EROSION OF VEGETATED COASTAL DUNES

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Coastal dunes can protect communities and infrastructure against storm surge and wave attack. They provide a natural barrier of granular material that erodes during storm conditions and dissipates wave energy in the process. Vegetation is abundantly present in most coastal dunes and may enhance the capability of the dune to withstand erosion. However, reliable data allowing quantification of the erosion process of dunes are sparse, in particular, data involving live plants. In this study, physical model experiments in a moveable-bed wave flume were carried out to investigate the effect of live plants on the wave-induced dune erosion process. The dune grass *Sporobolus virginicus* was grown in pots with dune sediment, transplanted into test dunes and subjected to both regular and irregular wave attack. Measurements of hydrodynamics and profile evolution show that the vegetation does affect the eroded dune volume and the dune scarp retreat rate. During wave flume testing vegetation density ranged from 0 to 80 plants per square meter and plant maturity (i.e. age) was varied between 0 and 12 weeks but further tests are necessary to substantiate the observed trends. The maturity of the plants' root system yielded the most significant impact on dune erosion as plants with more developed roots were able to reduce the eroded dune volume more than plants with less mature root systems.

Keywords: live dune plants; Sporobolus virginicus; physical model test; moveable bed experiment; storm impact; sediment transport; morphodynamics; profile evolution

INTRODUCTION

The motivation, background, and current state of knowledge for this interdisciplinary study, as well as its scope, are explained in this section.

Motivation and Background

Vegetated natural dunes are an essential part of most of the world's sandy coastlines. In fact, a majority of dunes along the coast include some form of vegetative cover. While these dunes occupy a rather small areal footprint compared to other terrestrial landforms, they fulfill a large variety of beneficial functions in this highly dynamic coastal zone. As an integral part of the coastal morphology, they are a sacrificial sand source during storm events when water levels are high enough for attacking waves to erode the dune substrate. In this process, wave energy is dissipated as waves break in the surf zone, run up and down the beach and dune face, and mobilize sediment for offshore transport. This offers protection to landward infrastructure against storm surge and wave action damage and reduces hinterland flooding.

Vegetation influences dunes in many ways. Plants can help to gradually grow and replenish dunes by trapping wind-blown sediment on the beach. Plant roots bind sediment grains together, which may lead to improved erosion resistance as investigated in this study. In addition to their aesthetic appeal, vegetated dunes also have value as unique ecosystems and eco-corridors providing habitat to local plants and wildlife as well as shelter and food for migratory species traveling along coastlines. Furthermore, healthy dune systems in conjunction with adjacent beaches may attract tourists and can play an important role in supporting local tourism industries.

The various beneficial functions fulfilled by dunes, and specifically vegetated dunes, are of course important, but the main point to be investigated here is whether and how much vegetation actually increases the capability of coastal dunes to resist wave-induced erosion. Most dune restoration projects specifically call for vegetation to be planted as additional erosion control (e.g. Patterson 2005) but only limited quantitative data is available on the actual benefit of vegetated versus non-vegetated dunes regarding their resistance against wave-induced erosion. Knowing how plants affect the erosion resistance of dunes will be increasingly valuable as we seek natural, sustainable, soft solutions to combat the effects of growing pressure on our coastlines from population increase, rising sea levels and increased storm frequency and intensity.

Existing Capabilities and Literature Review

Our understanding of dune erosion processes without vegetation has greatly improved in recent years (e.g. van Gent et al. 2008; Kobayashi et al. 2009) and numerical models are getting better at simulating even difficult morphology and sediment transport problems like dune overwash and breaching (e.g. Figlus et al. 2011, McCall et al. 2009). However, reliable data sets on erosion of

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vegetated dunes are sparse and most numerical morphology change models do not consider the above- and below-ground effects introduced by live vegetation. This may be, in part, due to the hard-to-measure interactions between waves, sediment, and vegetation occurring in the intermittently wet and dry region of the beach profile. Other reasons may be related to the uncertainty of plant impact on erosion in general, or the fact that a multidisciplinary approach including engineers and biologists is needed to tackle this problem. Nonetheless, the influence of vegetation on erosion in other environments has been documented in the literature and provides a valuable background for the present study. Coops et al. (1996) investigated the effect of emergent plants on wave and erosion attenuation on a model river bank and found erosion reduction of up to 72% for certain plants. Kobayashi et al. (2013) simulated overwash and erosion of vegetated dunes in a laboratory wave flume. A grid of wooden dowels placed in a model sand dune represented woody plant stems. The dowel setup was intended to mimic both above- and below-ground effects of vegetation on hydrodynamics and morphodynamics, albeit with a simplified model of plant structural complexity.

Scope of this Study

 Vegetated dune system dynamics happen on various time scales with multiple processes occurring simultaneously. Long-term coastal morphology changes related to sea level fluctuations, land subsidence/emergence and barrier island formation set the stage for dune dynamics on a decadal or even centennial scale. However, the intermittent short-term impact of extreme events is generally more dramatic and brings about immediate changes to the dune morphology. These intermittent changes due to storms (i.e. erosion, overwash, and breaching) compound over time to contribute to the long-term morphology changes of dunes. Vegetation may affect both long-term and short-term dune evolution processes. Sediment transported by wind and water can be trapped by the above-ground portion of the vegetation (i.e. stems and leaves) to spur dune growth while the below-ground components of the plants (i.e. roots) may provide extra strength to the dune substrate to resist erosion. On the other hand, above-ground plant components may transfer wave energy through the stems into the substrate, leading to uprooting and increased sediment mobilization, ultimately expediting the dune erosion process.

