures. The focus of this study is on a dynamic restoration project in northern California, where the goal of restoration was reinstating ecomorphodynamic function to an invasively vegetated and stabilized foredune.

This study examines the impact of vegetation type on sand transport and deposition patterns over the foredune. Native vegetation, which maintains a lower plot density, should exhibit better sediment connectivity and a broader shape compared to *Ammophila arenaria*, which grows at a much greater density. Such differences have longer-term implications for the ability of the foredune to migrate in response to sea level rise while maintaining a positive sediment budget and resilient morphology. This study addresses a gap in the assessment of coastal dune restoration efforts (Pickart et al., 2021) by examining meso-scale (months to years and hundreds of metres, as per Walker et al., 2017) changes across an established foredune. Six years of observations using biannual high-resolution terrestrial laser scanning (TLS) surveys and topographic differencing methods quantified foredune morphodynamics and sediment budget responses to a dynamic restoration strategy designed to remove invasive species and reintroduce different native plant assemblages. Changes in plant cover and biomass were assessed from vegetation point clouds and uncrewed aerial system (UAS) products from November 2015 to September 2021, to provide insights into the coupled trends of foredune change and vegetation development.

2 | STUDY SITE

The Lanphere Dunes are part of the Humboldt Bay National Wildlife Refuge located in northern California, USA (Figure 1). Typical aeolian forms include seasonal nebkha/incipient dunes, formed within seasonal vegetation on the upper beach, a single, continuous, established foredune ridge, a vegetated transgressive dunefield featuring long-walled parabolics and blowouts, and relict, forested dunes at the landward extent of aeolian deposits (Pickart & Hesp, 2019; Rader et al., 2018). The property is managed by the United States Fish and Wildlife Service and the study area encompasses 350 m of protected established foredune. Foredunes within the Humboldt Bay region have a history of restoration efforts, primarily focusing on the removal of invasive species (Pickart, 1988, 2013, 2021; Pickart & Hesp, 2019; Pickart & Sawyer, 1998; Pickart et al., 2021). This project is part of a larger coastal vulnerability assessment and serves as a demonstration site for methods to improve landform resilience to coastal erosion and sea level rise.

Continuous foredune ridges, formed by rhizomatous and perennial herbaceous species, are typical of temperate climates (Hesp et al., 2021). Climate in the region is classified as a Csb (Köppen–Geiger) climate, featuring temperate weather with warm, dry summers and wet winters. Precipitation ranges from an average of 0.4 cm in July to 16.1 cm in December, with an average of 96.7 cm of precipitation between October and May. Prevailing winds are bimodal, ranging from north-northwest (spring–autumn) to south-southeast in the winter (Pickart & Hesp, 2019). The peak wind season occurs in April and May, when sand transport events occur and wind gusts can reach 27.5 m s^{-1}. Beaches are characterized by high-energy, dissipative to intermediate, multi-barred surfzone–beach systems with west-northwest swells between October and April. Prominent foredune vegetation includes native alliances (e.g. *Elymus mollis*, dune mat herbaceous alliance), exotics (e.g. *Cakile edentula*, *Cakile maritima*), and invasive species (e.g. *A. arenaria*, *Lupinus arboreus*) (Pickart & Hesp, 2019).

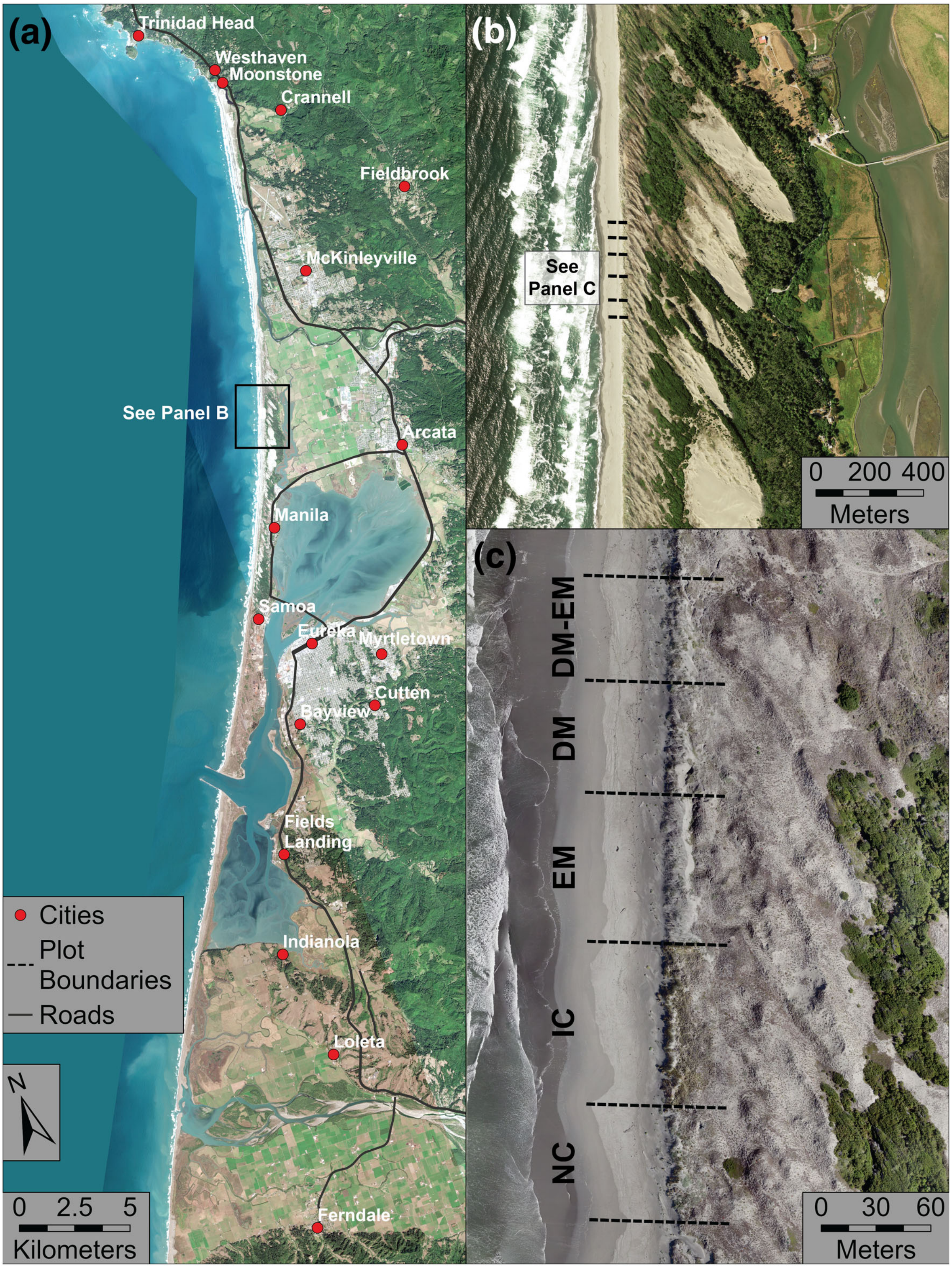

FIGURE 1 (a) Study area at the Lanphere Dunes in northern California, USA. Sentinel 2 orthomosaic from 09 Oct 2021. (b) Airphoto of the Lanphere Dunes study area. Image from the 2020 National Agricultural Imagery Project (NAIP) orthomosaic. (c) Restoration treatments at the study site, UAS-based orthophoto from 29 Sept 2021. DM-EM = dune mat–*E. mollis* mix; DM = dune mat; EM = *E. mollis*; IC = invasive control; NC = native control. The foredune crest is oriented with a 19° bearing (true north).

3 | DYNAMIC RESTORATION EFFORTS

The history of restoration at Lanphere started in the 1980s (Pickart, 2013), initially focusing on the removal of invasive species, including *A. arenaria*. Methods aimed at invasive plant species eradication and native revegetation were locally developed between 1982 and 1990 (Pickart & Sawyer, 1998). Further restoration projects occurred between 1992 and 1998 and 2005–10 (Pickart, 2013). This project was initiated in 2015 and, at the time, the foredune was fronted by an incipient foredune that had been building seaward since at least 2012. Sparse vegetation on the incipient foredune consisted primarily of *Cakile* spp., with *E. mollis* (native dune grass) and *Abronia latifolia* (yellow sand-verbena). *Cakile* spp. are an introduced species but play an important role in incipient dune formation in the region and rarely displace native plants on established foredunes. Due to its lack of persistence, *Cakile* is not considered invasive and serves as a nurse cover in some restoration projects (Pickart & Sawyer, 1998).

