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PHYSICAL MODEL EXPERIMENT INVESTIGATING INTERACTIONS BETWEEN DIFFERENT DUNE VEGETATION AND MORPHOLOGY CHANGES UNDER WAVE IMPACT

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Abstract

Vegetated coastal dunes were subjected to wave-induced erosion in a physical model wave flume experiment. Four different plant morphotypes including tall and short dune grasses, spreading vines, and shrubs were tested at different maturity levels to assess the effects of above- and below-ground vegetation characteristics on beach/dune erosion. Multivariate statistical analyses were carried out to identify relationships between plant parameters and erosion processes. Wave-induced fluid-sediment-vegetation interactions in the swash zone were analyzed using high-resolution (200 Hz) acoustic Doppler velocimeter data near the sediment bed within the vegetation patch on the beach/dune slope. Results show a significant negative correlation between turbulent kinetic energy levels in the vegetated swash zone produced by irregular wave forcing and above-ground plant surface area in touch with the swash flow.

Key words: vegetated dunes, swash hydrodynamics, dune/beach morphodynamics, ecomorphology, physical modeling, coastal engineering

1. Introduction

1.1. *Motivation*

Vegetated coastal dunes fulfil multiple functions ranging from protection of landward development and infrastructure against storm surge and wave action damage to provision of valuable ecosystem services such as plant and species habitat (e.g. Feagin et al., 2015; Figlus et al., 2014). Most dune restoration projects specifically call for vegetation to be planted as additional erosion control but only limited quantitative data is available to assess how different plant morphotypes influence wave-induced dune erosion (e.g. Silva et al., 2016). Coastal dune vegetation varies widely in appearance, including above-ground shape, rigidity, and biomass, as well as below-ground root structure and sediment binding capacity. Reliable data sets on erosion of vegetated dunes are sparse and most existing numerical morphology change models do not yet explicitly consider the above- and below-ground effects introduced by live vegetation. Anecdotal evidence and a limited number of experiments suggests, that the different physical traits of different dune plant morphotypes influence wave-induced erosion in a variety of ways. One way to address this knowledge gap is by systematic controlled laboratory physical model testing with real vegetation. This study addresses this knowledge gap by testing different dune plant morphotypes under wave-driven erosion in a sediment wave flume physical model experiment.

1.2. *Background*

Results from multiple studies on the apparent link between vegetation and the accretion of dune sediment have suggested that vegetation plays an indirect role in storm protection by aiding in accumulation of sediment (Buckley, 1987; de M. Luna et al., 2011; Mendelssohn et al., 1991. The extra built up volume of sediment over time can act as an increased buffer during a storm. The question how exactly vegetation plays an active role in reducing dune erosion during wave impact remains to be answered in more detail. Several flume studies have shown vegetation reduces erosion in small scale dune settings (Sigren et al.,

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2014; Silva et al., 2016), but the physical causal role that vegetation plays in dune erosion resistance has not been established. This physical causal role is likely to be complex, involving both below- and above-ground characteristics of vegetation.

Reduced erosion caused by plants has been observed in marsh, mangrove, creek bank, and terrestrial ecosystems (Coops et al., 1996; Gedan et al., 2011; O'Dea, 2007; Thampanya et al., 2006) and provides a basic framework for the ways in which vegetation could affect erosion in dunes. In general, there are two ways in which plants can impact erosion in dunes: substrate modification belowground and hydrodynamic modification aboveground. In other ecosystems such as marshes, seagrass beds and river banks, the stems and leaves of plants provide resistance to attacking waves and currents (Augustin et al., 2009; Leonard and Luther, 1995; Yang et al., 2012; Ysebaert et al., 2011), reducing the amount of erosion occurring in landward sediment (Coops et al., 1996; Thampanya et al., 2006). The above-ground fluid-vegetation interactions could increase the dissipation of wave energy, and reduce wave reflection, swash/backwash velocities, and turbulence levels. Reduction of wave energy (Yang et al., 2012; Ysebaert et al., 2011), flow velocity, and turbulence (Leonard and Luther, 1995) caused by vegetation has been observed in other ecosystems with emergent and submerged vegetation. Below ground, plant roots and their associative microbial communities, primarily arbuscular mycorrhizal fungi (AMF), interact with surrounding sediment to reduce erosion by improving soil aggregation and shear strength (Burri et al., 2013; Fan and Su, 2008; Miller and Jastrow, 1990; O'Dea, 2007).