    This study investigates the role of live vegetation in the short-term dune erosion process induced by wave impact during elevated water levels. In an interdisciplinary effort, a project team consisting of coastal engineers and plant biologists has contributed to the findings presented herein. Fig. 1 displays a schematic visualizing the swash zone interactions between storm waves, substrate, and plants of interest in this investigation. Dune overtopping, overwash and breaching are outside the scope of this study, which focused on the process of dune face erosion.
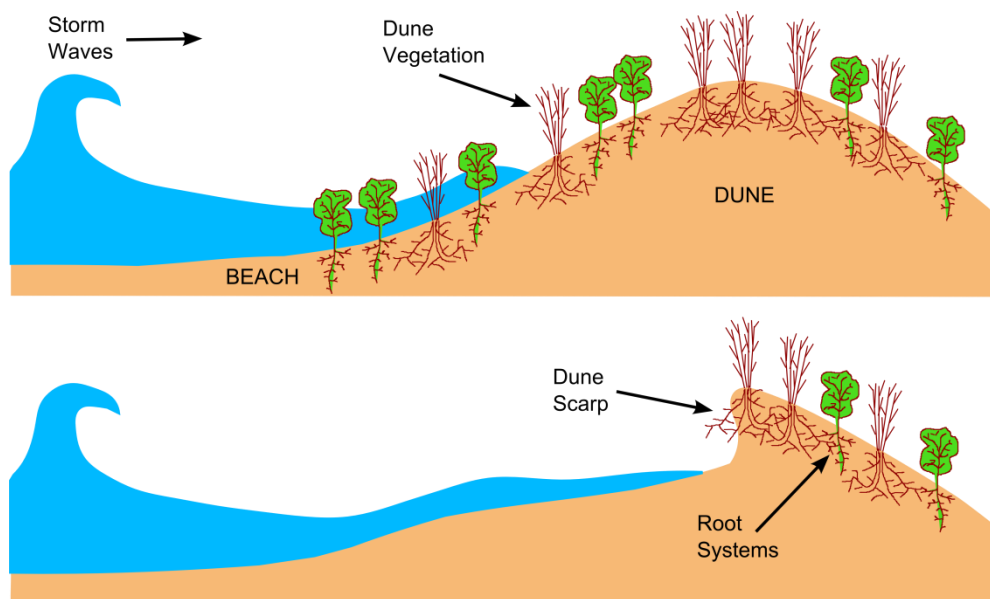

Figure 1. Schematic showing interactions between storm waves, substrate and plants during elevated water level conditions (top panel) leading to scarp formation and dune erosion (bottom panel). Plants influence the wave-induced dune erosion process by modifying both the above- and below-ground characteristics of the dune.

We are testing the hypothesis that vegetated dunes are more resistant to erosion via a series of laboratory experiments involving wave flume and substrate shear testing. Above- and below-ground effects of vegetation on the erosion process were investigated. *Sporobolus virginicus*, an abundant perennial dune grass on the Texas coast, was used in this study as its morphology is typical of the dune grasses present along many of the world's sandy coastlines. Preliminary flume tests in a small-scale wave flume were conducted to get a first impression of the effect of dune grass on erosion. The plants used for all experiments were grown in a greenhouse to different levels of maturity (plant age) prior to testing. After encouraging preliminary flume experiments with regular waves, further test runs were conducted in a larger moveable-bed wave flume where the same type of dune grass and substrate were subjected to irregular wave attack at elevated water levels. Variations among individual tests included plant maturity and vegetation density. In these flume tests hydrodynamic forcing conditions were kept constant for each wave run and were measured via a series of capacitance wave gauges. A laser line scanner system collected dune and beach profiles at frequent intervals throughout each test to track profile evolution. In the following, the experiments are explained in detail and the methodology and results of the data analysis are presented.

EXPERIMENTS

The experiments include wave testing with live plants in two different wave flumes, as well as substrate shear testing to investigate the resistance of vegetated dunes against erosion. In this section the general setup is described.

Live Plants

All the tests described in this paper involve live plants. This adds a level of complexity to the experiments and proper timing of the test runs is crucial. One specific vegetation parameter of importance throughout the study was plant maturity, i.e. the age of the plant and root system, since more mature plants usually have more developed root systems and a larger overall biomass. Hence, the growing cycle of the plants has to be taken into consideration when scheduling individual wave flume tests. Over 100 pots with the perennial dune grass *Sporobolus virginicus* were set up in a greenhouse at the TAMUG wetland center (Fig. 2). Each pot had dimensions of 10 x 10 x 10 cm and was filled with the same fine sand ($D_{50} = 0.14$ mm) that was used in the mobile bed wave flume tests. This allowed the plants to develop their root systems in the actual dune substrate. Plants were regularly watered and fertilized during their growing phase. Once a batch of plants had grown a certain number of weeks in the pots, the plants including roots and substrate were transplanted into the model dunes for wave testing.

Figure 2. Photos of greenhouse setup to grow the dune grass *Sporobolus virginicus* for live plant wave flume experiments. The left panel shows the greenhouse plus extension. The right panel shows a batch of the dune grass being grown in 10cm x 10cm x 10cm pots. Each pot contained one plant and the same fine sand substrate as used for wave flume testing.

Sporobolus virginicus was the plant of choice in this experiment for various reasons. It is abundantly present on Texas dunes which made it easy to populate the pots with plant tillers. Furthermore, this plant can be viewed as the generic prototype for dune grasses on sandy coastlines

worldwide. It grows in bundles of several thin stems with attached long and narrow leaves. The roots spread out rather uniformly in both the horizontal as well as the vertical direction resulting in a homogeneous root distribution throughout the substrate. Shear testing of the substrate without roots and at increasing root maturity levels was performed on subsets of three pots for each maturity level tested in the wave flume, respectively. Shear stresses were measured via a constant strain rate test in a pre-defined failure plane along the vertical axis of the substrate to emulate the dune face scarping and slumping process.