The restoration area was divided into four approximately equal zones which were randomly assigned to one of three treatments or a control (Pickart, 2017). A native control plot (NC) was situated directly south of three restoration treatment plots and an invasive control (IC). The restoration treatment plots consisted of *E. mollis* (EM), dune mat herbaceous alliance (DM), and a combined dune mat–*E. Mollis* mix (DM-EM) (Figures 1C and 2). The three treatment plots were planted with different configurations of native species, at a planting density of approximately 1 plant m^{-2}. *A. arenaria* was removed by the California Conservation Corps through manual techniques that have been successfully tested in other local restoration projects (Pickart, 2013; Pickart & Sawyer, 1998). Surviving plants were spot retreated with a herbicide (imazapyr) in 09/2016. Much of the eastern edge was not treated due to the presence of native plants that were already beginning to colonize. Surviving *A. arenaria* resprouts were dug prior to native planting (12/2016) and after spring emergence. To date, *A. arenaria* has been confined to the control plot and has been effectively removed from all restored plots.

Native species were harvested from local populations and replanted by USFWS staff within the restoration plots. The rationale for the following planting strategies was determined by USFWS staff to stimulate establishment of plant communities that mimic local populations without overcrowding. The EM plot consisted of *E. mollis* planted at a density of 1 planting node m^{-2}. The DM plot was planted with consideration for preferred burial/disturbance regimes for plants within the dune mat herbaceous alliance. Some species are better adapted to grow where rapid changes in burial/disturbance are common (e.g. on the seaward slope; near the dune toe) or less common (e.g. along the landward slope; within more stable, unchanging surfaces). Species adapted to unstable substrates, including *Erigeron glaucus* (seaside daisy), *Poa macrantha* (beach bluegrass), and *Lathyrus littoralis* (beach pea), were planted on the seaward face of the foredune. Later successional species, including *Solidago spathulata* (dune goldenrod), *Armeria maritima* (sea thrift), *Achillea millefoliata* (yarrow), and *Polygonum paronychia* (dune knotweed), were planted in the interior. A mixture of the two groups was planted on the foredune crest. Juvenile individuals were alternated with native seeds for a 1 plant m^{-2} density. The DM-EM plot was planted with *E. mollis*, dune mat individuals, and native seeds, for a 1 plant m^{-2} density. In this treatment, in an area of 4 m^2, there was one *E. mollis* plant and three dune mat plants, two of which were planted as seeds and one as a division.

4 | METHODS

4.1 | Terrestrial laser scanning

TLS data were collected in the spring and autumn each year from 11/2015 to 09/2021, resulting in 13 intervals of change (Table 1). Spring collections captured the effects of the erosive winter regime

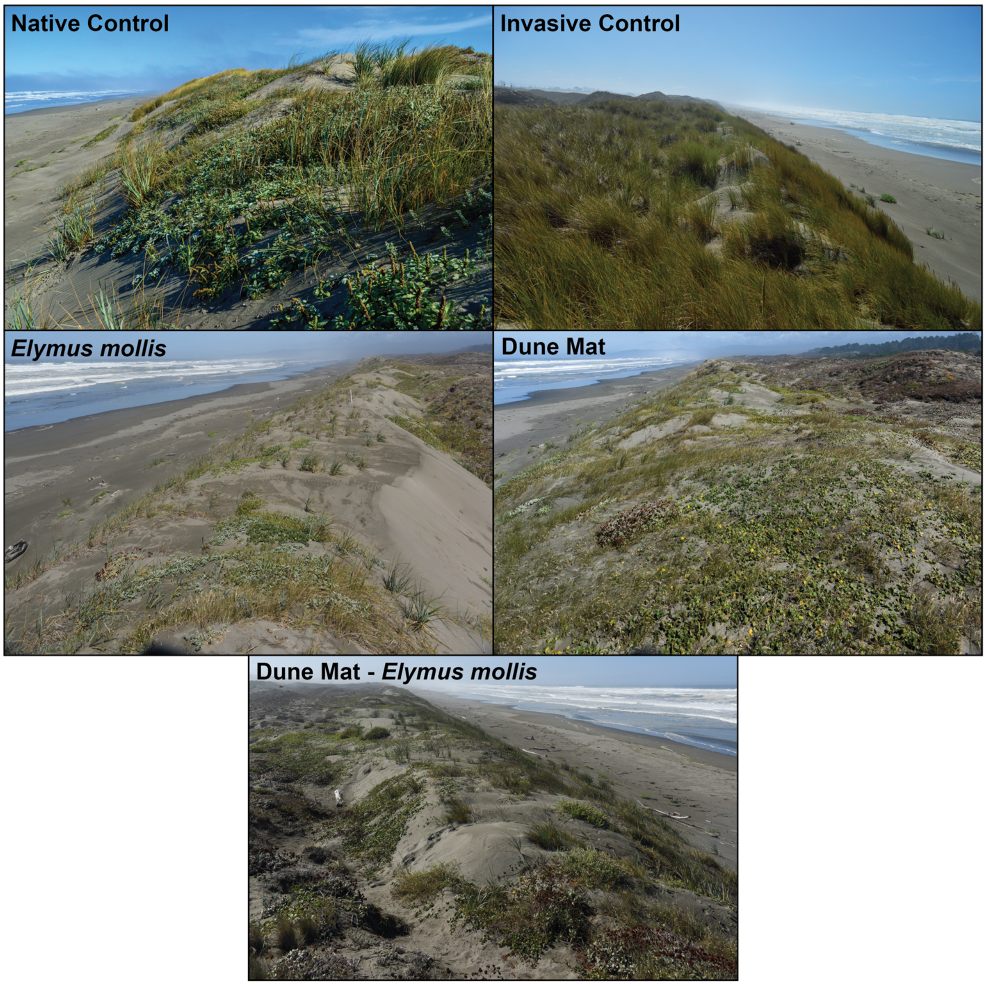

FIGURE 2 Photographs of the five plots from 28 Sept 2021. The NC, EM, and DM vantages are looking towards the north, while the IC and DM-EM vantages are looking towards the south. Photo credit for the NC and IC panels to A. Hilgendorf. Photo credit for the EM, DM, and DM-EM panels to Z. Hilgendorf.

TABLE 1 Field collection specifications and observations for TLS data. Cumulative uncertainty (m) refers to the combination of collection-based and processing-based uncertainties as described in Hilgendorf et al. (2021). The presence of an erosional scarp during collection was also noted, if present, for each collection

Collection date	Scan positions	Scarp present	Cumulative uncertainty (m)
09 Nov 2015	41	No	0.037
28 Apr 2016	35	All Plots	0.037
07 Sept 2016	32	No	0.037
04 May 2017	38	All Plots	0.038
23 Oct 2017	44	All Plots	0.036
22 May 2018	59	All Plots	0.035
06 Oct 2018	54	IC Only	0.037
17 May 2019	78	IC Only	0.033
16 Sept 2019	53	IC Only	0.035
11 Oct 2020	48	No	0.039
23 Feb 2021	51	No	0.032
21 May 2021	57	No	0.036
14 Aug 2021	44	No	0.040
28 Sept 2021	51	No	0.032

and the senesced to early growth state of vegetation. The early autumn campaign captured typical summer beach-dune rebuilding, as well as the extent of vegetation growth and expansion. No spring collection campaign occurred in 2020, due to COVID-19 travel restrictions. Winter and summer campaigns were added in 2021 to capture more detailed geomorphic and vegetation change over the year. Campaigns from 11/2015 through 05/2017 utilized a RIEGL VZ-1000 TLS system and reflector rods that were surveyed with a Trimble R10 GNSS receiver to co-register scan positions. Scanning campaigns after 05/2017 utilized a RIEGL VZ-400i TLS system integrated with a Trimble R10 system in RTK mode that recorded each scan location for co-registration with positional accuracy to 0.015 m. Scan positions were chosen in the field to reduce the effects of shadowing and ensure sufficient interscan overlap, similar to methods highlighted by Bangen et al. (2014), Grilliot et al. (2019), and Guisado-Pintado et al. (2019).

TLS campaigns were processed in RiSCAN Pro (2.7.1 to 2.12.1). Point clouds were cleaned and separated into bare earth and vegetation components and then rasterized to a cell size of 0.1 × 0.1 m in ArcMap 10.7.1 (ESRI, 2019) for further processing and analysis. Further details and information are provided in the online Supplementary Material.

