EXPERIMENTAL TEST OF THE INFLUENCE OF NATIVE AND NON-NATIVE PLANT SPECIES ON SAND ACCRETION ON A U.S. PACIFIC NORTHWEST DUNE

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Abstract (150 words): The U.S. Pacific Northwest (PWN) coastal dunes are mainly colonized by two non-native beachgrass species (i.e., *Ammophila arenaria* and *A. breviligulata*) and a native dune grass (*Leymus mollis*) that capture sand and build dunes of different morphology. Recently, a hybrid beachgrass was discovered with unknown consequences for dune evolution. We set up a common garden experiment including seven treatments and two control plots to understand the effect of native and non-native plant species on sand accretion and dune morphological evolution. After 1.6 years, sand volume increased the most in the non-native species plots with levels at least twice as high for *A. arenaria* as compared to the other plots. The hybrid species had moderate sand accretion but a survival rate of 1.4 and 2.1 times higher than its parent species and native species, respectively. These results provide new insights for U.S. PNW coastal dune management.

Introduction

Worldwide sandy shores are vulnerable to climate change (e.g., sea level rise, changes in storminess patterns, Vousdoukas et al., 2020) and anthropic pressure (e.g., Merkens et al., 2018), both of which may limit the ability of these environments to provide coastal protection. Coastal dunes form on sandy shores where the combination of sufficient sand supply and dominant onshore winds favors their establishment. The development of coastal dunes is related to interactions between marine and aeolian physical processes (Hesp, 2002) and biotic processes (Maun, 1998). The presence of dune building plant species tolerant to sand burial and salinity promotes sand deposition, which in turn promotes plant growth, leading to positive feedbacks that determine the pace and style of dune evolution over time (Maun, 1998, Zarnetske et al., 2012). As they develop, coastal dunes provide many ecosystem services (Martinez et al., 2013) such as acting as natural barriers to storm waves and flooding. Thus, during the last century, many managed coastal dunes have been built and stabilized using soft engineering methods such as planting vegetation (Arens et al., 2001), in order to protect infrastructure from marine driven erosion and from windblown sediment transport. Marram grasses such as *Ammophila arenaria* and *A. breviligulata* are popular plants used in these engineering efforts and they are known to produce dunes of different morphology (Hacker et al. 2012). *A. arenaria* has a vertical growth form with high density shoots that capture more sand deposition for a given area, and thus have been shown to build tall and narrow dunes. In comparison, *A. breviligulata* has a more lateral growth form with a lower shoot density, resulting in better space occupation, but less sand accretion over a given area, creating shorter and wider dunes (Hacker et al., 2012; Zarnetske et al., 2012).

Nearly 45% of the U.S. Pacific Northwest (PNW) coast, is dune backed (Ruggiero et al., 2018). Historically, the PNW dunes were sparsely covered by the native dune grass species *Leymus mollis*, which has a lateral growth form and low-density shoots, and mainly forms short and wide dunes (Hacker et al., 2012). In the early 1900's, the non-native European beachgrass *A. arenaria* was intentionally planted along the Pacific coast (Cooper, 1958), followed in the 1930's by the US East coast and Great Lakes native American beachgrass *A. breviligulata* (Seabloom et al., 1994), to stabilize the open shifting sand environment. Today, the two species co-occur from central Oregon to northern Washington but *A. breviligulata* is dominant in this region and does not occur south of Cascade Head, Oregon (Hacker et al., 2012). The spread of these beachgrasses serves an important coastal protection service as they build tall stable foredunes thus decreasing flooding risk (Hacker et al., 2012; Ruggiero et al. 2018). However, they also negatively impact biodiversity by outcompeting native plants and reducing habitat value for native shorebirds (Biel et al., 2017). Recently, a new hybrid species between *A. arenaria* and *A. breviligulata* has been discovered on the PNW dunes (Mostow et al., 2021). Possible changes in dominant beachgrass species as a result of the spread of this new invader could have substantial effects on dune geomorphology, coastal protection, and biodiversity conservation (Biel et al., 2017).

