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Sargassum as a Natural Solution to Enhance Dune Plant Growth

Amy Williams · Rusty Feagin

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Abstract Many beach management practices focus on creating an attractive environment for tourists, but can detrimentally affect long-term dune integrity. One such practice is mechanical beach raking in which the wrack line is removed from the beach front. In Texas, *Sargassum fluitans* and *natans*, types of brown alga, are the main components of wrack and may provide a subsidy to the ecosystem. In this study, we used greenhouse studies to test the hypothesis that the addition of sargassum can increase soil nutrients and produce increased growth in dune plants. We also conducted an analysis of the nutrients in the sargassum to determine the mechanisms responsible for any growth enhancement. *Panicum amarum* showed significant enhancement of growth with the addition of sargassum, and while *Helianthus debilis, Ipomoea stolonifera, Sporobolus virginicus*, and *Uniola paniculata* responded slightly differently to the specific treatments, none were impaired by the addition of sargassum. In general, plants seemed to respond well to unwashed sargassum and multiple additions of sargassum, indicating that plants may have adapted to capitalize on the subsidy in its natural state directly from the ocean. For coastal managers, the use of sargassum as a fertilizer could be a positive, natural, and efficient method of dealing with the accumulation of wrack on the beach.

Keywords *Panicum amarum* · Sargassum · Dunes · Nutrient analysis · Beach management · Raking

A. Williams (✉) · R. Feagin
Texas A&M University, ESSM, 1500 Research Parkway, Suite B223, College Station, TX 77843-2120, USA
e-mail: oceanwaves7171@gmail.com

Introduction

Beaches and dunes are extremely important natural resources (Costanza and Farley 2007; Costanza and others 2007; Martinez and others 2007) that contribute to the coastal environment, benefit the economy by attracting recreational users and protect landward ecosystems and anthropogenic structures. One major issue of coastal stability is the establishment of dunes in order to provide environmental habitats and defenses to landward structures. Establishment of dunes can be impaired by both anthropogenic and natural impacts. Human and car traffic can negatively impact the structure of the dunes while wind, water and rain erosion can cause a loss of sediment to the ecosystem. One strategy to maintain dune structure is to establish natural vegetation which helps stabilize sediment against erosion by trapping and binding sand (Bressolier and Thomas 1977; Conaway and Wells 2005; Kuriyama and others 2005; Labuz and Grunewald 2007; Lancaster and Baas 1998; Mountney and Russell 2006; Stallins 2005; Udo and Takewaka 2007). However, nutrient limitation of beach sediments (Allaway and Ashford 1984; Bouchard and Bjorndal 2000; Hannan and others 2007) can make it difficult to establish plants on dunes.

Beach sediment is often lacking in nitrogen (N), potassium (K) and phosphorus (P) availability (Hester and Mendelssohn 1990; Kachi and Hirose 1983; Van den Berg and others 2005) which are critical nutrients for plants. One natural subsidy of these nutrients is marine wrack that gets deposited on the beach from the ocean (Heatwole 1971; Hemminga and Nieuwenhuize 1990; Ince and others 2007; Lewis and others 2007; Orr and others 2005; Polis and Hurd 1995). Wrack in and of itself can help control erosion by absorbing wave energy and trapping sediment (Feagin and others 2005; Gheskiere and others 2006; Smith and others 2007), but can also provide nutrients to dunes that will help plants to grow (Sivasankari and others 2006; Trono Jr 1999). In Texas, *Sargassum fluitans* and *natans*, types of brown alga commonly known as gulfweed or simply as sargassum, are the main components of wrack (Gower and others 2006). Masses of sargassum hundreds of meters wide are deposited by currents and wind from the Sargasso Sea and collect along the forefront of the beach (Tanaka and Fosca 2003) typically between May and August each year.

A common maintenance practice is beach raking in which mechanical equipment (i.e tractor) is used to remove the wrack line of seaweed and other marine deposits off of the beach. Though many coastal communities completely remove wrack from the beach to dumpsters, a common alternative is to move wrack to the base of the dunes where large piles of sand and wrack mixtures are formed (Conaway and Wells 2005; Dugan and others 2003; Gheskiere and others 2006; Nordstrom and others 2006; Williams and others 2009). Subsequently, the piles are then buried by more sand through aeolian movement and other natural processes. While this practice alters the nature of the ecosystem by moving sand, nutrients and material for habitat from one coastal niche to another (Storrier and others 2007; Williams and others 2008), the natural subsidy of nutrients does remain within the ecosystem.