4.1.1 | Topographic change analysis

Topographic differencing is a widely utilized method that compares older and newer input surfaces to compute a pixel-based volume of change for a given interval (Brasington et al., 2000; Lane et al., 2003; Walker et al., 2021; Wheaton et al., 2010). We utilize the Geomorphic Change Detection (GCD) plugin for ArcMap 10.7.1 (Riverscapes Consortium, 2020; Wheaton et al., 2010; see the online Supplementary Material for processing specifications). Results provide area-normalized volumetric change ($m^3\ m^{-2}$), which is then normalized by months between collections and subset for further analysis.

Each of the 14 surveys were delineated to include the five different vegetation plots and three different geomorphic units (beach, seaward dune slope, lee-slope base), following methods previously used at the site (Hilgendorf et al., 2021; Rader, 2017). The thinnest beach width was used to define the seaward boundary of the 'beach' zone for all intervals. The different geomorphic units of a foredune are difficult to distinguish and the debate over where the seaward slope ends and the upper beach begins, for example, highlights these difficulties (e.g. Smith et al., 2020). To be consistent across all campaigns, a single user digitized all subregions using a combination of slope, aspect, shaded relief, transects extracted from the LAS data, and topographic openness (red relief image; Chiba et al., 2008). The crest position of the foredune, which represents the boundary between the seaward and lee slopes, was delineated using the Basin tool in the ArcMap Spatial Analyst package, to automatically define a continuous peak elevation line along the top of the foredune.

4.1.2 | Foredune morphometrics

Foredune morphometrics were calculated with vector- and raster-based approaches. The Digital Shoreline Analysis System (DSAS) V5.0 (Himmelstoss et al., 2018) was adapted to measure change rates of the seaward dune toe, the crest, and the base of the lee slope. The DSAS tool uses intersection points between transects and input line features to analyse change rates. Transects are binned by plot to calculate discrete change rates for each plot and each geomorphic boundary. End point rates (EPRs) were calculated for each set of transects, which divides the distance between the oldest and youngest input lines by the time between them. The resulting outputs were analysed to assess changes in average foredune width per plot over time. Average foredune seaward toe and crest heights were calculated by using the intersection points from the transect tool to extract raster values.

4.1.3 | Vegetation analysis

Vegetation data were also processed using the GCD toolset, by comparing a vegetation raster against the bare-earth DEM raster of the same campaign to provide a proxy for vegetation volume. The resulting data included the same subset outputs as the topographic change analysis, but did not include change maps between TLS collections. Cumulative area and volume by subunit were compared numerically, rather than through a separate change analysis. Vegetation area and volume changes were compared to foredune width, crest elevation, aspect ratio, and surface volumetric change to assess relationships between foredune morphometrics and vegetation development.

4.2 | Wind analyses

Wind velocity and directional data were obtained for the California Redwood Coast–Humboldt County Airport (Station ID: KACV) from the MesoWest meteorological data repository (https://mesowest.utah.edu/). This station is located 8 km north-northeast of the study site and 1.3 km inland, providing the closest data source for wind and precipitation. Two products, wind power density and drift potential, were calculated for each interval to assess potential atmospheric drivers of deposition or erosion across the foredune. Wind power density (WPD) is defined as (e.g. Kalmikov, 2017)

$$\mathrm{WPD} = 0.5\rho_a (u)^3 \text{ in W m}^{-2}$$

where ρ_a (kg m^{-3}) is air density and u (m s^{-1}) is wind speed (at a known height). WPD provides a measure of the rate of kinetic energy flow per unit area imparted on the study area that could be mobilizing sediment. The total WPD was filtered to remove values below the transport threshold, informed by Rader et al. (2018), and during hours with precipitation, to provide a more realistic approximation. The drift potential model (Fryberger & Dean, 1979) informs on geomorphically effective winds by comparing directional variability and wind speeds for winds above threshold transport conditions through vector analysis. Resultant drift direction (RDD), drift potential (DP), and resultant drift potential (RDP) were produced from the wind data using the approach described in Miot da Silva and Hesp (2010).

5 | RESULTS

5.1 | Volumetric and sediment budget changes

Thirteen intervals depict change across the beach–dune system from 11/2015 to 09/2021 (Figures 3 and 4; Table 2). Point clouds from the native control plot were too sparse for accurate surface reconstruction between 09/2016 and 10/2017. Intervals using these three collections were omitted from consideration for only the NC plot.

Changes in the beach unit influence supply to the landward control and foredune treatment plots. A combination of the 2015–16 El Niño winter season (−0.81 m^3 m^{-2}) and strong storms in the following winter of 2016–17 (−1.00 m^3 m^{-2}) resulted in the most prominent lowering of the beach during the project. The general trend over subsequent collections was a net gain of sediment (vertical accretion), for all but two intervals (10/2018–05/2019 and 10/2020–02/2021). The beach had not yet accreted to 11/2015 levels by the 09/2021 collection, but had surpassed 05/2017 levels. Despite 10/2020–02/2021 (−0.55 m^3 m^{-2}) being the third most erosive interval on record, a scarp was not present upon collection and the seaward slope of the foredune remained connected to the beach across all plots. Intertidal bar welding and accretion on the upper beach were apparent throughout the rest of the 2021 campaigns. Five of the 13 intervals showed a deficit (net loss) of sediment from the beach, three of which were prior to native replanting. The remaining eight intervals showed a surplus (net gain) of sediment to the beach, with a net positive sediment budget following the winter of 2016–17.

The seaward slope of the foredune (see Figure 4) also experienced the greatest net erosion in all plots during the 11/2015–04/2016 and 09/2016–05/2017 intervals. The majority of plots exhibited net deposition, similar to the beach, following the 09/2016–05/2017 interval. The presence of a prominent scarp lasted along all plots from the winter of 2016–17 until the summer of 2018. A dune ramp had reconnected the foredune to the upper beach in all natively vegetated plots by 10/2018. The most pronounced change over the following intervals was the development and extension of a small blowout at the south end of the EM plot. A scarp remained in the *A. arenaria* (IC) plot until some time during the 09/2019–10/2020 interval, at least 3.5 years after the last major scarping event. The scarp at the IC plot was a sheer 1–2 m-tall cliff with exposed dense roots and evidence of block slumping. The IC plot reconnected after dune ramp rebuilding, which was accompanied by the development of a series of small blowouts along the seaward face of the foredune. A small ridge of newly deposited sediment was observed at the seaward edge of the dense vegetation in the final year of collection. Sediment budgets for the seaward slope foredune were primarily net positive, however the IC plot had the most intervals in deficit (4 out of 10).

The lee slope of the foredune (see Figure 4) exhibited a net gain of sediment in all restored plots, across nearly every interval. The EM plot experienced the greatest average rate of deposition after restoration (0.019 m^3 m^{-2} month^{-1}), followed by the DM (0.012 m^3 m^{-2} month^{-1}) and DM-EM plots (0.010 m^3 m^{-2} month^{-1}). Deposition was observed as small, localized instances of lee-slope avalanching and lobate deposition within an interdune swale behind the active established foredune. The 02/2021–05/2021 interval showed the greatest deposition and landward extension of the lee slope. This was most pronounced within the EM plot, where the base of the lee slope migrated landward nearly 1 m. All restored plots exhibited 0.006–0.010 m^3 m^{-2} month^{-1} of deposition during this interval. The control plots, however, did not exhibit similar responses, showing minor erosive events in a few of the intervals. Both control plots experienced a small pulse (0.010–0.015 m^3 m^{-2} month^{-1}) to the lee slope during the 02/2021–05/2021 interval. Sediment budgets were rarely in deficit within the natively vegetated plots following restoration, whereas the IC plot exhibited neutral to negative budgets.