Here we present results of an experiment designed to study the species-specific role of non-native and native vegetation on the morphology of dunes on the PNW coast. Specifically, we use a common garden experiment at Nehalem spit, Oregon, a site in which the existing foredune was graded and existing vegetation was removed, to test for the effect of the *Ammophila* and its hybrid and a suite of native plants including *Leymus mollis* on sand deposition and dune building.

Study site

The study site is located at Nehalem Bay State Park on Nehalem spit, Oregon, and is composed of a 5 km alongshore, 70 m to 180 m cross-shore, 10 m to 12 m high (NAV88) stretch of foredunes (Fig. 1.a). The system has a tidal range of between 2 to 4 m and is exposed to a highly energetic and seasonally variable wave climate. Significant wave height, period, and angle of incidence ranges from 1 m, 8s, and a WNW direction, respectively, in the summer (April to October) to 3 m, 12-13 s, and a WSW direction, respectively, in winter (October to April) (Ruggiero et al., 2005). The energetic winter climate is generated from extratropical storms from the northeast Pacific and results in a multi-decadal shoreline retreat rate at the study site of 0.67 m/yr (Ruggiero et al., 2013).

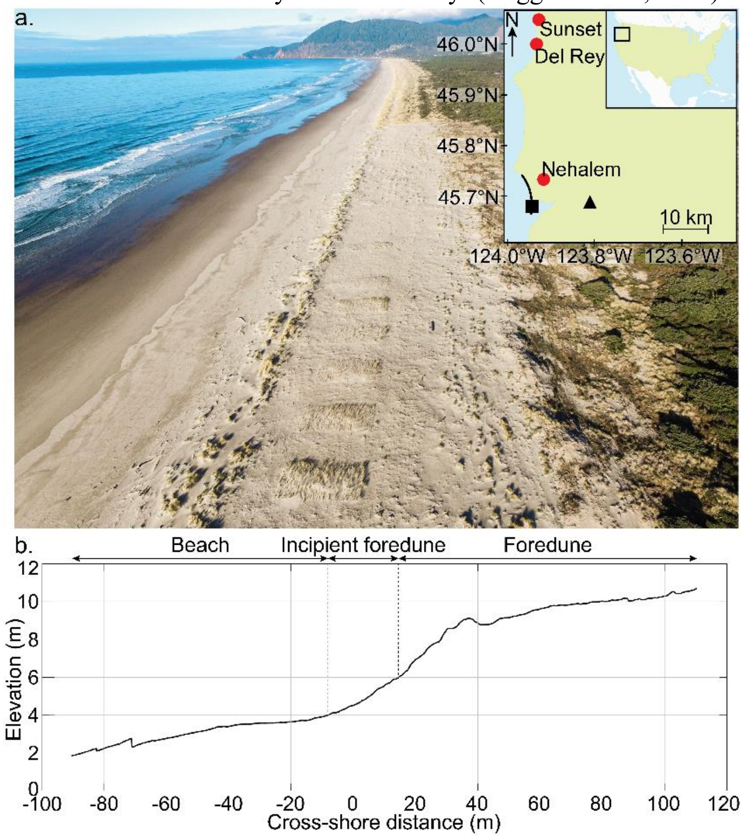

Fig. 1. (a) Aerial photograph of the Nehalem spit habitat restoration area (HRA) and site of the experiment (photo R. Edgell). The location map inset shows the Nehalem dune system (black line), the local weather station (black square), and the Nehalem rainfall station (black triangle; December 2021 to October 2022), (b) Alongshore-averaged beach dune profile of the HRA on the Nehalem dune system (October 13, 2022) with the different dune units delimitated by the dashed lines.

The foredune is mainly colonized by the European beachgrass *A. arenaria* with some patches of American beachgrass *A. breviligulata* and sparse but prevalent native dune grass species *Leymus mollis* (Hacker et al. 2012). Common native forb species include *Abronia latifolia*, *Lathyrus japonicus*, and *Lupinus littoralis*. The dune system at the site hosts a habitat restoration area (HRA, 900 m alongshore x 90 m cross shore) created for the federally listed native shore bird, the Western snowy plover (*Charadrius alexandrinus nivosus*). The HRA was created in 2019 by the Oregon Parks and Recreation Department by grading the existing foredune to an average elevation height of 10 m and removing most of the vegetation in the grading process and with herbicide applications (cross-shore profile of the HRA, Fig. 1.b).