Small-Scale Wave Flume

The first set of physical model tests was conducted in a small-scale wave flume (dimensions: L x W x H = 7.5 x 0.4 x 0.4 m) equipped with a plunger-type wave maker. A test dune made of fine sand material ($D_{50} = 0.14$ mm) was constructed by hand and subjected to regular wave attack. The difference between non-vegetated and vegetated dune erosion was investigated via two tests, each repeated three times. In the first test the dune without any vegetation was exposed to 60 minutes of waves (H = 5 cm, T = 0.8 s) at a constant water depth of 18 cm near the wave maker. The still water level was chosen such that significant dune erosion without overtopping would occur. For the second test the seaward slope of the same initial dune was vegetated with plants (Fig. 3) and subjected to the same waves and water level.
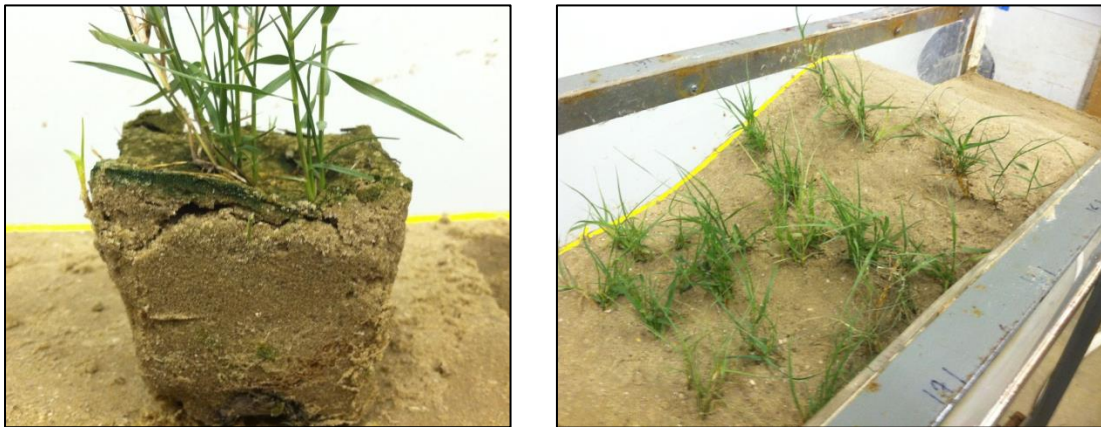

Figure 3. Photos of small-scale vegetated dune test setup. Dune grass with roots and substrate (left panel) was transplanted into the seaward slope of a test dune (right panel) before being subjected to regular waves.

The left panel of Fig. 3 shows an example of a dune grass plant with substrate before being implanted into the model dune. In the right panel, the vegetated dune at the beginning of one of the test runs is displayed. The vegetation was arranged in a 4 x 5 grid made up of mature plants which had been growing in the green house for 12-weeks prior to testing. The plant density was 80 plants/m^2 and plants occupied the dune face area from the still water line to the dune crest. Table 1 includes a summary of all relevant parameters for this small-scale test. Manual profile measurements were taken at fixed time intervals to track the evolution of the dune geometry. The comparisons between initial and final profiles are presented in the results section. During profile measurements the wave maker was turned off.

Moveable-bed wave flume

Irregular wave testing with vegetated dunes was carried out in TAMUG's moveable-bed wave flume (dimensions: L x W x H = 15 x 0.6 x 1.3m), a schematic of which is shown in Fig. 4. The beach and dune profiles were constructed using 6m^3 of fine sand (D_{50}=0.14mm) placed on top of a plywood bottom to reduce the overall sand volume required for testing. A smooth ramp connected the sand profile portion of the flume to its deep water portion. 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.

Table 1. Summary for small-scale wave flume test parameters		
Test	no vegetation	mature vegetation
number of runs	3	3
duration per run (min)	60	60
H (cm)	5.0	5.0
T (s)	0.8	0.8
h (cm)	18	18
D_{50} (mm)	0.14	0.14
Plant maturity (weeks)	N/A	12
Number of plants	0	20 (4 x 5)
Plant density (plants/m^2)	0	80

Four tests (V0 – V3) with varying plant density and maturity levels were completed to compare the resistance against wave-induced dune face erosion (Table 2). Again, dune grass (*Sporobolus virginicus)* grown in the TAMUG wetland center greenhouse was used to vegetate the seaward dune face. The baseline test V0 included no vegetation, tests V1 and V2 utilized two-week-old plants at densities of 25 and 54 plants/m^2, respectively, and the plants in test V3 were five weeks old with a density of 54 plants/m^2. The vegetation occupied the area between the foot and the crest of the dune over the entire width of the wave flume. The initial beach and dune profile as well as the still water level (SWL) and irregular wave pattern were kept the same for each test.
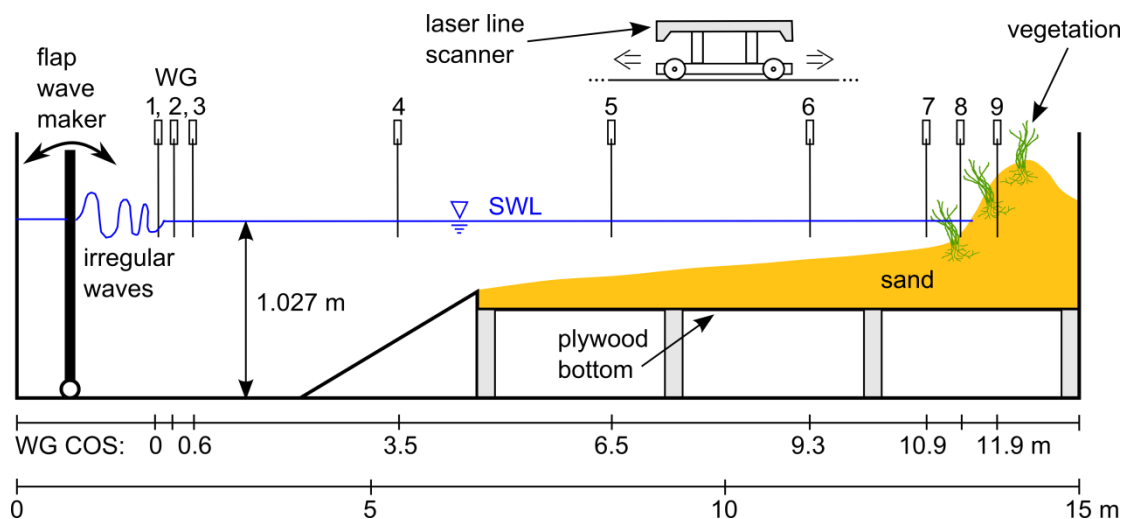