This aggregation/binding process is likely to also cause enhanced erosion resistance of vegetated substrate under the wave collision regime (Sallenger Jr, 2000), where waves impact the dune directly, forming and advancing a vertical scarp. Sediment conglomerates bound together by plant roots have a lower surface area to mass ratio, making them more resistant to entrainment by the pressures exerted by moving water. In addition, plant roots increase the shear strength of sediment (De Baets et al., 2006; Sigren et al., 2014). As waves erode the base of the scarp, gravity pulls on the overhanging sand, inducing shear stress across the dune sediment. At a critical overhang mass, the scarp will break off and slump into the oncoming waves. Plant roots theoretically prolong this process as the tensile strength of roots resists the shear stress better than sediment without roots. Ultimately, both above-ground and below-ground aspects of dune vegetation can help to delay wave-induced dune erosion. If the delay is long enough to avoid breaching or overtopping, the vegetation has contributed significantly to the protective value of dunes.

1.3. *Scope of this study*

This study investigates the effects of various plant morphotypes on wave-induced vegetated dune erosion by means of a physical model experiment. Four different plant species representing short dune grasses, tall dune grasses, spreading vines, and shrubs/forbs were used (Figure 1). Of specific interest was the effect of variations in plant parameters such as root biomass, stem flexural rigidity, and plant surface area on the morphological evolution of the dune under elevated water levels and wave attack. By assessing the specific interactions between vegetation, sediment, and hydrodynamics a statistical model for vegetation's role in dune erosion resistance can be created. Specifically, the idea was to explore which aspects of vegetation and which physical processes are linked to enhanced erosion resistance. Understanding this causal role could shape the discussion of dune restoration and management in that practices and goals could be set to maximize certain protective aspects of vegetation and to choose the optimal type or mix of dune restoration vegetation based on these insights.

Figure 1. Photos of initial vegetated dunes inside wave flume. From left to right: *Sporobolus virginicus, Panicum amarum*, *Sesuvium portacastrum, Rayjacksonia phyllocephala*.

To accomplish this objective, a wide range of variation in above- and below-ground aspects of vegetation were tested within a controlled wave flume setting. During testing, data was collected on erosion, dune morphology, sediment properties, and swash hydrodynamics so that these processes could be statistically modeled and linked to the vegetation aspects. In the following, specific focus is placed on the statistical importance of various above-ground and below-ground plant parameters in modifying dune erosion evolution and swash hydrodynamics.

2. Methodology

2.1. *Wave flume physical model setup*

All tests carried out in this study involve live plants grown in dune sediment before being subjected to wave action in a sediment wave flume (dimensions: L x W x H = 15 x 0.6 x 1.3 m). The beach and dune profiles were constructed using 6 m^3 of fine sand (D_{50} = 0.14 mm). The dune volume and crest were chosen such that a significant volume of sand was available for erosion without allowing for wave overtopping of the dune crest. A schematic of the wave flume experiment setup is depicted in Figure 2. The experiment consisted of 5 test series; one control series and 4 series with plants. Each test series comprised 3 runs with varying plant maturity levels ranging from 3 to 9 week growth time, respectively (except of course the control runs without any plants). The increasing growth time lead to increasing biomass both above-ground and below ground for each plant morphotype. Each run included 12 wave bursts each with a duration of 210 seconds for a total of 42 minutes. The irregular wave time series followed a JONSWAP spectral shape and had a significant wave height of H_s = 6.7 cm. Hydrodynamics were measured using nine capacitance wave gauges, two Nortek Vectrino II acoustic Doppler profilers, and one side-looking Nortek Vectrino acoustic Doppler velocimeter, each placed at strategic cross-shore locations, respectively.

An Acuity AP820-1000 laser line scanner system mounted on a moveable cart above the flume measured the beach and dune profiles between wave bursts. For every laser scan, the water level in the flume was lowered and then filled back up to the previous level before the next wave burst. The system utilized a high-power blue laser diode (540 nm wave length) in concert with a 200 Hz 2D charge-coupled device (CCD) detector to measure the elevation of the sand surface. The laser diode was set up to project an alongshore blue laser line vertically down onto the beach and dune surface. The CCD detector registers the diffuse reflected laser light and computes elevation with millimeter accuracy based on reflective light intensity. The cart was moved in the cross-shore direction along the flume and line scans were carried out every 1 cm across the entire sand portion. The resulting detailed 3D representation of the measured surface elevations were used to verify alongshore uniformity of the beach and dune evolution process. To assess the profile changes, above-ground vegetation components were excluded from the scans during post-processing and only the sediment surface was considered. For further analysis the 3D profiles were collapsed into single average profile lines.