Material and methods

Experimental design

We used a common garden experiment to test for the effect of vegetation type on sand accretion and dune evolution. The experiment was conducted on the HRA where, in February 2021, a portion of the graded region was re-graded and existing vegetation was removed. We then established 9 rectangular plots that were 20 m in the cross-shore direction by 10 m in the alongshore direction, each separated by a 10 m wide strip in the alongshore direction (Fig. 2.a). In each of the plots, experimental treatments were applied as follows: two control plots without vegetation (Plot #0 and #7), four monoculture plots with single species [i.e., *A. arenaria* (AMAR, Fig. 2.b,j), *A. breviligulata* (AMBR, Fig. 2.c), the hybrid *A. arenaria* x *A. breviligulata* (HYBR, Fig. 2.d) and *E. mollis* (LEMO, Fig. 2.e)], and three polyculture plots with two or more species (i.e., AMAR and AMBR, a mixture of dune grasses including AMAR, AMBR, LEMO, and *Festuca ammobia* (FEAM, Fig. 2.f), and a mixture of all native plants including LEMO, the sedge *Carex macrocephala* (CAMA), and the forbs *Abronia latifolia* (ABLA, Fig. 2.g), *Lathyrus japonicus* (LAJA, Fig. 2.h) and *Lupinus littoralis* (LULI, Fig. 2.i), all three gathered under the name forbs).

All vegetated plots were planted with approximately 946 plants in 22 x 43 rows, separated roughly 0.45 m apart. Plants were obtained from the following locations: AMAR from the experimental site at Nehalem Spit (Fig. 1.a); AMBR and HYBR from Sunset Beach Recreation Site, OR (Fig. 1.a); LEMO from Del Rey Beach Recreation Site, OR (Fig. 1.a); FEAM, CAMA and all other native forbs were grown from seed in a greenhouse at Oregon State University for six months prior to being transplanted into plots. The wild-collected grasses were stored in paper harvest bags upon collection, brought to the site, and transplanted within two days.

After transplantation was complete, we surveyed the plots for plant survival and growth in May 2021, July 2021, September 2021, and September 2022. We counted the individual plants of each species in each plot over time and compared those counts to the number of individuals initially planted. We also randomly chose 20 plants of each species in each plot and counted the number of shoots per plant. To determine the number of shoots per m^2 per species, we multiplied the number of plants by the average number of shoots per plant and divided by the total area of the plot.