Raking is done to provide a cleaner, more aesthetically pleasing experience for beach users (Colombini and Chelazzi 2003; Nordstrom and others 2004) but can detrimentally affect long-term dune integrity to the initial attraction (McGlashan and Williams 2003; Perez-Maqueo and others 2007). Studies have shown that beach raking causes negative impacts on the natural environment in terms of biota (Defeo and others 2009; Gheskiere and others 2006; Martin and others 2006), pollution (Kinzelman and others 2003) and vegetation (Freestone and Nordstrom 2001; Nordstrom and others 2009). While these studies have suggested ceasing or limiting the location of raking, alternative methods to traditional raking approaches are lacking.

We have personally observed vegetation growing vigorously on top of large piles of wrack debris that have been mixed with sand during the raking process. While the plants appear to be growing on top of the already established piles, it is unclear how they are establishing on the piles (whether previous plants are increasing growth, producing asexual clones or germinating). While dune plants grow in nutrient low sediment, they are likely to be able to capitalize on the nutrients in and leached from the wrack. Additionally, even though the wrack would contain salt from the ocean, dune plants grow in an environment where they encounter salt-spray and salt water inundation and therefore are mostly salt tolerant (Greaver and Sternberg 2006). If sargassum is determined to be beneficial to plants, it could be used as a natural fertilizer for the dune plants by minimal alterations to the current mechanical raking procedures, such as routinely spreading the large piles out along the base of the dunes to establish new embryonic dunes.

In this study, we used greenhouse experiments to test the hypothesis that the addition of sargassum can increase soil nutrients and produce increased growth in dune plants. First, we analyzed the effects of sargassum on the growth of the dune plant *Panicum amarum*. We hypothesized that the addition of sargassum to the soil would increase the growth of this plant. Three factors were tested (amount, location and condition) to determine what type of sargassum treatment would be most beneficial to plants. We hypothesized that both unwashed sargassum and large amounts of sargassum would be most beneficial. We then conducted similar experiments on several other dune plant species, with slight alterations in the experimental design. Lastly, we analyzed the nutrients contained in the sargassum to determine the mechanisms responsible for any enhanced plant growth. In the discussion, we suggest alternative methods for beach raking that will best manage the beach for both environmental and recreational uses.

Materials and Methods

Greenhouse Study

In July 2006, field samples of *P. amarum* were collected from Galveston Island, Texas and 144 plants were asexually grown through propagation of individual nodes at the Plant Growth Facilities greenhouse at Texas A&M University, College Station. *P. amarum*, or bitter panicum, is native to Texas and is one of the commonly used plants for dune stabilization projects (Hester and others 1994; Palmer 1975). Individuals were grown in nutrient poor sand from an inland sand pit in 16 oz plastic containers.

The most robust 72 individuals were selected as candidates for this study, randomly assigned to treatment groups and replanted in individual 40 oz plastic pots. The individuals were grown for 15 weeks with vegetative length being measured every five weeks. Total vegetative length was determined as the sum of the stem tip height and the length of all leaves, and is a particularly relevant measure for *P. amarum* as described in Feagin and Wu (2005). The change in total vegetative length was calculated for each plant over the course of 15 weeks.