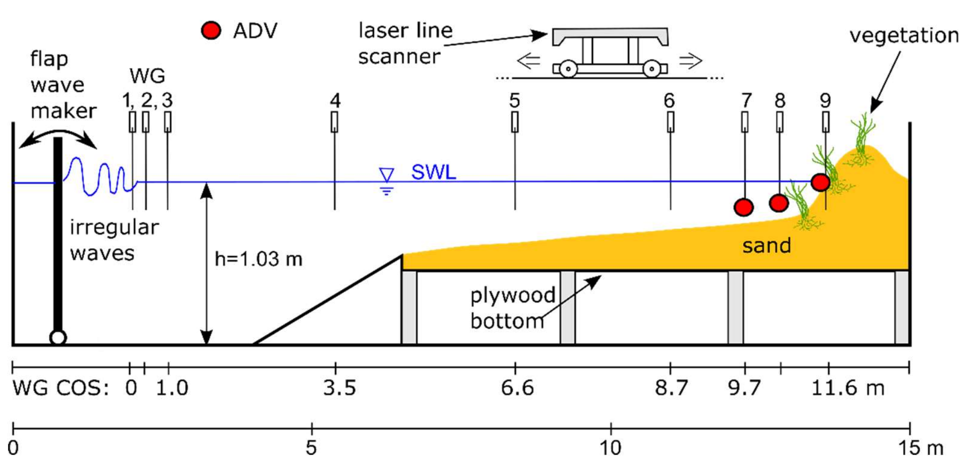

Figure 2. Wave flume experiment schematic.

Initial beach and dune profiles were kept the same for all test runs. The initial geometry included a 1:30 beach slope in front of the dune which is typical for the upper Texas coast. The dune volume and crest were chosen such that a significant volume of sand was available for erosion without allowing for wave overtopping of the dune crest. Thus, the experiment focus was on swash-interactions between waves, sediment and vegetation. The vegetation occupied the area between the foot and the crest of the dune over the entire width of the wave flume as shown in Figure 1. The still water level (SWL) and irregular wave pattern were kept the same for each test. Table 1 gives a summary of all experiment parameters.

Table 1. Summary of wave flume experiment parameters

Plant Species	None (Control)			*P. amarum* (Tall Grass)			*R. phyllocephala* (Short Shrub)			*S. portulacastrum* (Vine)			*S. virginicus* (Short Grass)		
Test	C1	C2	C3	PA1	PA2	PA3	RP1	RP2	RP3	SP1	SP2	SP3	SV1	SV2	SV3
Plant Maturity (weeks)	N/A	N/A	N/A	3	6	9	3	6	9	3	6	9	3	6	9
No. of Plants	0			15											
Plant Density	0			28 plants/m^2											
Total Duration	42 min														
No. of 3.5-min Wave Bursts	12														
H_s	6.7 cm														
T_p	1.9 s														
h	103 cm														
D_{50}	0.14 mm														
No. of Profile Scans	6														
Time of Profile Scans	0, 3.5, 7, 14, 28, 42 min														
WG x-Locations	0.0, 0.2, 1.0, 3.5, 6.6, 8.7, 9.7, 10.4, 11.6 m														
ADV x-Locations	9.7, 10.4, 11.6 m														

Nine capacitance wave gauges (WG1 – WG9) placed strategically along the center line of the flume measured free surface fluctuations from deep water to the dune at a frequency of 20 Hz (Figure 2). The origin of the local coordinate system is set at the cross-shore location of WG1. The x-axis coincides with the center line of the flume at still water level (SWL) pointing positive onshore with x=0 at the WG 1 location. The three most offshore gauges (WG1 – WG3) were used to separate incoming and reflected wave spectra and time series and to calculate reflection coefficients for each wave burst.

2.2 *Live vegetation*

To establish a wide range of above and below ground variation for different flume trials, two vegetation growth parameters were manipulated. The first was that 4 different species of plants, each a unique morphotype, were tested. The species used were *Sporobolus virginicus* (a short dune grass roughly 5 – 15 cm in height), *Panicum amarum* (a tall dune grass that can grow over a meter in height), *Rayjacksonia phyllocephala* (a dune forb/shrub that grows typically about 50 cm in height, though shorter 5 - 10 cm tall seedlings were used within the flume), and *Sesuvium portulacastrum* (a spreading dune vine which rarely grows higher than 5 cm off the ground). These morphotypes differ greatly in above-ground surface area and stem flexibilities and have different allocations of above- and below-ground biomass. Furthermore, different plant species have different root size distributions, some with coarser roots/rhizomes while others have finer roots. The second growth parameter that was manipulated was the maturity of the plants. For each species, plants were grown in a greenhouse for 3, 6, and 9 weeks prior to transfer into the wave flume.