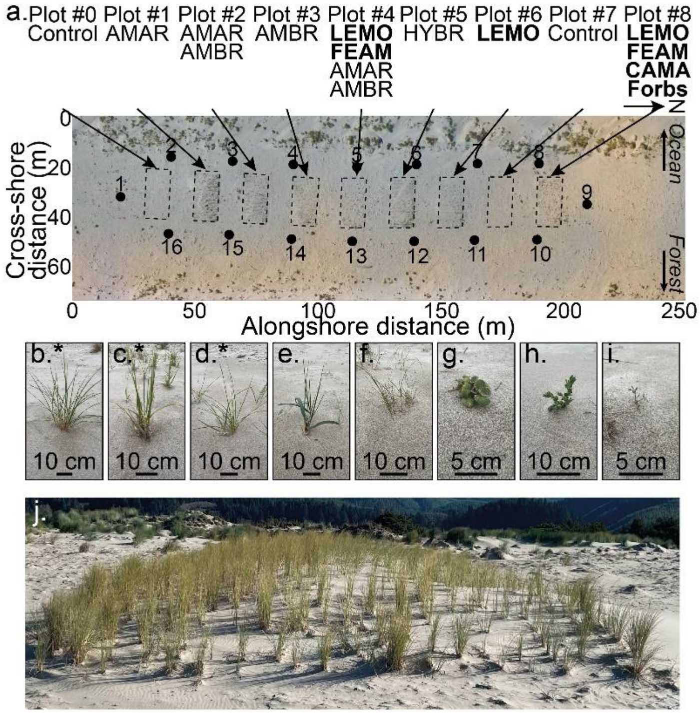

Fig. 2. (a) Unmanned aerial vehicle orthomosaic photo of the experiment with the location of the 9 plots (represented by the black dashed rectangles), the abbreviations of plant species names present in each plot (native species are in bold) and the 16 positions of the lidar surveys (black dots). Pictures showing the species used in the experiment with (b) *Ammophila arenaria* (AMAR; non-native grass), (c) *Ammophila breviligulata* (AMBR; non-native grass), (d) the hybrid species *A. arenaria* x *A. breviligulata* (HYBR; non-native grass), (e) *Leymus mollis* (LEMO; native grass), (f) *Festuca ammobia* (FEAM; native grass), (g) *Abronia latifolia* (ABLA; native), (h) *Lathyrus japonicus* (LAJA; native) and (i) *Lupinus littoralis* (LULI; native). ABLA, LAJA and LULI are grouped under the name forbs, pictures with asterisks are non-native species. (j) Photograph of the Plot #1 looking eastward (November 18, 2022, photo Q. Laporte-Fauret).

We also deployed a multi-parameter weather station (Vaisala WXT536) (black

rectangle Fig. 1.a) at the site to measure local weather conditions. We measured the 14.5m-hourly wind speed and direction from February 20, 2021 to October

13, 2022. The daily rainfall was measured at the local weather station from February 20, 2021 to December 27, 2021 and then, because of a sensor malfunction, at the Nehalem rainfall station (black triangle, Fig. 1.a) until October 13, 2022. In addition, morphological surveys were carried out at the plot with lidar and on the whole HRA with an unmanned aerial vehicle (UAV).

Dune topographic surveys

Topographic surveys were performed bi-monthly (i.e., 9 surveys during the study period) using a terrestrial lidar (Leica P50) and a Differential Global Positioning System (DGPS, Leica GS14) with the antenna fixed on the top of the lidar (Fig. 2.j). The entire survey of the area required 16 survey positions to create a sufficient Digital Elevation Model (DEM, Fig. 2.a). The lidar coordinates were monitored with the DGPS for each position. The 16 3D dense point clouds were then referenced, gathered, and cleaned using Cyclone software (Leica Geosystems, AG). Vegetation was removed from the 3D dense point cloud using Rambo (Rockfall Activity Morphological Bigdata Optimizer, EzDataMD LLC) with a progressive refinement algorithm for ground filtering and hole filling algorithm (Olsen et al., 2020). Finally, the structured textured DEMs are built with MATLAB from the dense 3D point cloud using natural neighbor interpolation to compute the morphological evolution of the plots on a 0.05 x 0.05 m structured grid.

Results

Wind and precipitation climatology

Over the 20-month period (February 20, 2021 to October 13, 2022), the wind data, monitored locally on the study site, reveals a mean (± std) wind speed of 4.02 m/s (± 2.80 m/s) with some seasonal variation (Fig. 3.a). The prevailing winds had a mean speed and direction of 4.45 m/s (± 2.87 m/s) and 215° (± 85°) in winter (Fig. 3.c, here defined as from October 1st to April 1st) and 3.71 m/s (± 2.71 m/s) and 282° (± 89°) in summer (Fig. 3.d, here defined as from April 1st to October 1st). The 99th percentile of wind speed was $u_{z,99\%} = 12.1\ m/s$ and the maximum hourly wind speed was observed during a storm on January 2, 2022, with a value of 18.8 m/s. Following the definition of Debernard et al. (2008), a storm event is defined when the hourly wind speed exceeds $u_{z,99\%}$. Events with less than 48h intervals are considered the same storm. The time series is composed of 33 storm events with 17 during the winter period. The winter storms had a mean (max; std) wind speed and duration of 13.5 m/s (18.8 m/s; ± 1.58 m/s) and 4.4 h (17 h; ± 4.3 h), respectively. The measured daily rainfall has an average (std) of 0.44 cm/day (± 1.60 cm/day) with strong seasonal variation, reaching 0.72 cm/day (± 1.54

cm/day) in winter and 0.25 cm/day (± 0.74 cm/day) in summer, with a maximal value of 10.95 cm/day during the longest storm event on March 1st, 2022.