Figure 4. Schematic of moveable-bed wave flume setup. Irregular waves produced by the flap-type wave maker were measured by 9 capacitance wave gauges strategically placed near the centerline of the flume at cross-shore locations indicated by the vertical bars. A laser line scanner system mounted on a moveable cart was used to track beach and dune profile evolution.

Each of the four tests consisted of 12 identical five-minute wave bursts for a total of 60 minutes of wave action per test. Wave bursts were produced by a flap-type wave maker based on a JONSWAP spectral shape resulting in a significant wave height $H_s = 6.9$ cm and a peak period of $T_p = 1.2$ s in front of the wave maker. The still water depth at that location was kept constant throughout at h = 102.7 cm. Wave bursts were limited to five minutes each to avoid excessive distortion of the results from wave re-reflection and seiching and to facilitate intermittent laser scans of the profile. 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.

An Acuity AP820-1000 laser line scanner system mounted on a moveable cart above the flume measured the beach and dune profile six times per test between wave bursts at 0, 5, 10, 20, 40, and 60 min, respectively. 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. No "time-of-flight" measurement of the laser light is necessary for this method which increases accuracy significantly. For this experiment the cart was moved in the cross-shore direction along the flume and line scans were carried out every 2 cm in the most active profile region on and near the dune and every 10 cm further offshore where less profile changes were observed. The resulting detailed 3D representation of the measured surface elevations were used to verify alongshore uniformity of the beach and dune evolution process. For further analysis the 3D profiles were collapsed into single average profile lines as discussed further in the data analysis and results section.

Table 2. Summary for moveable-bed wave flume test parameters				
Test	V0	V1	V2	V3
No. of plants	0	16 (4 x 4)	35 (7 x 5)	35 (7 x 5)
Plant density (plants/m^2)	0	25	54	54
Plant maturity (weeks)	N/A	2	2	5
Total duration (min)	60			
No. of 5-min wave bursts	12			
H_s (cm)	6.9			
T_p (s)	1.2			
h (cm)	102.7			
D_{50} (mm)	0.14			
No. of profile scans	6			
Time of profile scans (min)	0, 5, 10, 20, 40, 60			
WG x-locations (m)	0.0, 0.3, 0.6, 3.5, 6.5, 9.3, 10.9, 11.4, 11.9			

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 (Fig. 4). 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. 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. Transformation characteristics of the shoaling waves approaching the dune were tracked by WG4 – WG9, with WG7 – WG9 located directly in front of the dune or on the dune face, respectively (Fig. 4). Table 2 gives a summary of all relevant test parameters and includes the cross-shore locations of all gauges in local coordinates (x = 0 at WG1 positive onshore).

DATA ANALYSIS and RESULTS
The wave-induced erosion process of vegetated dunes is affected by both above- and below-ground parameters. Above-ground parameters include plant height, stem width, canopy density, biomass, and rigidity. Below-ground parameters address the plants' root and substrate and include root density, root size and depth distributions, mycorrhizal activity, soil aggregation and shear strength. In this study the combined effect of above- and below-ground parameters on vegetated dune erosion was investigated by analyzing wave flume hydrodynamic and profile evolution data. Erosion volumes and dune scarp retreat rate were calculated from profile evolution measurements. In addition, shear testing was performed on substrate samples at different plant maturity levels.

Measured Hydrodynamics

For the moveable-bed wave flume tests, free surface elevation η was measured via WG1 - WG9 for every 300-s wave burst comprising the four tests V0, V1, V2, and V3. The measured time series were used to examine shoaling characteristics, estimate wave spectra, and calculate wave reflection coefficients of the irregular wave trains attacking the vegetated dunes. A 20-s sample of the measured free surface elevations is shown in Fig. 5.