These different increments of growth allowed a gradual accumulation of biomass within plant pots, creating additional variation between trials with regards to above and below ground aspects. All plants were grown in pots (cylinders with a 16 cm diameter and 16 cm depth) in a greenhouse over the spring and summer of 2016. All plants were watered comparably, fertilized with 7 grams of Osmocote slow release fertilizer, and grown in the same sediment that comprised the dune and beach profile in the wave flume. The content of 15 plant pots were transplanted to the seaward facing slope of the dune within the wave flume in a 5 x 3 grid (Figure 1)..

2.3 *Data analysis*

Six profile scans were conducted for each run: An initial scan and then after wave bursts 1, 2, 4, 8, and 12. After filtering out plant obscuration, the three-dimensional topography/bathymetry evolution data were averaged over the alongshore direction. The resulting two-dimensional cross-shore dune and beach profiles were used to calculate 3 erosion/morphological change parameters: erosion volume, scarp retreat, and profile center of mass shift during the erosion process. Scarp retreat was defined as the distance from the initial base of the dune to the steepest portion of the dune in the final profile. The overall movement of dune sediment to a location further offshore on the beach profile was captured by assessing the geometric area centroid, *C*, of the active profile between the back-dune and the apparent depth of closure for each profile measurement:

$$C = \frac{\sum_{x_1}^{x_{dc}} (Z_x \cdot D_x)}{\sum_{x_1}^{x_{dc}} (Z_x)} \tag{1}$$

Here, x_1 is the cross-shore profile point furthest away from the wave paddle (back-dune), x_{dc} is the cross-shore profile location at depth of closure, Z_x is the vertical profile elevation at *x*, and D_x is the horizontal distance from the wave paddle at *x*. The shift, *S*, in centroid between the initial and final profiles of a run represents an average distance sediment has moved during wave impact and was calculated as:

$$S = C_f - C_i \tag{2}$$

where the indices *f* and *i* indicate measurements for the final and initial profile, respectively.

For the hydrodynamic analysis the focus here is on the swash velocity data collected by the side-looking Nortek Vectrino acoustic Doppler velocimeters (ADV). This instrument was located within the vegetation patch just seaward of the SWL intersection with the initial beach/dune profile (collocated with WG9). The sensor head configuration allows for high-resolution (200 Hz) 3D velocity measurements at a point in very shallow water depth. For each wave burst the instrument measuring volume was placed about 1 cm above the initial sediment bed to capture swash up- and downrush velocities in the vegetated zone. Due to the nature of swash hydrodynamics the instrument head was only intermittently submerged leading to some gaps in the measured velocity time series when the head was out of the water. The collected data was quality-controlled and only valid velocity measurements during submergence of the instrument head were retained for analysis based on water level readings from the collocated wave gauge. Noise and erroneous readings that could be caused by entrained bubbles, especially at the front end of uprush bores, were removed based on an acceleration filter. For the remaining data, velocity signals were decomposed into mean and turbulent components where the mean velocity signal was estimated via a 20-point running average filter. After filtering, the average turbulent kinetic energy (TKE) for each wave burst was calculated from the valid swash velocity data as

$$TKE = \frac{1}{2}(u'^2 + v'^2 + w'^2) \tag{3}$$

where u', v', and w' are the averages of the turbulent velocity fluctuations in the cross-shore, alongshore, and vertical direction over each 210-second wave burst, respectively.