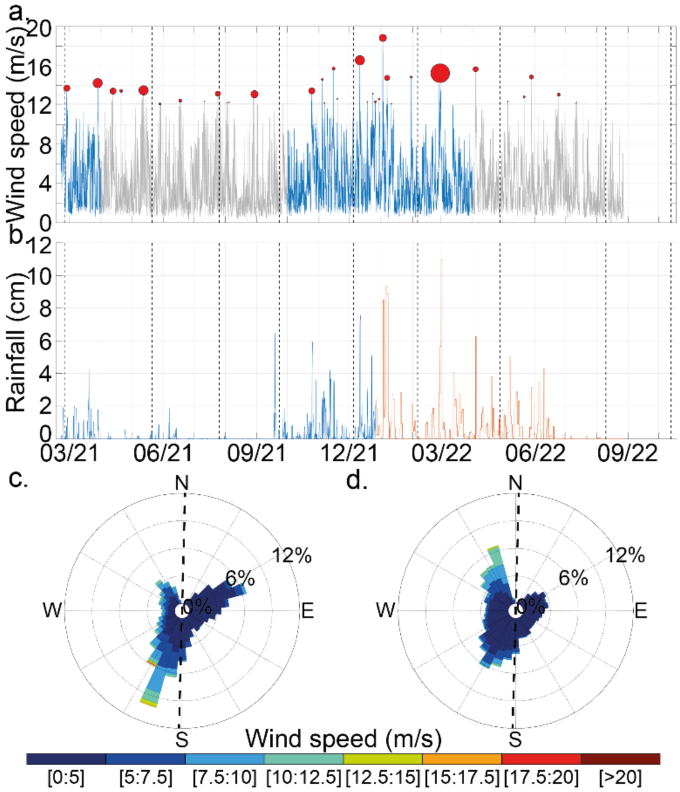

Fig. 3. (a) Time series of 14.5-m hourly wind speed measured at the local Nehalem weather station (black square in Fig. 1.a) with red bubbles indicating the wind speed at the peak of the storm, with size proportional to the storm duration. The horizontal black dashed line represents the 99th percentile ($u_{z,99\%} = 12.1\ m/s$). Blue color highlights the winter period (here defined as from October 1st to April 1st). (b) Time series of daily rainfall measured at the local Nehalem weather station (black square in Fig. 1.a) until December 27, 2021 (in blue) and then measured at the Nehalem rainfall station (black triangle in Fig. 1.a) until October 2022 (in orange). Vertical black dashed lines represent lidar surveys. Wind rose for the entire study period during (c) winter and (d) summer period. The dashed black line represents the main orientation of the Nehalem coast (1.5°).

Vegetation survival and growth

After 20 months, there was an overall plant survival of 45% but with a wide disparity between species and plots (Fig. 4.a). The non-native species plots had the best survival with 82% survival for the hybrid monoculture (Plot #5), 66% survival for AMAR and AMBR polyculture (Plot #2), and 69% for the AMBR monoculture (Plot #3). The native species plots had much lower survival with 37% survival for the LEMO monoculture (Plot #6) and 42% for the native polyculture (Plot #8). The polyculture of native and non-native species also had a low survival rate (43%), but this value was mainly driven by the high mortality of the native species in this plot (Plot #5). Finally, the hybrid species had a survival rate 1.4 times higher than its parents and 2.1 times higher than the native species. The two other non-natives had a survival 1.5 times higher than the native species.

Grass growth varied among species and plots with non-native grass species generally growing faster than native grass species (Fig. 4.b). AMAR shoot density increased by a factor of 7–10 [i.e., mean shoot number ± SE per plant (fold difference) of 28 ± 4.2 in Plot #1 (7 fold increase), 20 ± 2.2 in Plot #2 (9.4 fold increase), 27 ± 2.7 in Plot #4 (9.7 fold increase)], AMBR shoot density increased by a factor of 3–9 [i.e., 12 ± 1.7 in Plot #2 (9.4 fold increase), 12 ± 1.5 in Plot #3 (7.1 fold increase), 10 ± 1.2 in Plot #4 (3 fold increase)] and the hybrid shoot density increased by a factor of 8 [i.e., 18 ± 2.9 in Plot #5 (8.3 fold increase)]. In contrast, native grass species were marked by a lower growth rate with LEMO shoot densities increasing by a factor of 1.5–2 [i.e., 3 ± 0.4 in Plot #4 (1.4 fold increase), 4 ± 0.3 in Plot #6 (1.8 fold increase), 6 ± 0.9 in Plot #8 (1.9 fold increase)] and FEAM shoot densities increasing by a factor of 2.5–3.5 [i.e., 45 ± 5.1 in Plot #4 (2.6 fold increase), 49 ± 7.1 in Plot #8 (3.5 fold increase)].