Inspection of the measured free surface elevations showed steepening of the wave crests as they continued to shoal over the 1:30 sediment bed slope (WG5 – WG7). At the WG8 location most waves are near their breaking point or have already broken. This produces a fairly short surf zone with most of the wave energy available to erode the dune face as would be the case during elevated water levels in nature. The swash signature of waves rushing up and down the dune face is visible in the WG9 records where distinct wave crests have transformed to broken wave bores at shallow water depths. WG9 was initially buried in the dune face above SWL and records display local bed elevation during dry periods and free surface elevation during wet periods when water is touching the gauge above the bed level.
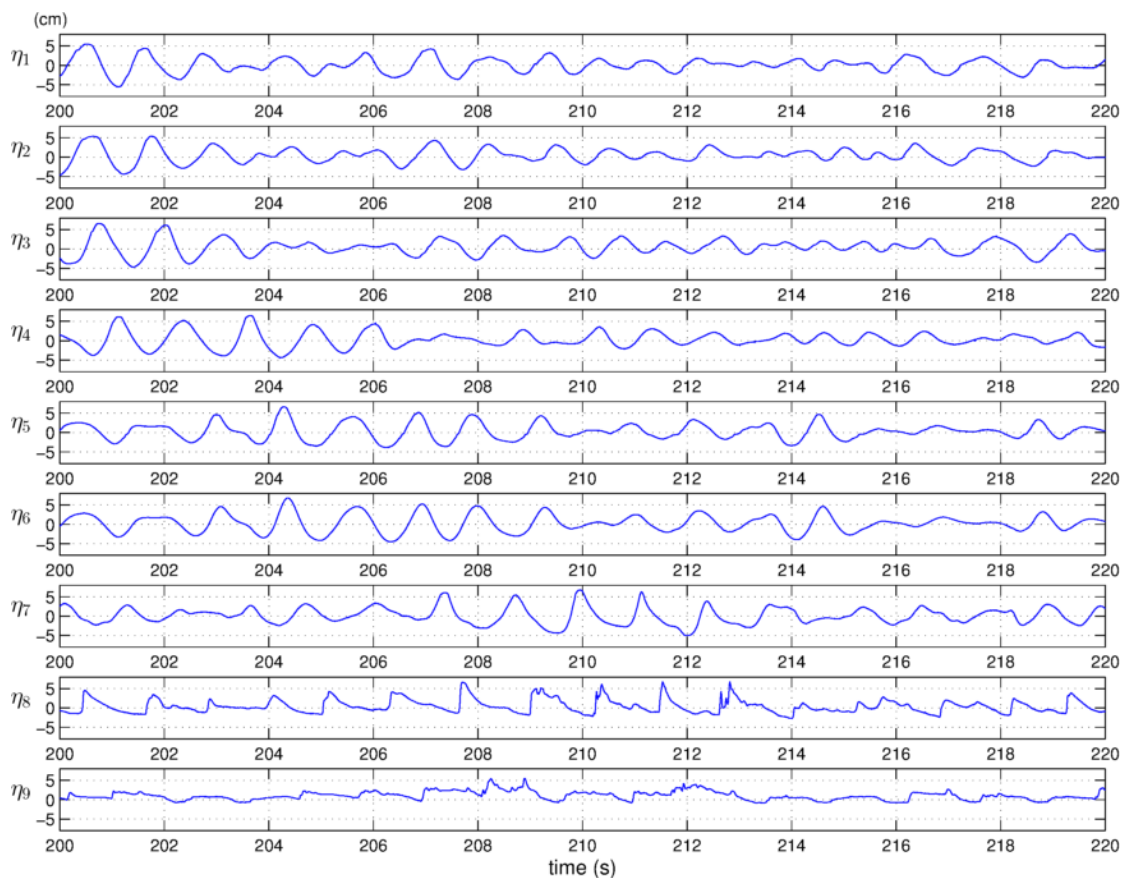

Figure 5. Measured free surface elevation η_i *(cm)* as a function of time (s) with the subscript *i* denoting the location of the respective gauge (WG1 – WG9). This 20-s window was recorded during wave burst 5 in test V0. Steepening of the wave shape is most noticeable between locations 6 and 7. At location 8 most waves are broken or near breaking as indicated by the almost vertical wave fronts. Location 9 shows up- and downrush measured near the dune face.

The measured time series from WG1 – WG3 were used to separate the incident and reflected waves as outlined by Mansard and Funke (1980). The analysis of incident and reflected wave spectra was utilized to estimate low-frequency contributions to the measured wave data.

Under certain conditions, low frequency motions (i.e. seiching) may occur in a flume during wave runs but the computed incident and reflected wave spectra did not show any significant low frequency signature. Estimates of incident and reflected wave energy were used to assess the energy dissipation potential of the tested beach and vegetated dune systems. Low values of reflected wave energy indicate

higher levels of wave attenuation by the respective beach and vegetated dune system. The dimensionless wave reflection coefficient R for each 300-s wave burst was calculated from the incident and reflected wave heights as

$$R = \frac{H_r}{H_i} \tag{1}$$

with H_r and H_r being the root-mean-square wave height H_{rms} of each incident and reflected wave burst, respectively (Goda 2000). Fig. 6 shows the evolution of the reflection coefficient for all four tests. Since the initial beach and dune shape for each test was not at equilibrium, the beach profiles changed most dramatically during the first wave burst in each test, leading to high reflection coefficients (R = 0.27 - 0.31), with the highest value calculated for the baseline test V0 without vegetation. After the initial drop in all tests, the reflection coefficient remained fairly constant with values ranging between 0.16 and 0.22 for the following wave bursts. On average, a slight trend towards the lower end of that range was observed as the tests progressed. Most noticeable was the relatively large reduction in wave reflection coefficient for tests V1 and V3 during the first six wave bursts. Test V1 had a relatively low vegetation density (25 plants/m^2) and plant maturity level (2 weeks), whereas test V3 had the highest vegetation density (54 plants/m^2) and plant maturity level (5 weeks) in this experiment. The vegetation density for test V2 was the same high value as for test V3 but the plants were still at the maturity level of test V1 (Table 2). This seems to suggest that at some point the number of immature plants per area may be too high to produce a noticeable beneficial effect on dune erosion, stressing the importance of mature and well developed root systems.
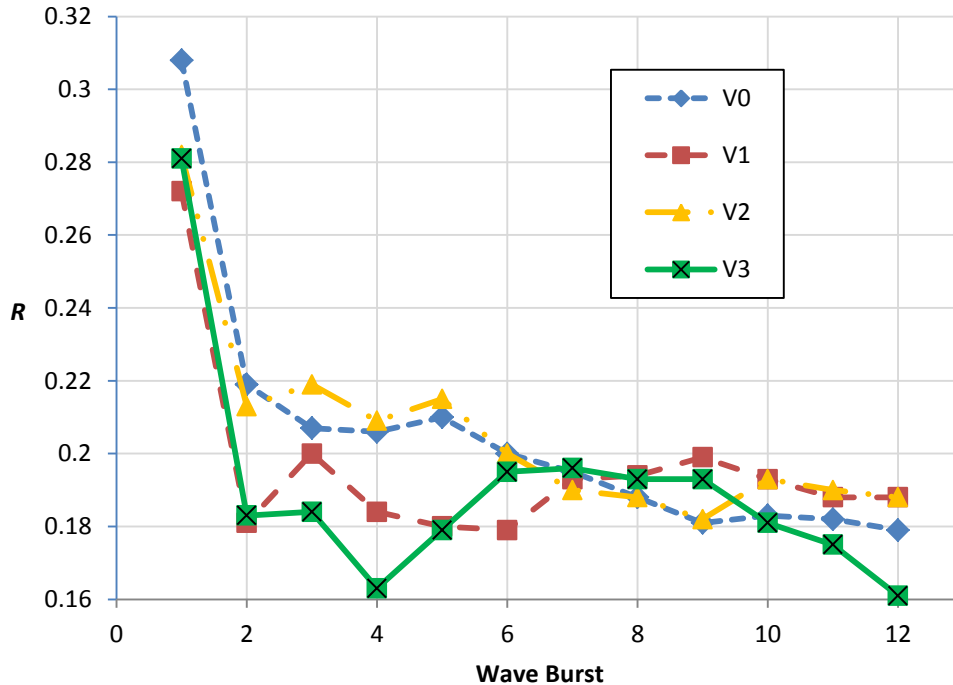