After each trial, all plants were exhumed from the flume sediment, washed, separated into above-ground and below-ground components, dried, and weighed for biomass. Below-ground components were also separated into fine roots (diameter less than 1 mm) and coarse roots (diameter greater than 1mm). The number of stems was counted prior to drying. For vines, which possess laterally growing stolons which are anchored at nodes by roots, each time the plant emerged from a rooted stolon node was counted as a stem. The average surface area for each stem (attached leaves included) was calculated by taking a picture of five sample stems against a white sheet of paper including a length scale benchmark. The number of pixels that were plant material (green) was summed and the benchmark was used to determine the number of pixels per square centimeter. This technique allowed for the calculation of the average two-dimensional surface area for each stem and the total surface area for each trial (average surface area of each stem multiplied by the total number of stems). Only the bottom 5 cm of plant stem pixels were summed as this length was the maximum depth in contact with swash zone flows. A sample of five stems from each trial was also tested for stem rotational stiffness. This variable was measured by applying a force to a known location while the stem was anchored on one side. The angle of deflection of the stem could then be used to obtain rotational stiffness. Lastly, mycorrhizal colonization was measured by staining a subsample of fine roots with Trypan Blue. Stained roots were placed on a slide and 35 cm of roots (at 1 cm increments) were examined at 200X magnification. Presence of mycorrhiza was identified when hyphae, arbuscule, vacuole, or spore structures were identified within or on the plant root. The percentage of roots with mycorrhizal presence was then calculated based on total root length.

Stepwise multivariate regression analysis was used to model the relationships between various plant-related parameters and parameters related to the morphological response of the vegetated dune (eroded volume, scarp retreat, geometric centroid shift). The 5 plant parameters used for potential predictor variables were fine root biomass, coarse roots biomass, above-ground surface area of stems and leaves in touch with swash flow, stem rotational stiffness, and mycorrhizal colonization. If a variable was not found to be a significant predictor of any morphological response it does not necessarily mean it is not related or causally linked to that response, but simply could mean that an inadequate range of that variable was tested during the flume trials. This concept could apply to either vegetation or confounding variables.

3. Results

3.2 *Morphodynamic response and vegetation*

Three morphodynamic change metrics were calculated from the beach and dune morphological data from each trial: dune erosion, scarp retreat, and the offshore shift of the cross-shore dune area centroid, *S*. All three of these variables were modeled by vegetation variables as well as confounding variables. The statistical model data indicated that root biomass and above-ground plant surface area in touch with swash flows were significantly and negatively related to eroded dune volume, i.e. less erosion occurred for test runs with higher amounts of fine roots and above-ground plant surface area. The model also indicated that both fine root biomass and above-ground plant surface area were significantly and negatively related to dune scarp retreat. Again, less scarp retreat occurred for trials with higher amounts of fine roots and above-ground plant surface area.

Substantial variability in different aspects of vegetation was observed as a result of using different species and growth increments. Figure 3 summarizes the variability of vegetation aspects in multiple star plots (green). The axes represent the following terms: fine root biomass, coarse roots biomass, above-ground plant surface area of stems and leaves affected by swash flows, stem rotational stiffness, and mycorrhizal colonization. The rings of the star plots represent data values relative to all other trials. For example, *S. portulacastrum* at 6 weeks growth had the highest amount of above-ground plant surface area as indicated by a far reaching spoke on the “SA" axis. The axis for mycorrhizal colonization, however, simply represents percent colonization with each ring representing a 20 % increment. Each control trial consisted of basically no star at all (the center ring is actually zero). Generally, trials can be grouped into three categories based on the approximate green area of the plant star plots: controls, low vegetation, and high