Given the differences in survival and growth of the grass species among plots, by the end of the study period, the hybrid beachgrass had the highest mean (± SE) shoot densities of 71 shoots per m^2 (± 11.2), followed by its parent species AMAR (58 ± 8.7 shoots per m^2 in Plot #1) and AMBR (39 ± 5.0 shoots per m^2 in Plot #3) (Fig. 4.c). The native grass species had mean shoot densities of less than 10 shoots per m^2 (except FEAM in Plot #8 with 18 ± 2.7 shoots per m^2).

Sand accretion and dune morphological change

The bi-monthly change in sand deposition and sand volume changes of the 9 plots over the 20-month period of the experiment (February 4, 2021 to October 13, 2022) are shown in Fig. 5 and Fig. 6, respectively. At the end of the study period, all plots with vegetation are characterized by an average total deposition (sand volume changes) ranging from 0.12 m (+2.5 m^3/m) to 0.43 m (+8.8 m^3/m). The AMAR monoculture plot (Plot #1) had an average (± std; sand volume changes) sand deposition of 0.43 m (± 0.25m; +8.8 m^3/m), nearly twice as high as the other plots. The control plots without vegetation had limited change, with an average deposition of 0.02 m (± 0.04m; +0.4 m^3/m) for the south plot (Plot #0) and erosion of 0.03 m (± 0.03m; -0.7 m^3/m) for the north plot (Plot # 7).

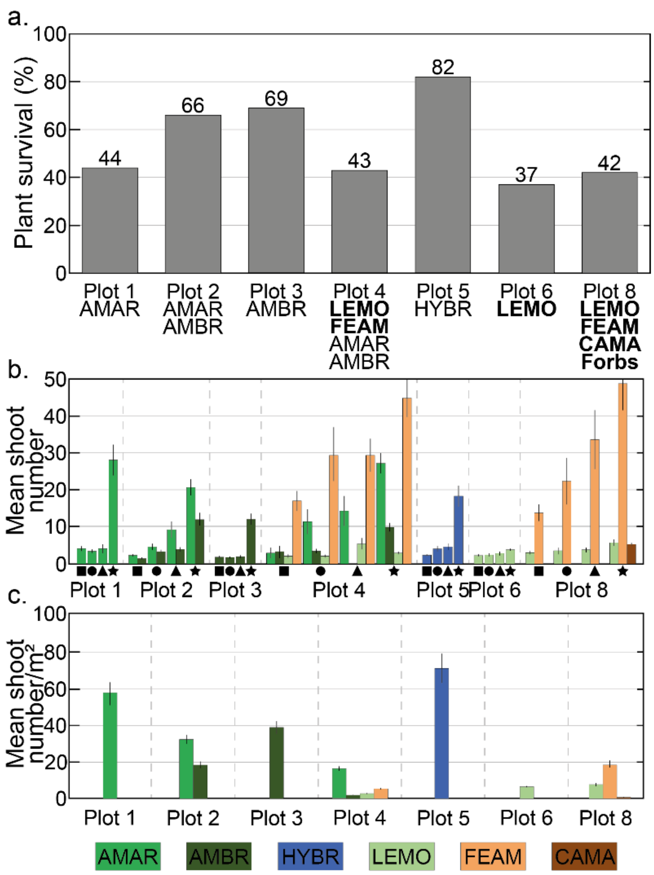

Fig. 4. (a) Plant survival after 20 months (i.e., September 24, 2022) in each experimental plot. Native species typeset in bold, (b) Time series of the mean (±SE) shoot number for each species in each plot. The square, circle, triangle and star under the bars represent the surveys dates May 5, 2021 (square), July 26, 2021 (circle), September 23, 2021 (triangle) and September 24, 2022 (star), (c) Mean (±SE) shoot number per m^2 for each species in each plot after 20 months (i.e., September 24, 2022)