Figure 6. Wave reflection coefficients *R* calculated from the measured WG1 – WG3 records for each wave burst in tests V0, V1, V2, and V3. After initial profile adjustment during wave burst 1, wave reflection reduces from approximately 30% to 20% and below with increasing burst numbers. Specifically, V1 and V3 show reduced reflection during the early stages of the respective tests when compared with V0.

Bottom Profile Evolution

Bottom profiles were measured for both wave flume setups. For the regular wave tests conducted in the small-scale flume, the initial and final beach and dune profile was recorded manually before and after each of the three trials, respectively. The resulting average profiles of those recordings are displayed in Fig. 7 where the initial profile (blue dashed line) was the same for all trials. After 60 minutes of regular wave attack (H = 5 cm, T = 0.8 s, h = 18 cm) the final measured profiles of the trials

without any vegetation (red dash-dotted line) showed significantly higher erosion volumes than the final measured profiles of the trials with mature vegetation (green solid line). The average reduction in eroded dune volume was 33%. In addition, the dune scarp retreated at a 30% slower rate in the vegetated tests and formed a steeper slope. These findings can be attributed to the combination of above- and below-ground effects the mature and fairly dense vegetation had on the erosion process.
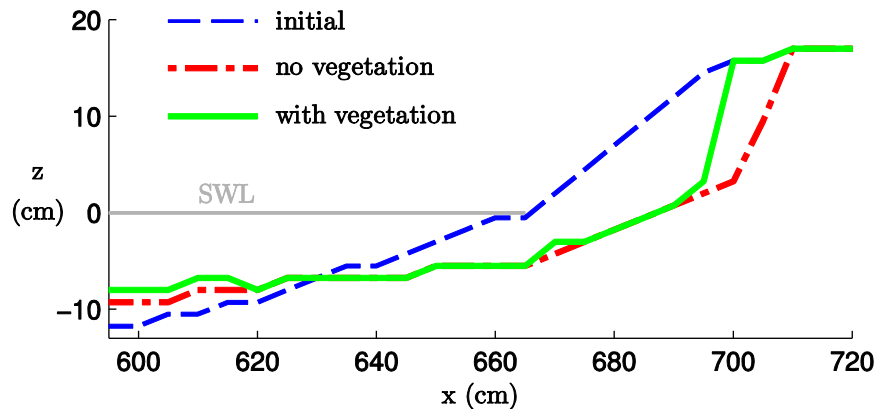

Figure 7. Measured initial and final dune profiles of regular-wave small-scale flume tests. The initial profile was kept the same in all tests (dashed blue line). The red dash-dotted line shows the final profile of the dune without any vegetation after 60 minutes of regular wave attack. The green solid line displays the final profile of the vegetated dune after being exposed to the same waves, clearly indicating a reduction in eroded dune volume.

During the irregular-wave tests in the moveable-bed flume, dune and beach profiles were collected by the AP820-1000 laser line scanner at strategic intervals as listed in Table 2. The raw topography data allowed detailed visual inspection of the dune erosion process (Fig. 8). While the laser was not intended to measure the vegetation on the dune, vegetation features such as plant stems and leaves could still interfere with the profile measurement as can be seen in the bottom panel of Fig. 8. Outliers due to vegetation interference were removed during post-processing of the laser data and the resulting profiles were cross-checked with manual profile measurements in the vegetation zone. Relative alongshore uniformity of the dune erosion process was observed visually during the experiment and confirmed via the 3D visualization of each measured profile from the laser scans. For further analysis of the measured data, the 3D profiles were averaged in the alongshore direction to yield 2D cross-shore beach and dune profiles.

During the dune erosion process, waves attacked the dune face and transported dune material offshore to form a beach shape more closely related to equilibrium conditions with the incident wave energy. The steep dune scarp that formed during this process moved onshore with each subsequent wave burst, effectively reducing the volume of sand contained in the sub-aerial dune. Dune volumes were calculated from the 2D profiles as the volume of sand contained above SWL. Both erosion and accretion volumes along the beach and dune profile were calculated with respect to the initial profile. Time series of eroded dune volumes expressed in percent of the initial sub-aerial dune volume are displayed in Fig. 9 for all four tests. This figure shows that the immature plants (2 weeks old) used in tests V1 and V2 had a relatively small effect in reducing the eroded dune volume, regardless of plant density. In fact, during the first three wave bursts, tests V1 and V2 showed slightly larger eroded dune volumes compared to test V0 without any plants. After one hour of waves, tests V0, V1, and V2 ended up with fairly similar dune erosion values of around 45%. The more mature plants (5 weeks old) used in test V3 showed reduced dune erosion volumes up to approximately 8% when compared to the non-vegetated dune in test V0. The results indicate that the presence of the mature plants increases the stability of the substrate leading to a reduction in lost dune volume as well as a reduction in scarp retreat rate.