There were nine different treatments with eight individual replications each. The first treatment was a control in which plants were grown without sargassum. Three factors were varied for the other eight treatments of sargassum (Table 1). First, the “amount” was varied between

Table 1 Description of the nine sargassum treatments on *P. amaraum*

Treatment	Amount of sargassum	Location of sargassum	Condition of sargassum	Representation
1	None	None	None	Plants grown without sargassum
2	Small	Top of soil	Unwashed	Nutrient/sand condition of sargassum that is deposited on surface of the dunes
3	Small	Top of soil	Washed	Nutrient/sand deprived condition of sargassum placed on top of the dunes—also typical of garden use by local residents
4	Small	Mixed into soil	Unwashed	Nutrient/sand condition of sargassum that is mixed into the soil when raked onto the dunes
5	Small	Mixed into soil	Washed	Nutrients/sand deprived condition of sargassum that is mixed into soil when raked onto the dunes
6	Large	Top of soil	Unwashed	Double of #2
7	Large	Top of Soil	Washed	Double of #3
8	Large	Mixed into soil	Unwashed	Double of #4
9	Large	Mixed into soil	Washed	Double of #5

a small amount of 22.2 g ± 4.0 S.D (treatments 2, 3, 4, 5) and a large amount of 42.0 kg ± 5.0 S.D. (6, 7, 8, 9) of wet sargassum to determine if different levels caused different reactions from the plants. In nature, sargassum amounts are varied throughout the season, therefore it is difficult to directly link a “natural” amount of sargassum to the experimental amount as it fluctuates. For the small amount, sargassum was added to cover the surface of the sediment in the pot, and the large amount was double in height.

Then, the “location” was varied by placing sargassum either on top of the sand (2, 3, 6, 7) where it would naturally be deposited onto the dunes and plants by aeolian and other processes, or mixed into the sand (4, 5, 8, 9) where it would be deposited through beach raking. Since the plants were already established for the greenhouse study, the plants would retain nutrients from the sargassum through their roots in order to increase growth during the growing period. Also, when piles are deposited on the dunes, they subsequently cover previous plants. Plants then either use the sargassum to grow, or new plants are established on top of the sargassum. However, this distinction is still unknown therefore both methods of sargassum on top of sediment and mixed in were tested. Sargassum may help to germinate seeds or establish asexual clones; however that was not tested in this study.

Last, the “condition” was varied by either leaving the sargassum unwashed by water (2, 4, 6, 8) to represent the natural deposition or washed with water (3, 5, 7, 9) to represent the method of use by local residents in their gardens.

Statistical differences between treatments were analyzed using a three-way Analysis of Variance (ANOVA) model in SPSS 14.0 for Windows (Release 14.0.1 18 Nov 2005). Dead plants were removed from the analysis. Then, a Post-hoc Dunnett’s T test was performed to determine which treatments were significantly different from the control (Lentner and Bishop 1993).

In the second experiment of the study, we analyzed the growth response of *Helianthus debilis*, *Ipomoea stolonifera, Panicum amarum*, *Sporobolus virginicus* and *Uniola paniculata*. These typical Texas dune plants grow on different areas of the dunes (Tiner 1993). *P. amarum*, *U. paniculata* and *Helianthus* grow on the top of the dunes. *S. virginicus* grows on the embryonic dunes and the beach. *I. stolonifera* grows along the dunes and coastal flats. We hypothesized that there might be an accordingly different response of each species. These species were obtained from a nursery in Florida and grown in the same greenhouse with the same initial methods as the previous experiment. The most robust 40 plants of each species were selected for the experiment, randomly assigned to treatment groups with eight plants per treatment and replanted accordingly in 40 oz plastic pots.

Each plant species was subjected to a control treatment that was grown without sargassum, “condition” treatments and “frequency” treatments. As in the first experiment, the two levels of “condition” were washed and unwashed sargassum of the same amount as the large treatments in the first experiment. The two levels of “frequency” of sargassum additions (once or multiple) were used to test if repeated additions were better for plant growth. For both levels of the frequency factor, the amounts of 47.2 g ± 12.2 S.D. of wet seaweed (similar to the large amounts in the first experiment) was added at the beginning of the experiment. For frequency treatments with multiple additions, sargassum amounts equivalent to the initial addition was added two more times (once a month).

Overall change measurements were based on the characteristics of each species. The measurement selected for *H. debilis* and *I. stolonifera* was the change in amount of leaves, for *P. amarum* was the change in overall length (base heights plus leaf lengths) and for *S. virginicus* and *U. paniculata* was the height of the individuals. Though the use of biomass would have been the optimal measurement method, it was necessary to have a beginning measurement that could be subtracted from the final measurement in order to compensate for differences in growth at the beginning of the experiment. While attempts to correlate biomass with morphological measurements were made, the results were not conclusive. Therefore, analysis will be limited to within species results.