During the study period sand deposition changes were not linear; it is possible to identify three distinct periods of change. The first period (i.e., from February 4, 2021 to May 21, 2021) was characterized by the greatest change with an average (± std) sand deposition of 0.10 m (± 0.03 m) and an average (± std) increase in sand volume of 2.1 m^3/m (± 0.7 m^3/m) in the vegetated plots. The second period (i.e., from September 23, 2021 to December 5, 2021) was characterized by an average sand deposition of 0.03 m (± 0.01 m) and an average increase in sand volume of 0.5 m^3/m (± 0.2 m^3/m) in the vegetated plots. Finally, during the third period (i.e., from April 28, 2022 to August 10, 2022), the sand deposition and the sand volume increased within the vegetated plots with an average of 0.05 m (± 0.03m) and 1.1 m^3/m (± 0.6 m^3/m). These changes were mainly driven by large sand deposition within the AMAR monoculture (i.e., Plot #1) with an average sand deposition of 0.11 m (i.e., +2.3 m^3/m). Indeed, in the described time periods, there were no strong storms (Fig. 3.a), precipitation was small, and wind speeds were an average of 4.16 m/s (± 2.8 m/s) (Fig. 3.b), which may have facilitated sand transport. During the period with the strongest storms (i.e., December 5, 2021 to April 28, 2022; Fig. 5.e-f), morphological changes in the plots remained limited, possibly due to heavy rainfall during these storms (Fig. 3.b).

Discussion

Our common garden experiment in a dune system on the Pacific Northwest coast highlights the effects of native and non-native plant species on sand accretion and dune morphological change over time. The highest sand deposition was found within the non-native *Ammophila* plots, which were also characterized by the highest plant survival and growth rates. *Ammophila arenaria* (AMAR) and *A. breviligulata* (AMBR) are tolerant to sand burial and given their high shoot densities, low blade flexures, and vertical (AMAR) or horizontal (AMBR) growth forms were able to capture more sand than their non-native counterparts (Zarnetske et al., 2012). The sand deposition in the hybrid beachgrass plot was intermediate to that of its beachgrass parents but the plants had the highest survival of all the plantings, suggesting that it is equally or more tolerant to being transplanted and/or sand burial. A mesocosm study by Mostow (2022) showed that the hybrid beachgrass was able to grow faster than, and under some conditions outcompete, its parent species.

The native species plots had the lowest sand deposition and plant survival and growth rates of all the plots. Although the native grass species *Leymus mollis* (LEMO) has a larger shoot morphology that can theoretically capture more sand on a per tiller basis, its low shoot density and high blade flexure is not favorable for windblown sand capture (Zarnetske et al., 2012). Moreover, just after transplantation, strong winter storms generated large sand depositional events that covered the entire experimental area (i.e., an average of 0.1 m sand depth between February 4, 2021 to May 21, 2021, Fig. 5.a). Notably, within the native species plots, there were areas with up to 0.2 m of sand deposition during this period (e.g., Plot #6). It may be that the higher mortality of the native species plantings is a result of lower tolerance to these sand burial events, especially given that many of the native species were small seedlings at the time of transplantation. In this common garden experiment, it is possible that sand deposition is partially related to the location of the plot in the system. Sand deposition was twice as high