Substrate Shear Testing

Shear testing of vegetated and non-vegetated substrate samples was carried out in the laboratory and indicates that dune plant roots contribute to the mechanical strength of non-cohesive dune sediment as has been investigated by other researchers (e.g. De Baets et al. 2008). For these tests the substrate

was subjected to shear in the direction of root growth corresponding to a vertical plane (i.e. dune scarp) in a real dune. Substrate with *Sporobolus virginicus* roots at two different levels of maturity (i.e. with varying levels of root densities) was compared to substrate without any roots to determine the impact of root accumulation on sediment shear strength.
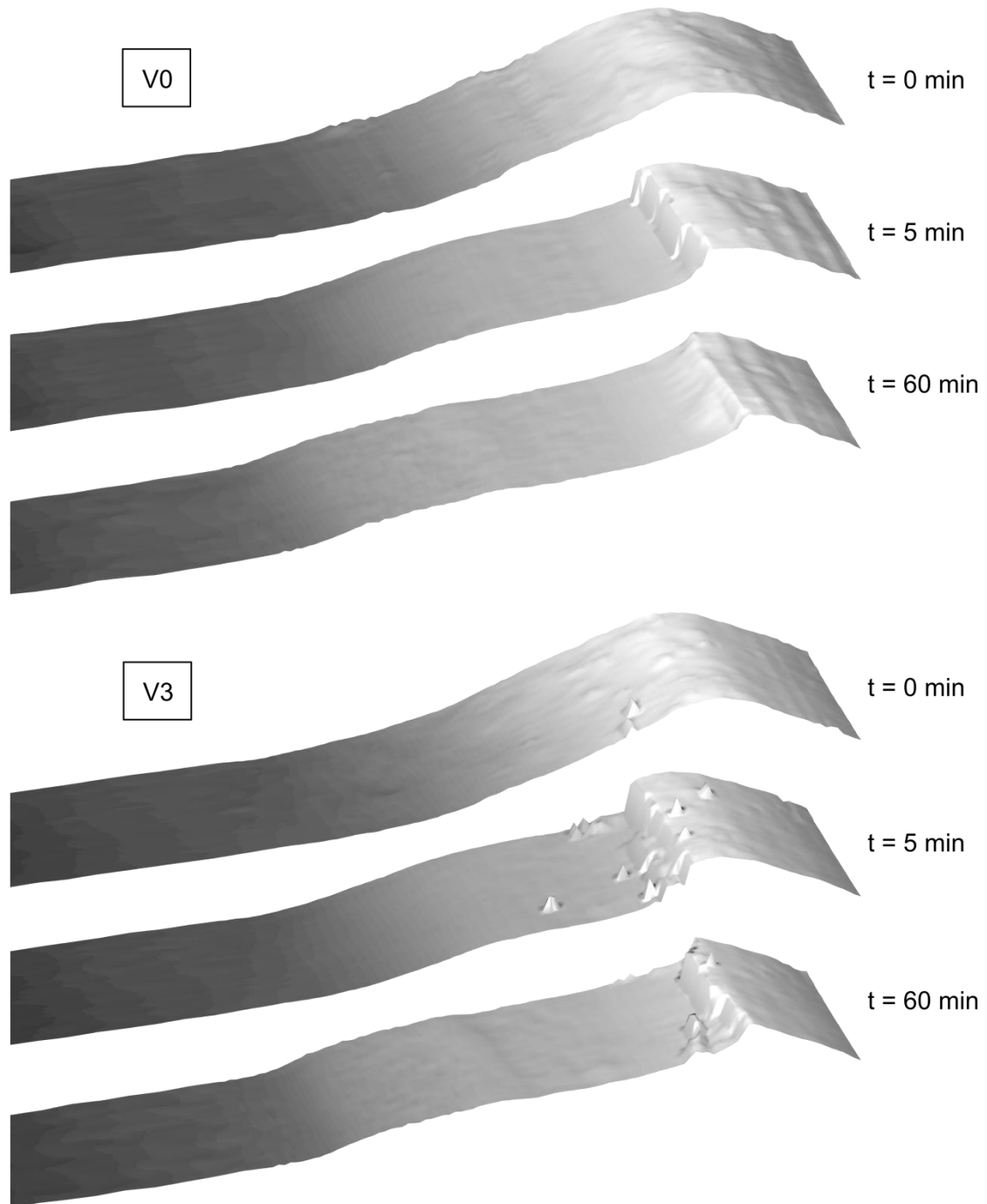

Figure 8. Measured 3D beach and dune profiles (raw data). The dune and beach face geometry at *t* = 0, 5, and 60 minutes is displayed for tests V0 (top panel) and V3 (bottom panel), respectively.

Figure 10 compares the results of the constant velocity shear tests for the case of no plant roots to two cases with 6-week-old and 9-week-old plant roots, respectively. The plotted curves were obtained as averages from three substrate samples (10 x 10 x 10 cm pots) for each maturity level. A substrate moisture level of 15% was maintained for all shear tests. The ultimate shear strength of the substrate