5.2 | Foredune morphometrics

All natively vegetated plots experienced foredune widening over the course of the study, in both landward and seaward directions (Figure 5). Widening occurred primarily through dune ramp development and seaward extension over time, though landward migration of the lee-slope base was also observed. The DM-EM plot exhibited the least seaward expansion and the greatest landward expansion. The NC plot experienced the greatest seaward expansion, but least landward expansion. The IC plot also exhibited seaward expansion as well

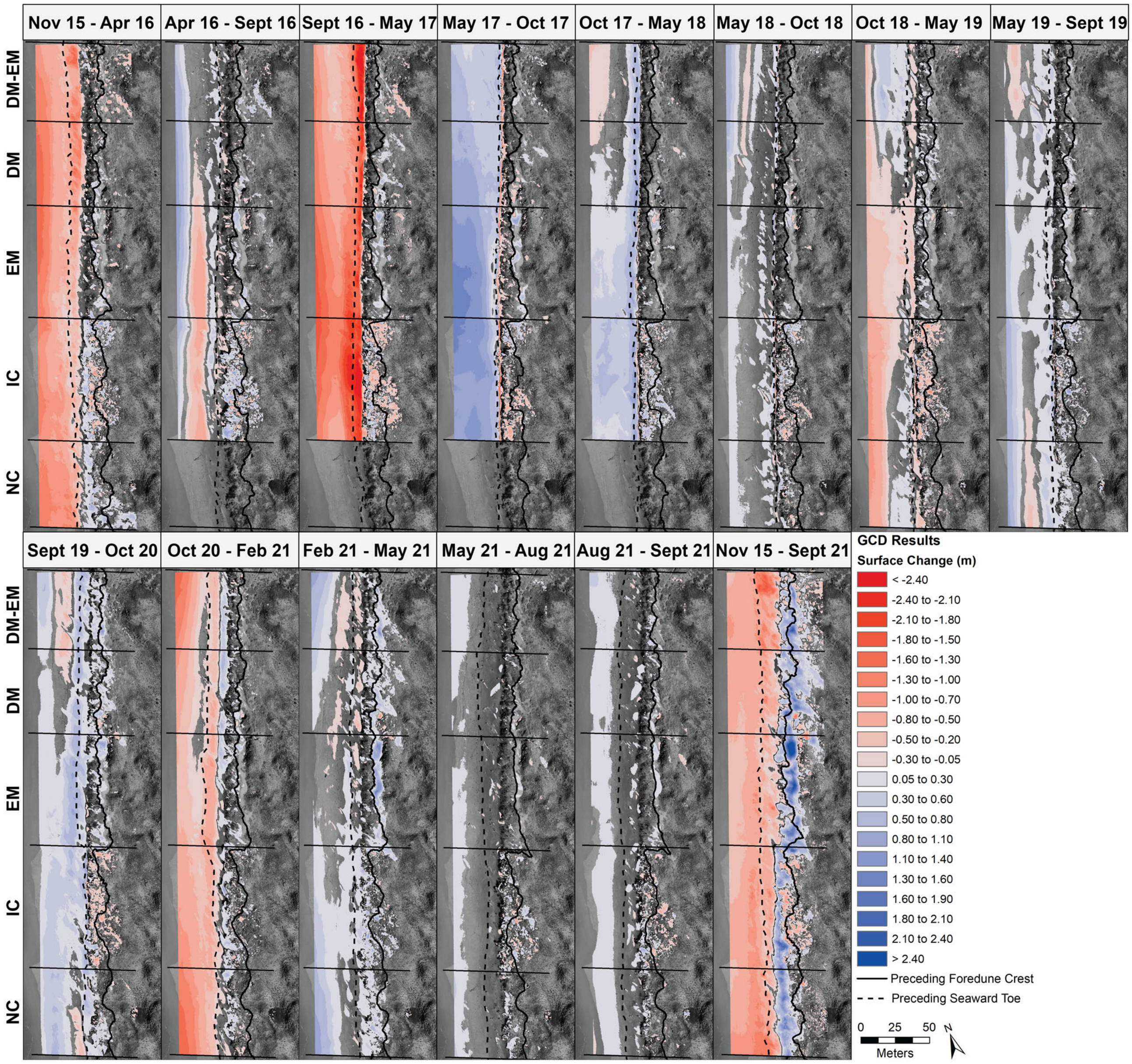

FIGURE 3 Thresholded GCD outputs for each interval and for the first and last collection. Results are expressed as cumulative surface change and are not normalized by month.

as seaward movement of the lee-slope base, resulting from the establishment of a depositional ridge during 02/2021–05/2021 that moved the crest and lee-slope base positions seaward. Minor landward translation of the foredune crest was evident across much of the restoration site since 11/2015. A small blowout at the south edge of the EM plot resulted in appreciable landward translation of the foredune crest. The DM and DM-EM crests recorded marginally less (~0.1 m yr^{-1}) average landward translation. The NC crest stayed relatively stable, but minor seaward movement of the crest was evident.

Foredune width exhibited an increasing north to south trend following the winter 2016–17 scarping, with the exception of the IC plot. The EM and DM plots were wider than the IC plot by the 09/2021 survey, while the DM-EM plot was nearly as wide as the IC plot. Average crest elevation also increased in the restored plots between 0.5 and 0.7 m, following restoration, with a decreasing north to south trend within the restoration plots. The native and invasive control plots were relatively stable, with minor (0.10–0.15 m) decreases in average height. These trends result in decreasing foredune aspect ratio (dune height/dune width) from north to south (Figure 6), suggesting that the treatment sites were all widening faster than they were increasing in height. However, while the dune aspect ratio followed similar trends across all plots, the IC plot exhibited a prolonged period of steeper slopes, compared to the natively vegetated plots. The EM plot consistently exhibited the lowest slopes within the restored plots, similar to the NC plot.

Aspect ratio results are supported by the DSAS width analysis and average slopes of the seaward face of the foredune over time (Figure 6). The seaward slope of the dune can indicate differences in the relationship between dune form and vegetation. McDonald (2020) examined a series of natively and invasively vegetated cross-shore topographic profiles, extracted from aerial LiDAR surveys, across the Humboldt Bay region. Profiles from natively vegetated or restored sites exhibited similar foredune height but significantly lower slope values than those that were vegetated with invasive species

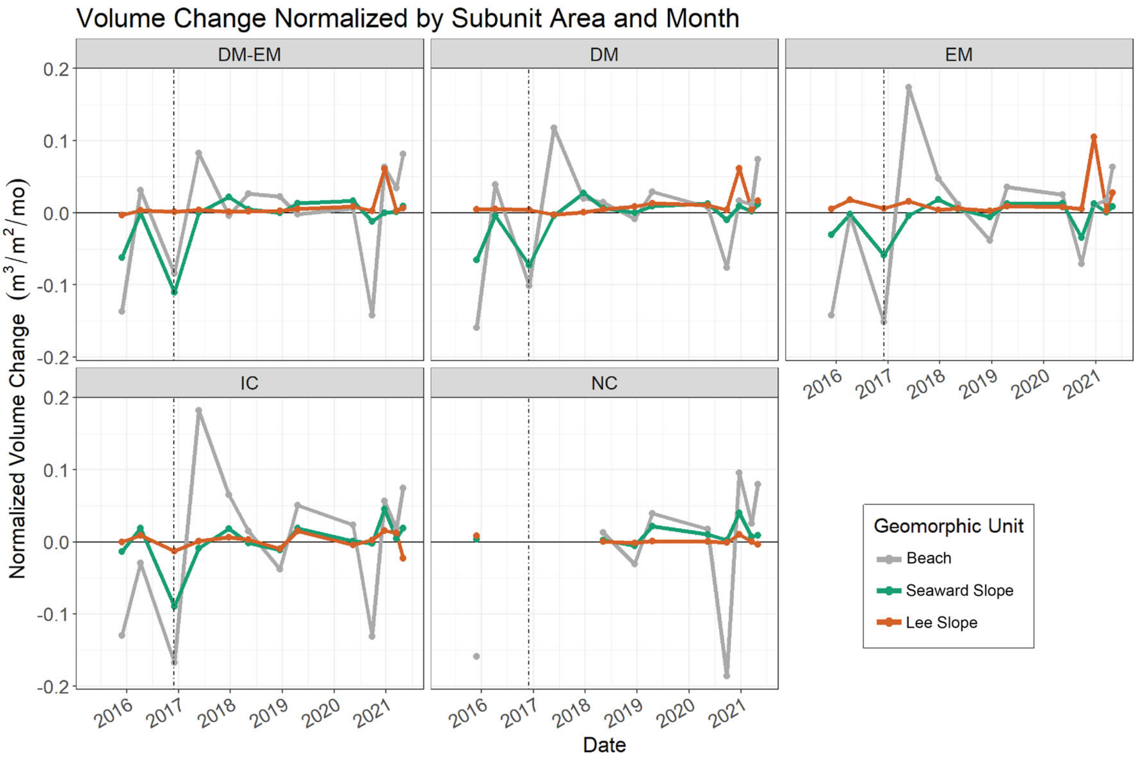

FIGURE 4 Plots showing volumetric changes of each interval for each treatment plot and geomorphic unit over the 6-year study period. Data points are plotted at the later of the two dates for each change interval. Dashed line represents the approximate end of treatment installation.