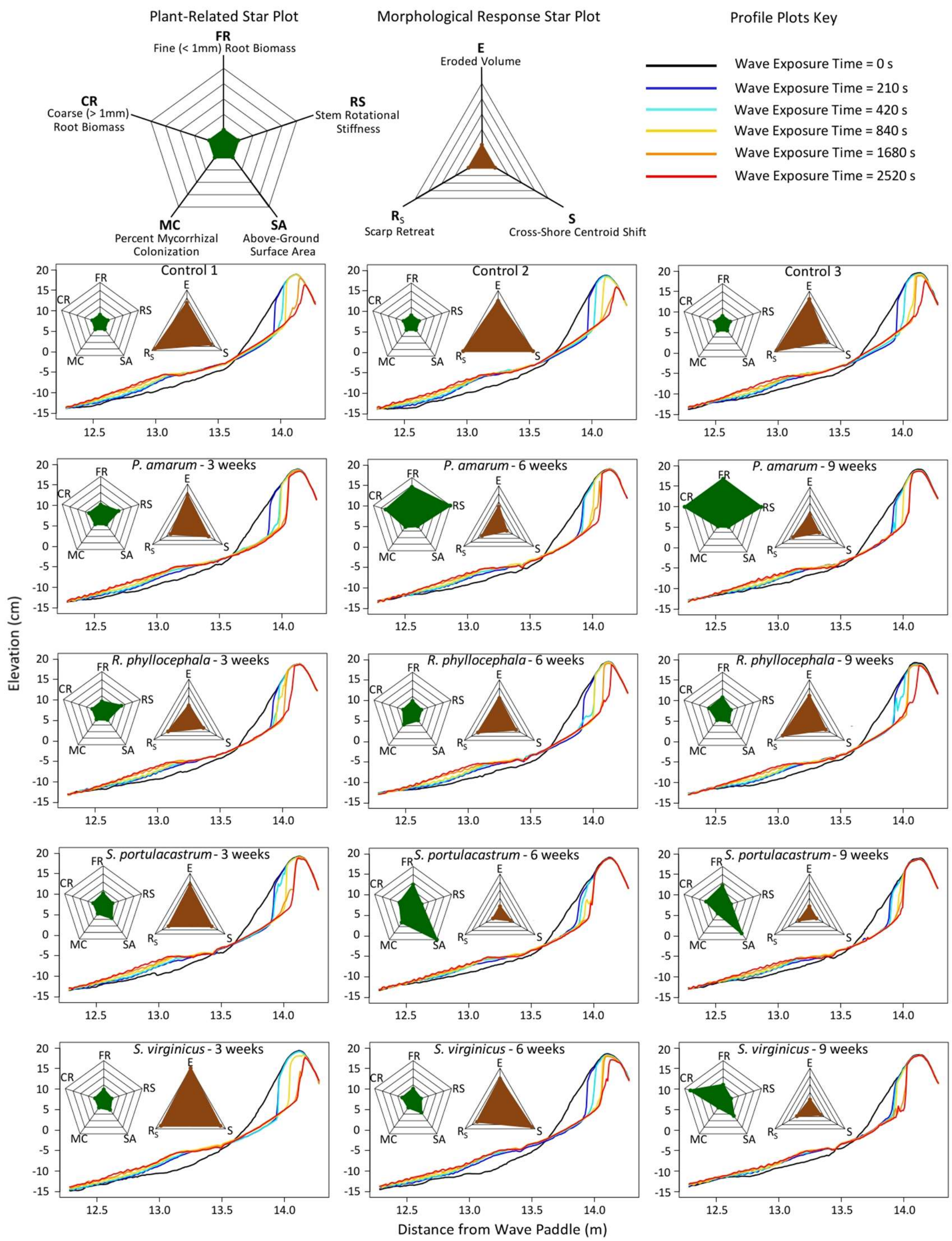

Figure 3. Measured profile evolution for all tests, results of plant parameter multivariate statistical analysis, and results of dune parameter statistical analysis.

vegetation. The morphological response is shown in star plot form including eroded dune volume (E), scarp retreat (R_S), and dune area cross-shore centroid shift (S), as well as actual measured profile evolution plots for each test run, respectively.

Control tests had zero vegetation and experienced high amounts of erosion (a large brown star plot area = high erosion, mean 64.8 cm of scarp retreat, mean 18379.4 cm^3 of dune erosion, and mean 11.9 cm for dune area centroid offshore shift). Low vegetation trials (*P. amarum* 3 weeks, *R. phyllocephala* 3, 6, and 9 weeks, *S. portulacastrum* 3 weeks, and *S. virginicus* 3 and 6 weeks), which typically were below average for all vegetation variables, experienced less erosion (mean 57.9 cm for scarp retreat, mean 17588.5 cm^3 for erosion, and mean 10.7 cm for area centroid shift toward offshore). Higher vegetation trials (*P. amarum* 6 and 9 weeks, *S. portulacastrum* 6 and 9 weeks, and *S. virgi*nicus 9 weeks), which typically were above-average for at least one vegetation variable, experienced much less erosion (mean 51.3 cm for scarp retreat, 13610.1 cm^3 for eroded volume, and mean 6.6 cm for area centroid shift toward offshore).

Differences can be seen in the growth patterns and vegetation characteristics of these 4 plant morphotypes. *P amarum* accumulated large amounts of both coarse and fine roots but had low amounts of above-ground plant surface area. This lack of surface area was largely a cause of low stem density and taller plant heights which caused the majority of the plant to be above the swash flow. *P amarum* also showed the highest amount of stem rigidity. *R. phyllocephala* did not grow much over its 9 week growth period and primarily had low amounts of all aspects of vegetation for all growth time increments. *S. portulacastrum* accumulated moderate amounts of fine and coarse root biomass and a large amount of above-ground surface area. This high amount above-ground surface area accumulated was primarily caused by the spreading nature of this plant, where nearly all of its above-ground structures were submerged in the swash zone. This plant lacked rigidity, however. Lastly, *S. virginicus* slowly accumulated high amounts of coarse roots and moderate amounts of fine roots and above-ground surface area. This plant also lacked rigidity. No morphotypes displayed substantial mycorrhizal colonization, the lowest value being 0% and highest being 34.6% (mean = 5.4%). The results show that both fine root mass and above-ground plant surface area significantly and negatively correlate with total dune erosion volume and dune scarp retreat rate.