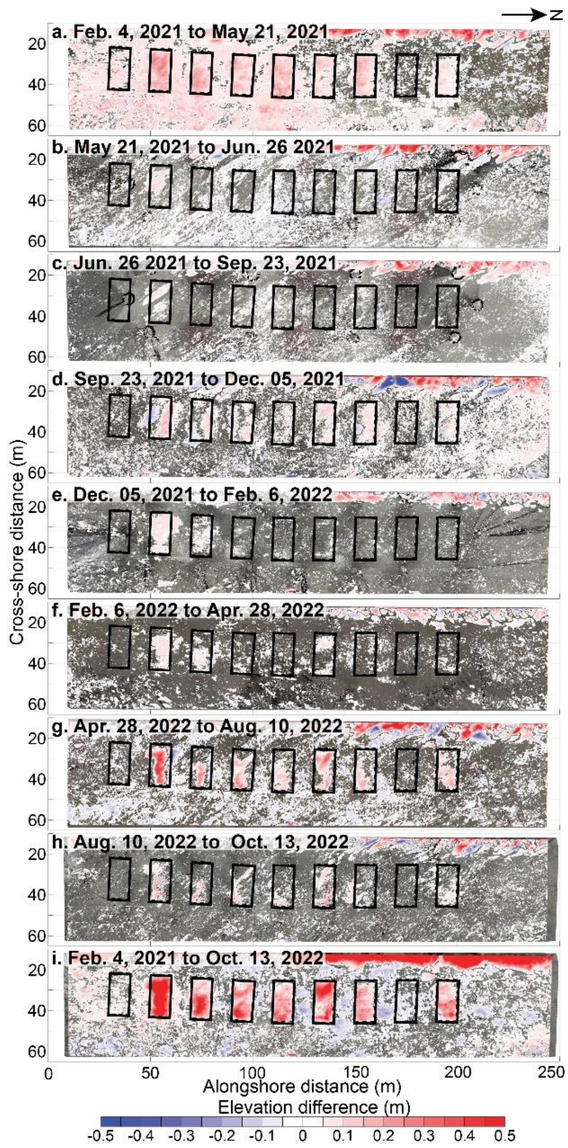

Fig. 5. (a-h) Elevation differences superimposed onto textured DEM (performed by lidar) of the experimental plots at approximately 2–3-month time periods from February 4, 2021 to October 13, 2022 and (i) net elevation differences in each plot for the entire time period.

in the AMAR monoculture plot, which is the southernmost vegetated plot. Most of the winter storms come from a S-SW incidence, favoring greater sand supply to this plot. Greater sand supply combined with the superior sand capture abilities of AMAR (Hacker et al., 2012; Zarnetske et al., 2012) has likely contributed to the much greater sand volume in this plot. Moreover, recent field observations show the presence of small sand dunes (i.e., 4 m long, 5 m wide, 0.7 m height) within the AMAR plot with S-SW oriented stoss sides, which may have been produced by an interaction between sand supply and AMAR growth form.

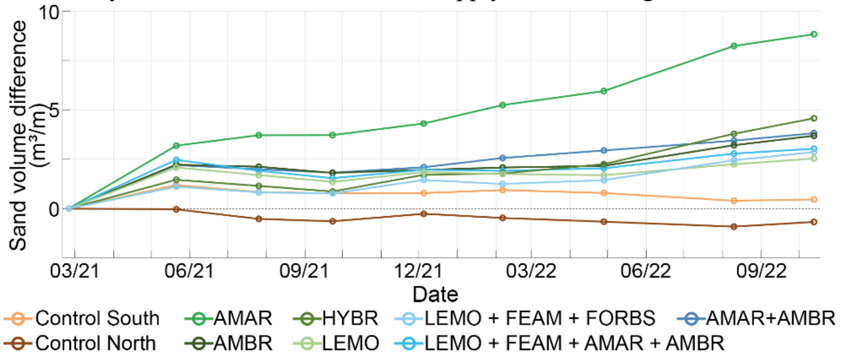

Fig. 6. Time series of sand volume changes between each lidar survey for each plot.

Conclusion

In this study, a common garden field experiment was conducted to understand the effect of native and non-native plant species on dune morphological evolution. After 20 months of monitoring, all vegetated plots increased in sand volume, with measured accretion at least twice as high for non-native species compared to native species. The sand volume captured by a hybrid beachgrass shows intermediate sand capture compared to its beachgrass parents, despite having the highest survival rate and shoot densities of all the plant species. However, given that the plots are oriented S-N and the strong winter storms have a main incidence of S-SW, it is possible that the position of the plots played a role in the windblown sand capture by favoring the southern plots. Our results provide early insights into the role of plants in the evolution of dune morphology. However, more time and analysis are required to determine the species-specific effects of plants on sand accretion and dune morphology, and the relative role of sand supply in this process.

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