TABLE 2 Normalized volumetric change of the beach and foredune units, with corresponding WPD and RDP values provided for comparison. Beach values represent the entire extent of the beach across the study area. Wind roses and other wind data provided in the online Supplementary Material. Erosional values are indicated by greyed cells

Interval	Time (months)	Beach (m^3 m^{-2} $month^{-1}$)	Foredune (m^3 m^{-2} $month^{-1}$)					WPD (kW m^{-2} $month^{-1}$)	RDP (vu)
			DM-EM	DM	EM	IC	NC		
11/2015–04/2016	5.6	−0.145	−0.053	−0.050	−0.021	−0.010	0.005	15.5	21
04/2016–09/2016	4.3	−0.008	0.001	−0.001	0.005	0.017	NA	57.4	15
09/2016–05/2017	7.8	−0.128	−0.079	−0.047	−0.039	−0.070	NA	216.7	47
05/2017–10/2017	5.6	0.146	0.002	−0.003	0.002	−0.005	NA	161.1	51
10/2017–05/2018	6.9	0.041	0.015	0.016	0.014	0.014	NA	134.4	8
05/2018–10/2018	4.5	0.016	0.004	0.006	0.006	0.000	0.002	165.5	26
10/2018–05/2019	7.3	−0.022	0.001	0.003	−0.004	−0.011	−0.004	140.7	5
05/2019–09/2019	4.0	0.033	0.011	0.011	0.012	0.017	0.016	207.8	25
09/2019–10/2020	12.8	0.017	0.014	0.012	0.011	−0.001	0.007	148.1	17
10/2020–02/2021	4.4	−0.124	−0.009	−0.007	−0.026	−0.001	0.001	81.9	14
02/2021–05/2021	2.9	0.048	0.016	0.024	0.039	0.035	0.033	360.4	34
05/2021–08/2021	2.8	0.021	0.002	0.002	0.001	0.006	0.005	99.1	12
08/2021–09/2021	1.48	0.074	0.009	0.013	0.013	0.009	0.006	113.6	22
11/2015–09/2021	**70.5**	**−0.637**	**−0.326**	**0.015**	**0.141**	**−0.020**	**0.176**	**1092**	**3**

(predominantly *A. arenaria*). Slopes in the natively vegetated plots were as much as 20% lower than the IC plot, after the dune ramp had been rebuilt by summer 2018. Slopes were still 2–7% lower in the natively vegetated plots by the 09/2021 collection, after the sand ramp fronting the invasively vegetated foredune had reconnected to the foredune.

5.3 | Vegetation change

Vegetation within the restoration plots exhibited seasonal and longitudinal (temporal) trends in development (Figure 7). The relationship between vegetation area and volume exhibited expected relationships, with steeper regression lines for the taller, denser vegetation

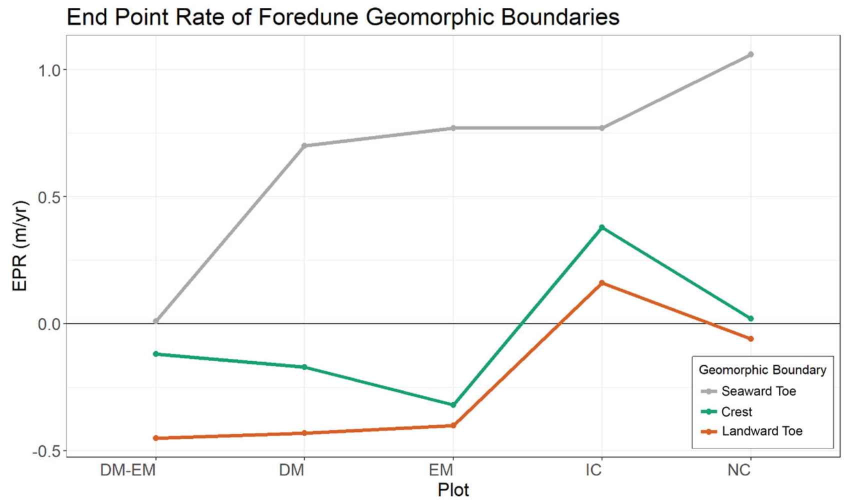

FIGURE 5 DSAS EPR results for each plot. Positive values signify seaward movement, while negative values signify landward movement. The IC plot is the only plot with seaward movement of the lee-slope base and crest, and exhibited the thinnest overall widening.

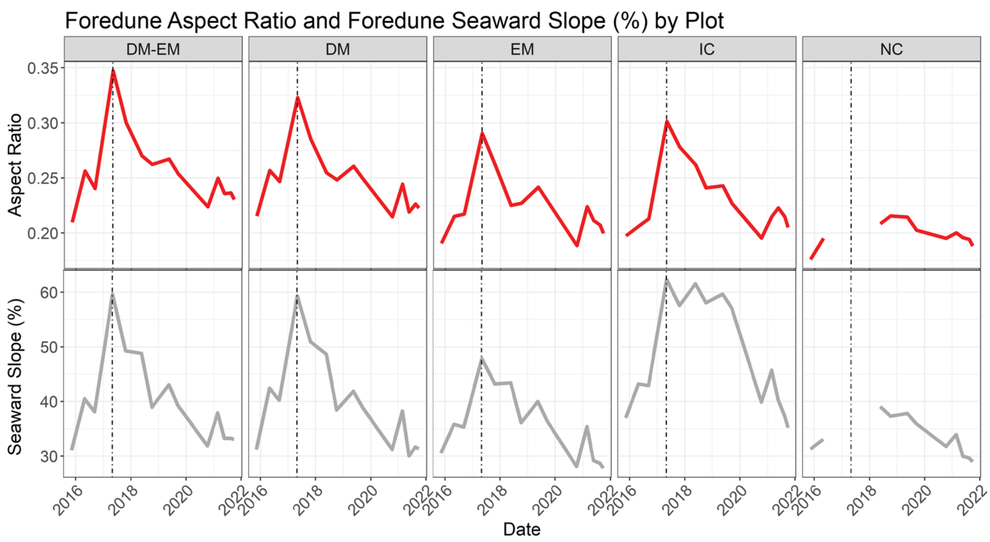

FIGURE 6 Trend in average foredune aspect ratio and average seaward foredune slope over the duration of the study. The highest peak in both aspect ratio and slope correlated to the scarping event of winter 2016–17. The dashed line signifies the approximate completion of planting within treatment plots.

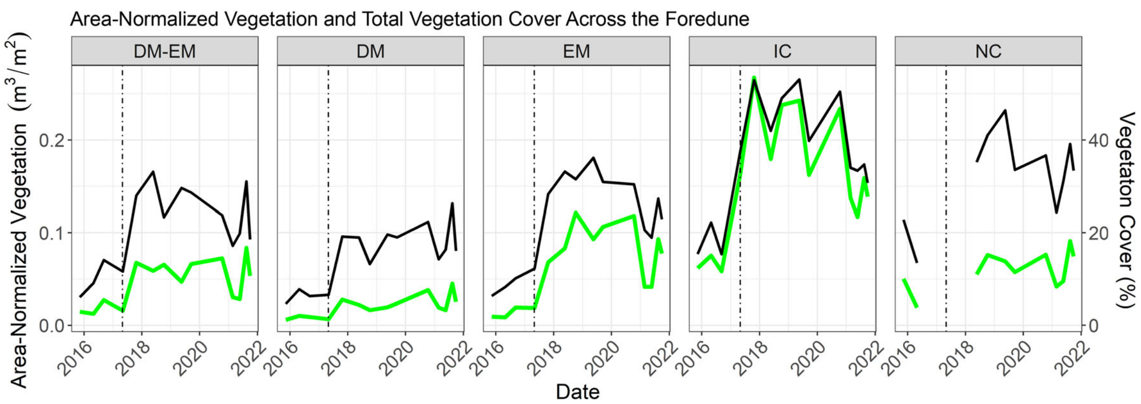

FIGURE 7 Trend in average area-normalized volume of foredune vegetation (green line) and vegetation cover (%, black line), by plot. The dashed line signifies the approximate completion of planting within treatment plots.