3.3 *Turbulent kinetic energy considerations*

The effect of the above-ground vegetation structure on levels of turbulent energy in the inner surf and swash zones was of particular interest in this analysis since turbulence is associated with sediment mobilization and erodibility. Leonard and Luther (1995), for example, reported on decreased strength of turbulent eddies by means of flow interaction with marsh vegetation. Similar measurements within vegetated dunes are rare and are complicated by the fact that the hydrodynamic interaction with the sediment bed and the vegetation is intermittent during swash cycles. The 200-Hz velocity data collected at approximately 1 cm elevation above the sediment bed near the pivot point between profile erosion (landward) and profile accretion (seaward) allowed for quantification of turbulent kinetic energy (TKE). Since these measurements were collected inside the vegetated beach/dune system, the change in average TKE over a test run could be compared to runs with different vegetation to analyze the effect of different plant morphotypes and above-ground biomass on turbulence levels. Figure 4 shows the change of measured average TKE (3) over the 12 wave bursts comprising each 42-minute test run. The y-axis shows the test run listing individual wave bursts from 1 to 12 with the first burst at the top. The colored symbols on the x-axis indicate morphotype and maturity of the tested vegetation as detailed in Table 1. Black downward pointing triangles indicate control test runs without vegetation. Green, yellow, red, and purple symbols indicate the type of vegetation as *Panicum amarum*, *Rayjacksonia phyllocephala*, *Sesuvium portulacastrum*, and *Sporobolus virginicus*, respectively. Plant maturity for a specific test run is indicated by symbol shape with circles, diamonds, and upward pointing triangles referring to 3, 6, and 9 weeks of growth time, respectively. The heat map colors represent average TKE per wave burst ranging from 0.07 J/kg (dark blue) to 0.12 J/kg (dark red). The heat map legend also provides a frequency count for individual average TKE bins.

The results show that TKE tends to decrease with test duration. The average TKE across all trials for the first 210 s of wave exposure (burst 1) was 0.027 J/kg and for the last 210 seconds of wave exposure (burst

12) was 0.015 J/kg. This reduction can be attributed to the changing geometry of the beach profile towards equilibrium in respect to subjected wave energy. However, as profile shapes approach equilibrium, the differences in average TKE values between different plant morphotypes become apparent. This significant negative correlation between above-ground plant surface area (or biomass) and average TKE levels is one way to assess the effect of vegetation on wave-induced dune erosion and to quantify a key element in fluid-vegetation interaction.

Plant trials, notably PA9, SP6 and SP9, as well as RP9, had lower average TKE towards the end of wave exposure than other trials (up to 50% reduction). This means that wave runs with more abundant above-ground surface area (or biomass) exhibited reduced turbulence in the swash zone. More abundant above-ground structure developed with increased plant maturity. In addition, plants with larger surface area near the sediment bed, such as *S. portulacastrum*, yielded reduced average TKE values earlier in the tests and already at lower maturity levels as indicated by the larger percentage of dark blue shaded fields for SP6 and SP9 in Figure 4.