without roots (i.e. peak of the blue dash-dotted curve) was found to be around 2,500 N/m^2 and occurred 7 seconds into the test. The ultimate shear strength of the substrate with 6-week old roots (peak of red dotted line) was about the same but occurred 3 seconds later at 10 seconds into the test. Substrate with a 9-week old root system (green solid line) showed significantly increased ultimate shear strength with a peak at 3,500 N/m^2 11 seconds into the test. In addition, the presence of roots improved the shear strength of the substrate beyond its peak value which is indicated by the increased area under the curve (cumulative shear). In sum, the presence of plant roots delayed the amount of time before structural failure occurred and increased the cumulative shear required to break down the sediment.
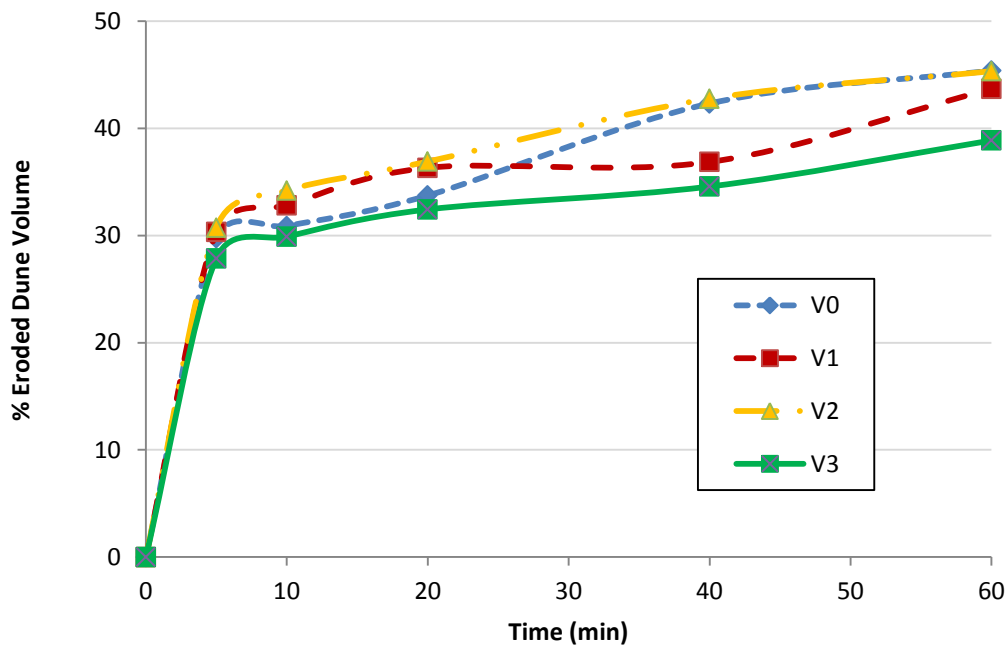

Figure 9. Percentage of eroded dune volume over time relative to the initial dune volume. Most of the volume adjustment occurred during the first wave burst in each test (up to 30%). Test V3 showed a reduction of 8% in eroded sub-aerial dune volume after one hour of wave attack compared to test V0 (no vegetation).
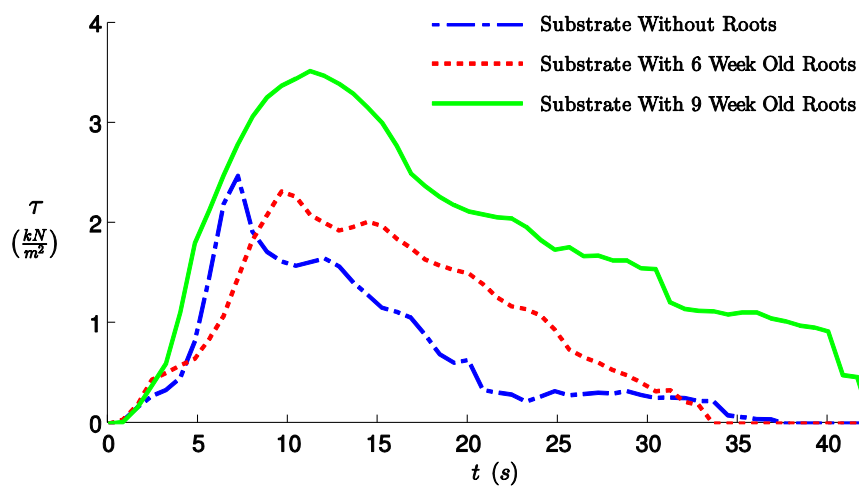

Figure 10. Results of constant-velocity shear tests on dune substrate with varying levels of plant root maturity.

CONCLUSIONS AND DISCUSSION

In this study the effect of live vegetation on wave-induced erosion of coastal dunes was investigated. Physical models of dunes consisting of fine sand were setup in two moveable-bed wave flumes and exposed to regular and irregular waves, respectively. The perennial dune grass *Sporobolus virginicus* was grown to different levels of maturity in substrate identical to the flume sediment and transplanted into the respective model dunes for wave testing at elevated water levels to simulate storm conditions. For the irregular wave tests varying vegetation densities and plant maturity levels were examined in four tests. The hydrodynamic forcing conditions and morphological profile response were measured in each test. In addition, samples of the substrate without and with plant root material at different maturity levels were tested for vertical shear strength to investigate how plant roots affect substrate stability.

The results show that above-ground and below-ground plant parameters may affect erosion of coastal dunes. However, due to the relatively short extent of vegetated dune areas in the cross-shore direction, below-ground effects seem to be more dominant factors in erosion control. In particular, the maturity or age of the plants and associated root systems seems to have a positive effect on dune erosion for both regular as well as irregular wave attack. Not only did the most mature and densely planted vegetation reduce reflected wave energy the most, it also slowed down the dune scarp advancement rate the most and reduced the total eroded dune volume by 8% in the irregular case and 30% in the regular wave case. Shear testing revealed that more mature – and thus more developed – root systems provided higher resistance against vertical shearing than substrate without any roots or with less mature roots.

More tests with further increased plant maturity levels and plant densities are required to substantiate the presented findings. In addition, while *Sporobolus virginicus* may be a good representation of dune vegetation for many coastal areas, tests with other plant species and even mixed species tests should be attempted to better represent actual dunes. In any case, the tests showed that the use of real plants is important since the interaction of their roots with the granular sediment plays a key role for substrate stabilization. In other scenarios (i.e. mangroves, marshes, submerged vegetation) where the wave attenuation by the above-ground plant component dominates, artificial plants may be suitable as substitutes but for dune erosion where the focus is on the below-ground effects of plants, real live plants are necessary to gain a better understanding of the processes occurring.

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