(see Figure S2 in the online Supplementary Material). Each of the restoration plots showed an increase in vegetation that corresponded to planting within the treatment plots, with the EM plot exhibiting the greatest increase. All plots experienced a decline in vegetation during the 10/2020–05/2021 intervals, related to seasonal vegetation senescence and winter erosion. Subsequent collections recorded seasonal growth that peaked in 08/2021, before declining in the early autumn (09/2021) collection. An influx of sediment into the restored plots during the 02/2021–05/2021 interval led to widespread burial of dune mat species as the lee slope migrated inland within the EM and DM plots. Many foredune species are burial-tolerant or burial-dependent (Maun, 2009), and there was evidence of individual plants exhibiting growth signatures that kept up with the rate of burial.

5.4 | Wind and sediment supply forcing

The wind regimes across each interval showed the expected seasonally bimodal trends (Pickart & Hesp, 2019), which were also reflected in the RDD, RDP, and WPD results (see Table S1 and Figure S1 in the online Supplementary Material for an interval-based breakdown). WPD values were highest in the 02/2021–05/2021 interval (360 kW m^{-2} $month^{-1}$), followed by 09/2016–05/2017 (217 kW m^{-2} $month^{-1}$) and 05/2019–09/2019 (208 kW m^{-2} $month^{-1}$). Linear regression results were poorly explained (R^2) by most comparisons, however WPD exhibited the strongest relationship to the area-normalized volume change (Figure 8). Each plot exhibited a positive relationship between WPD and area-normalized volume. A separate regression between area-normalized volume change of the beach and foredune produced a weak to moderate, positive correlation. The NC (0.78) and EM (0.64) plots exhibited the highest R^2 values, while the EM plot also recorded the steepest regression slope. These results support our hypothesis that there are differences between invasively and natively vegetated portions of the foredune, which are reflected in both the relationship between wind power and volumetric change, as well as supply to the beach and volumetric change on the foredune.

6 | DISCUSSION

6.1 | Difficulties in vegetation reconstruction

Repeat-collection TLS surveys are often used to quantify and interpret coastal change (e.g. Conery et al., 2019; Feagin et al., 2014; Grilliot et al., 2019; Young et al., 2021). This study provides another example of the application of TLS for assessing coastal foredune change, while also assessing vegetation development. Studies employing TLS to study coastal vegetation are not particularly common (e.g. Feagin et al., 2014; Guisado-Pintado et al., 2019; Owers et al., 2018), but can provide insight into the ecomorphodynamic evolution of a given system. Traditional methods for estimating biomass are often destructive (Owers et al., 2018), requiring the removal of plant material from the surface for off-site analyses. Other metrics, such as vegetation cover (%), only provide a two-dimensional value, without consideration for plant height. TLS surveys allow for insights into above-ground biomass and vegetation growth without harming sensitive or restored environments. Special attention needs to be paid to ensure that vegetation extraction accurately reconstructs the features of interest.

Dune mat species and *A. arenaria* presented the biggest challenge for accurate vegetation calculations, given their low profile (dune mat) or tall form and dense coverage (*A. arenaria*). TLS-estimated dune mat cover (%) was compared to results from manually digitized dune mat cover derived from five concurrently collected UAS surveys (Hilgendorf et al., 2021). These comparisons exhibited differences around ≤10% coverage, suggesting that the TLS was able to capture dune mat relatively well. The density of *A. arenaria* simply precludes the ability of the TLS to penetrate to the bare surface. Scan density was increased within the IC plot to attempt to improve surface reconstruction, however, it is clear that artifacts remained within the bare-earth surface reconstruction, influencing the signature of 'change' within vegetated portions of the IC plot.

A simple method to improve surface reconstruction in densely vegetated areas could employ the use of a total station or GNSS base station and receiver to collect a high density (e.g. 1 point per 1–3 m^2) of survey points to compare against the TLS-based surface. One

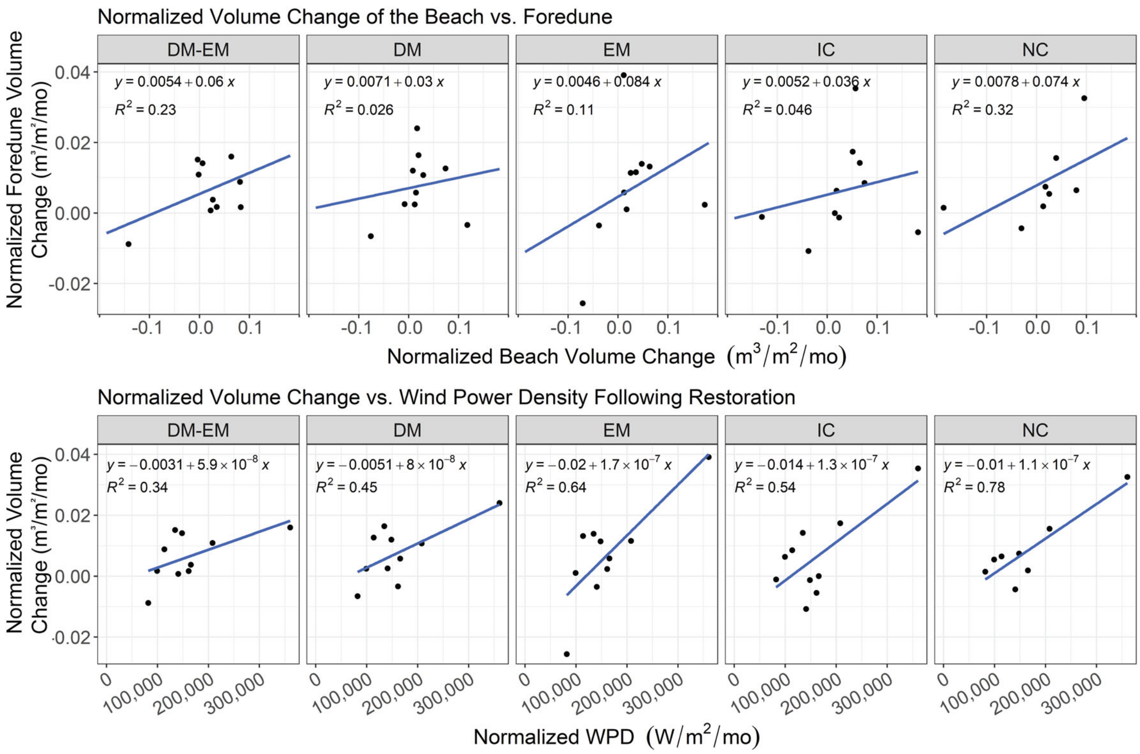

FIGURE 8 Linear regression results between area-normalized volumetric change and wind power density and area-normalized volume change between the beach and foredune. Variables were normalized by months between collections. Differences were noted between the invasively vegetated IC plot and the natively vegetated plots, though relationships were not strong.

approach would be to remove the densely vegetated surface from the TLS point cloud and replace it with the surveyed points. The resulting surface would be coarser than the rest of the point cloud, but would represent a consistent, bare-earth surface. Another approach could use the surveyed points to compare against the TLS-based bare-earth model, examining the residual differences between the survey and TLS points and better informing on uncertainty within the TLS data.

6.2 | Impacts of restoration on foredune morphodynamics

The relationship between vegetation density, wind, and sediment transport has been well documented through *in-situ studies* (Arens, 1996; Arens et al., 2001; Hesp, 1989; Hesp et al., 2005, 2019; Keijsers et al., 2015; Sarre, 1989; Walker et al., 2017, 2009, 2006; Zarnetske et al., 2015) and wind tunnel experiments (Burri et al., 2011; Charbonneau et al., 2021; Hesp et al., 2019; Miri et al., 2017; Suter-Burri et al., 2013; Zarnetske et al., 2012), highlighting the importance of vegetation density on wind and transport regimes over foredunes and flat beds. One primary impact is an increase in momentum extraction as plot density increases (Crawley & Nickling, 2003), limiting sand transport within denser vegetation to the seaward edge of the plot (e.g. Burri et al., 2011; Hesp et al., 2019). Low-lying vegetation, such as species in the dune mat herbaceous alliance, can impart increased drag force on airflow and trap sediment travelling through creep and saltation (Figure 2; Tobias, 2015). Taller grasses can help reduce near-surface wind speeds and distribute sediment in the wake of plants (Hesp, 2002; Pickart & Sawyer, 1998). Grasses with lower densities, like *E. mollis*, can grow to similar heights as *A. arenaria*, but produce wider, more gradually sloped foredunes that allow for better translation of sediment across the surface and over the dune (McDonald, 2020; Pickart & Sawyer, 1998). These relationships suggest that natively vegetated foredunes, which typically have lower plant densities in this region, can facilitate sand transport required to maintain dune form compared to higher-density, invasively vegetated foredunes because of enhanced sediment connectivity between the beach, dune, and landward system components.