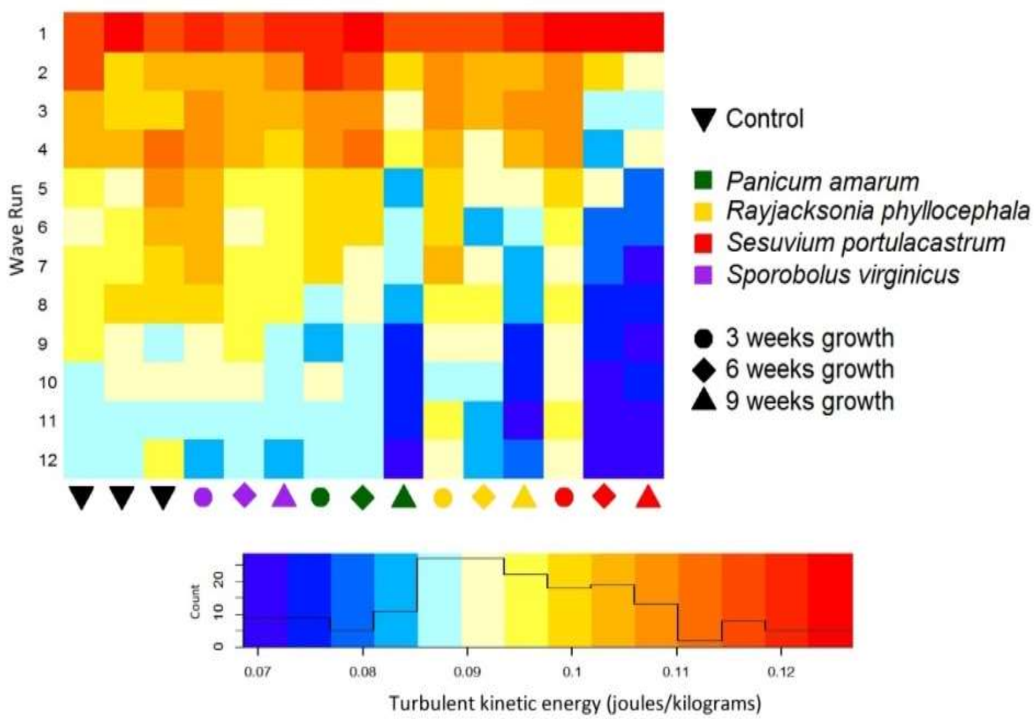

Figure 4. Average turbulent kinetic energy (TKE) measurements based on Reynolds decomposition of measured acoustic Doppler velocimeter time series 1 cm above the sediment bed within the vegetation canopy.

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4. Discussion and Conclusions

This flume experiment showed that both above-ground and below-ground aspects of vegetation are relevant in dune protective capabilities and wave-induced erosion resistance. The surface area of above-ground plant structures in touch with swash zone flows was a key factor linked to erosion reduction. As above-ground plant surface area increased, levels of average turbulent kinetic energy (TKE) in the swash zone decreased. This calming effect has been observed in other hydrodynamic settings with emergent vegetation (Leonard and Luther, 1995; Silva et al., 2016), but this is the first time it has been observed and quantified for different plant morphotypes within the swash zone of a vegetated beach/dune system. At the same time, multivariate statistical analysis showed that fine roots (D < 1 mm) of plants were also key determinants of erosion reduction, likely enhancing sediment shear strength and making dune systems less prone to slump and collapse. Overall, the effect of vegetation on beach/dune erosion in this physical model experiment was substantial. Vegetation with the above-ground surface area of *S. portulacastrum* at 9 weeks growth and the fine root biomass of *P. amarum* at 9 weeks growth experienced a reduction of 37% in eroded dune volume compared to control trials without vegetation. This is comparable to the results from other flume tests with real or artificial vegetation, which also found approximately 33% less erosion when vegetation was present on a dune's seaward face (Kobayashi et al., 2013; Sigren et al., 2014; Silva et al., 2016). This reduction in eroded volume, because it occurs over a period of wave exposure, can also be viewed as a reduction in the rate of erosion. If wave attack was allowed to continue until the dune breached, presumably the dune breach would be delayed by the presence of vegetation. The storm damage reduction afforded by coastal dunes with regards to homes and infrastructure could therefore be further enhanced by vegetation, specifically, if morphotypes with advantageous characteristics were chosen for dune restoration plantings.

Following this train of thought, managing and restoring dunes so that the above-ground surface area of plant structures and fine root biomass are increased would, in concept, create a dune system capable of mitigating more storm damage. This management practice would likely have to rely on multiple plant species, some that have higher allocation of resources to above-ground structures and some that have extensive and dense root systems with a relatively high percentage of fine roots. Additionally, above-ground structures would have the greatest impact in an area where they are coming into contact with incoming waves, notably the seaward base of the dune and embryonic dune systems. Roots, on the other hand, are more important in areas where a scarp is forming because of their contribution to sediment shear strength. Targeting different zones of the dune with specific plant morphotypes in this way could further enhance dune protective capabilities. Finally, the nature of scaled physical model experiments involving waves, sediment and real vegetation of course limits the ability to scale up these findings on a one to one basis to larger vegetated dunes in the field subject to wave attack. Nonetheless, the concept of delaying and reducing wave-induced erosion via above- and below-ground effects of different dune plants is certainly real and further laboratory and field experiments aimed at quantifying the effects of vegetation on dune erodibility are encouraged.

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