The restored plots at the study site exhibited lower plant densities that were more consistent with the NC plot, faster reconnection to the upper beach following scarping events (Table 1, Figure 9), and seaward slopes that were consistently less steep than the IC plot (Figure 6). The general trend of the foredune and vegetation, following restoration, has been towards growth. An incipient foredune has not redeveloped on the upper beach, following the El Niño of 2015–16, but the foredune has grown in height and width and, hence, sand storage volume, since restoration. Vegetation has expanded and matured within the treatment area and early stages of succession and reorganization were observed (Hilgendorf et al., 2021; Pickart, 2020). The extent of vegetation coverage in the natively vegetated plots has always been significantly less compared to *A. arenaria* (IC plot). The invasively vegetated control exhibited almost total foredune coverage with the exception of the lower portions of the seaward slope. Our results show that vegetation type and cover have played a key role in allowing the foredune to readjust and recover its form more readily to scarping events. The natively vegetated plots all exhibited faster rebuilding of sand ramps that reconnect the beach to the stoss slope

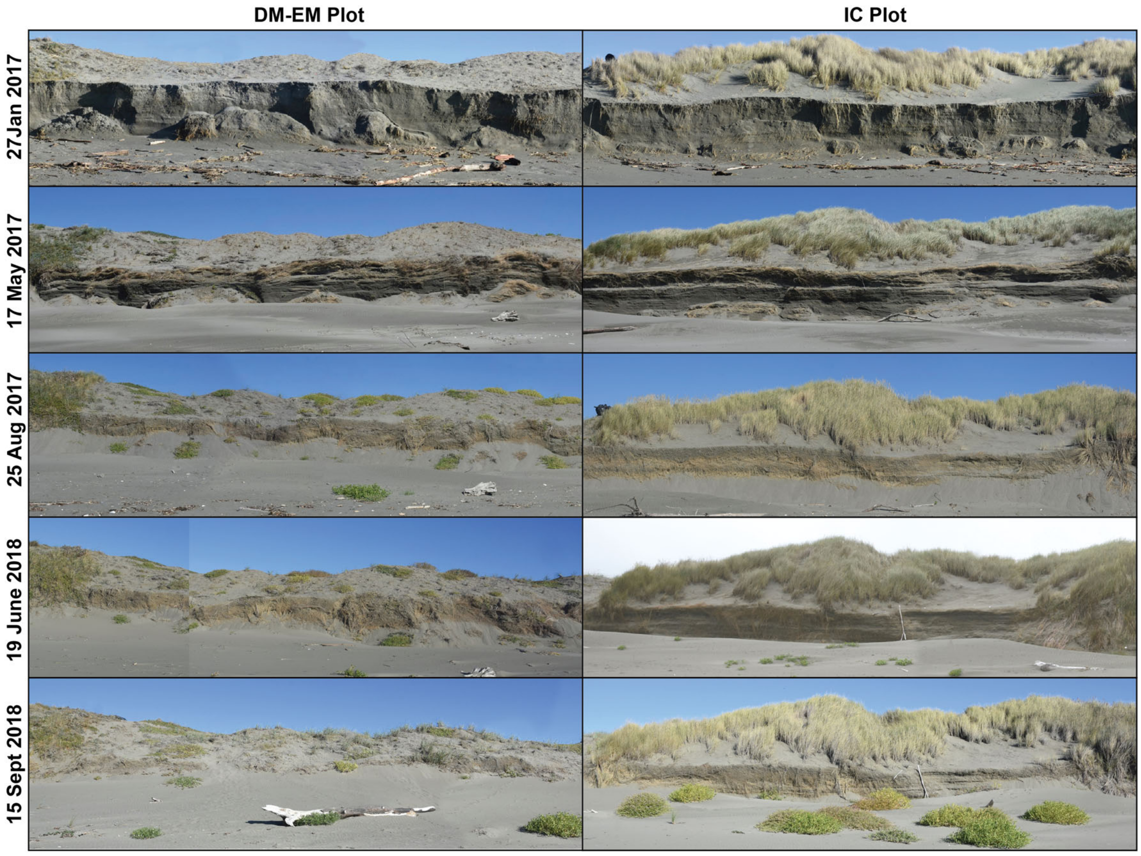

FIGURE 9 Panoramic images of the evolution of the erosional scarp and dune ramp rebuilding between 27 Jan 2017 and 15 Sept 2018. The DM-EM plot was used as an example, but all natively vegetated plots exhibited a similar trend.

and generally stronger relationships between beach and foredune sediment budgets (Figure 8).

Below-ground biomass can play a role in limiting the extent of dune erosion during scarping events by binding sand and increasing dune stability (Davidson et al., 2020; De Battisti & Griffin, 2019). However, little work has been done to consider the impact that vegetation type has on the longevity of a scarp and the longer-term implications of prolonged flow deflection on dune ramp development. Recent studies (e.g. Davidson et al., 2020; Hesp & Smyth, 2021; Hesp et al., 2013, 2009; Piscioneri et al., 2019) have provided insights into the characteristics of flow over a foredune scarp. Flow stagnation, deflection, and the development of helicoidal flow along the base of the scarp were commonly observed during onshore to obliquely onshore conditions (Hesp & Smyth, 2021; Piscioneri et al., 2019). In this study, the natively vegetated plots, which recovered more quickly to scarping, would not be subject to such complex flow conditions during onshore flow compared to steeply scarped sections of the invasively vegetated portions of the dune. There was no evidence of sediment transport over the scarp of the invasively vegetated dune (e.g. deposition along the scarp crest, etc.), but a low sand ramp with alongshore-oriented ripples was often present, indicating that flow and transport were frequently deflected along the scarp and thus onshore sand transport into the invasive plot was very limited.

While onshore winds are important contributors to the sediment budget, moving sediment from the beach towards the dune, offshore and alongshore winds are often topographically steered towards the foredune. In turn, this can result in sand delivery from a variety of incident wind directions to the dune, thereby serving similarly important roles for dune maintenance (Bauer et al., 2012; Christiansen & Davidson-Arnott, 2004; Hesp & Walker, 2022; Lynch et al., 2013; Ollerhead et al., 2013; Walker et al., 2006, 2017). Offshore winds can remobilize sediment from the dune onto the seaward slope, working to broaden the foredune crest and rebuild the dune ramp following scarping events (Bauer et al., 2015; Hesp et al., 2009; Lynch et al., 2009). Foredune scarping effectively decouples the beach from the foredune by truncating landward sand transport pathways, deflecting flow and sand transport on the upper beach. Dune ramp rebuilding is an important process that reconnects the beach to the foredune and increases sediment storage on the upper beach that can help to mitigate potential damage from future high-water events that can occur during strong onshore winds (Bauer et al., 2009, 2015).

Dominant winds during the study were seasonally bimodal, with onshore winds during the summer months and alongshore to offshore winds during winter months. Without continuous morphological and sediment transport observations at the site, it is difficult to know the exact timing and nature of dune ramp rebuilding. However, increased deposition landward of the foredune crest and increasing dune height within the natively vegetated plots support a relationship between the potential for dune maintenance and the dominant vegetation type and serve as a proxy for understanding interactions between collections (Table 1, Figure 9).

The development of the sand ramp along the scarped seaward toe was captured through a series of photopoints. Photo collection started following the winter erosional event of 2016–17 (late 01/2017) through ramp reconnection within the restored plots (mid 09/2018) (Figure 9). The state of the scarped foredune remained relatively consistent between the first two dates (27/01/2017 and 17/05/2017), as deposition along the base of the scarp is apparent. The sand ramp along the DM-EM plot had nearly reached the top of the scarp in a few locations by 19/06/2017, whereas a ≥1 m scarp was still present along the *A. arenaria* vegetated foredune. The sand ramp had welded to the top of the scarp along the DM-EM plot within the next 3 months, while the scarp persisted along the invasively vegetated foredune. These observations held true across the other natively vegetated plots, providing better context for the trend of sand ramp rebuilding with respect to vegetation type.

6.3 | Foredune restoration for landform resilience

To consider the efficacy of the dynamic restoration project at the Lanphere Dunes, it is necessary to consider evidence that supports the ecomorphodynamic goals for the project and how well informed those goals were. Project design aimed at restoring geomorphic functionality and landform resiliency to the foredune through the restoration of native foredune vegetation. In a broader context, this project is part of a larger coastal vulnerability assessment and serves as a demonstration site for potential methods to improve resilience to coastal erosion and sea level rise. While some restoration strategies have been criticized for lacking regard for geomorphic processes (Cooper & Jackson, 2020), this project was focused directly on the interplay between geomorphic and ecological functionality. The restored plots were designed to test how different vegetation types influenced and maintained the foredune and sediment budget, as well as how the different treatment plots impacted the exchange of sediment with the beach and across the dune. Data collection campaigns were also designed to monitor and assess change in foredune form and vegetation extent over time. Throughout this 6-year assessment it was clear that both aims of the project—increased resiliency and increased dune ecosystem form and function—were being met.

To consider the long-term trends of the beach–dune system and how the current restoration project fits within those trends, we examined a previous study (Pickart & Hesp, 2019) that incorporated historic aerial imagery from 1939 to 2016. This study found that invasive vegetation did not start to overtake the study area until some time in the 1950–1960s. In this case, the introduction of invasive species fundamentally changed the ecological and geomorphic functionality of the transgressive dune system at Lanphere by limiting both the exchange of sediment from the beach into the landward dunes and natural ecosystem succession. The growth and expansion of *A. arenaria* led to a monotypic vegetation coverage along the established foredune.

In the current study, the removal of *A. arenaria* and replanting of native species signalled a shift towards not only a more biodiverse landscape, but one that exhibited enhanced sediment connectivity across the landscape and allowed the system to develop towards a more natural state. These trends signify an ecomorphodynamic response to restoration that relies on the interplay between flow, form, and ecological function, rather than solely on the static preservation or reintroduction of species of concern, or the reintroduction of bare-sand pathways for landward sediment transport (e.g. dune notching, cf. Laporte-Fauret et al., 2021; Nguyen et al., 2021; Riksen et al., 2016; Ruessink et al., 2018). Furthermore, the resulting landform has exhibited characteristics of a more resilient landscape, with more gradual slopes and faster reconnection to the upper beach following scarping (Figures 6 and 9). The faster reconnection of the beach and dune along the natively vegetated foredune signifies an accelerated response to disturbance and development towards a predisturbance state that the invasively vegetated foredune exhibited at a slower rate. These trends suggest that the restored and natively vegetated foredunes at the study site have developed differently and towards a more resilient state than the invasively vegetated foredune, supporting the success of the intended project. These short-term responses are promising, but a longer record would be necessary to comment on the resilience of this landform to changes in relative sea level or changes to the littoral sediment budget.

6.4 | Considering future morphological development

Although it is beyond the scope of this study to consider predictive modelling of the foredune system, we can consider the changes observed at the Lanphere Dunes in the context of Davidson-Arnott et al.'s (2018) model on sediment budget controls and morphological evolution of foredunes to provide some insights on the future trajectory of the site. Although the influence of a dense marram grass (e.g. *A. arenaria*) on foredune sediment budgets and morphodynamics in an invasive setting might be different from that of another marram grass (e.g. *Ammophila breviligulata*) in its native setting, there is some utility in comparing our results to those observed by Davidson-Arnott et al. (2018) in four respects:

1. Sediment budgets will remain essentially balanced and dune heights cannot increase above initial conditions if small inputs and large, relatively infrequent storm surges are common (Davidson-Arnott et al., 2018). Lanphere experienced large variations in erosion and deposition, with large and infrequent storm erosion, similar to the relationships described in the model. However, in regions with sparser vegetation coverage (the natively vegetated plots), the foredune aspect ratio changed at a rate that differed from the invasively vegetated control plot.
2. The foredune will grow if annual sediment inputs exceed losses due to the influence of larger storms on a decadal scale (Davidson-Arnott et al., 2018). Annual budgets at Lanphere were typically net positive, allowing the foredune to grow after restoration and after scarping.
3. The crest and lee-slope positions can migrate landward over time, even though the mid- to upper stoss slope is treated as fixed (Davidson-Arnott et al., 2018). The average position of the mid- to upper stoss slope at Lanphere, while not discussed in the findings presented, did remain relatively stable within all plots, while landward migration of the crest and lee positions was observed primarily in the restored plots. It is likely that rates of change and development would be more rapid in plots with sparser vegetation, given that wind energy and sediment transport are not impacted as greatly as they would be in a dense, monotypic stand of vegetation. Such trends were observed over the duration of this study and future research could examine the relationship between foredune morphological evolution and vegetation type, using Davidson-Arnott et al. (2018) as a framework.
4. Across the range of tested conditions in the model, rates of crest height increases were small after the foredune exceeded 10–12 m (Davidson-Arnott et al., 2018). The foredune at Lanphere did not exceed this height.

Considering these differences in our observations at Lanphere against the relationships proposed by the Davidson-Arnott et al. (2018) model, it makes sense that foredunes vegetated with sparser-growing vegetation, in general, would exceed the rates and trends of a denser species (e.g. *A. breviligulata*, *A. arenaria*). These observations highlight the importance and need for incorporating appropriate vegetation parameters for modelling approaches. Given our observations, it is likely that these developmental trends will continue at Lanphere if the system continues to function in relative stability.

7 | CONCLUSIONS

Sandy coastal environments are under increasing pressure from the impacts of rising sea levels and the associated impacts of coastal flooding and erosion. Foredune restoration is an oft used approach to mitigate the atmospheric, marine, and anthropogenic pressures within the coastal zone. Dynamic restoration projects focus on the interplay between geomorphic and ecological functionality to improve landform resiliency through nature-based methods (e.g. Arens et al., 2013; Bessette et al., 2018; Darke et al., 2013; Konlechner et al., 2015; Nordstrom & Jackson, 2021; Pickart, 2013; Rhind et al., 2013; Walker et al., 2013). The Lanphere Dunes in California serve as an important case study and approach to dynamic restoration and have a rich history of restoration efforts (Pickart, 1988, 2013). The trends in foredune sediment budgets and vegetation development explored in this study provide insights into the impact of vegetation on foredune form and resiliency. In addition, these trends address a gap in meso-scale foredune and restoration research that has been noted by others (Pickart et al., 2021; Walker et al., 2017).

TLS and topographic change analysis serve as important tools for assessing 4D foredune morphodynamics and vegetation development. We found that biannual collections were able to effectively capture changes in the surface and vegetation that spanned nearly 6 years, allowing meso-scale trends in foredune change and vegetation development to be assessed. The methods used were able to sufficiently capture low-lying vegetation (e.g. dune mat), but did struggle to penetrate the dense stands of *A. arenaria* for accurate surface reconstruction within the invasive plot.

Over the duration of the study, it was evident that the restored portions of the foredune developed characteristics more like that of the native control than the invasive control, in terms of dune ramp rebuilding, seaward slope steepness, aspect ratio, sedimentation, and vegetation coverage. These characteristics highlight the success of the restoration project at restoring natural form and function to the foredune.

We argue that restored and natively vegetated foredune plots exhibited enhanced foredune resiliency, compared to foredunes that were invasively vegetated. Dune ramp rebuilding, following scarping, was quicker along natively vegetated foredunes (∼1.5 years), compared to along the invasive foredune plot (∼3.5 years). This is likely driven by enhanced sediment connectivity in the lower-density, natively vegetated plots. The dense stands of *A. arenaria* reduced sediment transport potential to the seaward edge of vegetation, which was only observed after the dune ramp had been rebuilt.

Finally, restored and natively vegetated foredune plots exhibited increased sediment connectivity between the beach and foredune. Although scarping served to decouple the beach and foredune sediment budgets, appreciable deposition was observed across the landward side of the restored plots, suggesting a recoupling of the beach and foredune budget. While the crest and lee-slope base positions migrated landward in response to increased transport onto the restored foredune, seaward slopes prograded in the intervals following restoration, to a point where the foredune exhibited a net gain of sediment.

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AUTHOR CONTRIBUTIONS

ZH and **IJW** prepared the manuscript and collected field data. **ZH** prepared the figures. **IJW** and **AJP** developed the restoration project design. **AJP** provided *in-situ* monitoring of vegetation. **CMT** assisted in field collections and data processing.

DATA AVAILABILITY STATEMENT

Data is available from the authors upon request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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