Statistical analysis was done using SPSS 16.0 for Windows (Graduate Student Version, Release 16.0.1 16 Nov 2007). Again, dead plants were removed from the analyses. Procedures were not performed on *H. debilis* plants due to only one surviving plant in the control group. First a test of homogeneity of variance utilizing Levene's Statistic determined that the samples for the *P. amarum* ($F = 7.50.654$, $P = 0.628$) and *U. paniculata* ($F = 0.959$, $P = 0.447$) had equal variances, while *I. stolonifera* ($F = 7.599$, $P = 0.001$) and *S. virginicus* ($F = 4.886$, $P = 0.005$) did not have equal variances. A log transformation of the latter two data sets resulted in equal variance for *I. stolonifera* ($F = 2.072$, $P = 0.127$) and unequal variance for *S. virginicus* ($F = 3.367$, $P = 0.024$).

To determine if sargassum was producing positive growth results on the plants, a One Way ANOVA was performed on the four surviving species against the control (Lentner and Bishop 1993). Initial ANOVA tests indicated that there were differences between the five treatments ($P \leq 0.002$) for each species. For the log transformed data *of I. stolonifera* and the original values of *P. amarum* and *U. paniculata*, a Post-hoc Dunnett's *T* was used to determine if individual treatments were significantly larger than the control. For *S. virginicus,* a Tamhane's T2 test which does not assume equal variances was performed on the original values to determine if individual treatments were significantly larger than the control.

Nutrient Analysis

Sargassum was collected from Galveston Island, TX in July 2007 and was transported in an identical method as the sargassum that was used for the greenhouse studies to the Forest Science Laboratory at Texas A&M University, College Station. Unwashed versus washed sargassum samples were compared to determine potential differences in nutrient composition.

Washed sargassum samples were rinsed with tap water and the ten 100 ml samples of tap water that had been rinsed through the sargassum were then collected. Each filtered sample of rinse water was analyzed separately. Tap water samples were analyzed as a control (to represent the same water type as used during the greenhouse studies). No rinsing occurred for the unwashed sargassum samples.

The sargassum samples were then dried for approximately 24 h, crushed with a rolling pin and sieved to remove any sand grains. Next, the sargassum was passed through a steel electric "flail-arm" Soil Grinder (Humbolt Mfg Co. Northridge IL 60706) and a Tecator Cyclotec 1093 Sample Mill and ground into a powder.

The sargassum and water samples were analyzed for nitrogen (N), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg) and phosphorus (P). Additionally, the sargassum samples were analyzed for carbon (C). Analysis of N in water was conducted with flow injection spectrophotometer (AlpKem division of O.I Analytical, College Station, Texas, Model: #FS3000 with TKN -gas diffusion cartridge module). Analysis of N and C in the sargassum was conducted on the dried material by a flash dynamic combustion method using a furnace, separator and detector manufactured by Thermo-Finnigan (CarloErbaInstruments, Milano Italy, Model: Flash EA1112 carbon/nitrogen analyzer).

For the analysis of K, Na, Ca, Mg and P, the sargassum samples were subjected to a wet digestion procedure based on the method of Parkinson and Allen (1975), using a solution of sulfuric acid, hydrogen peroxide, selenium and lithium sulfate. The samples were slowly heated for approximately six hours until the material was completely digested (i.e. liquid was clear). Before being ready for analysis, the resulting liquid was cooled, diluted, cooled again and filtered.

Analysis of K, Na, Ca and Mg for the digested sargassum and water samples were conducted with an atomic absorption flame spectrophotometer (Varian Inc., Model: SpectrAA 220 Fast Sequential with SIPPs pump sample auto diluting system). Analysis of P for the digested sargassum and water samples was conducted with the same flow injection spectrophotometer used for the N analysis with a total phosphorus cartridge module.

T-tests were used to analyze the difference between nutrients in the washed and unwashed sargassum and between the rinse water and the standard tap water.

Results

Greenhouse Study

For the first portion, the comparison of the growth of *P. amarum* (Table 2) indicated a significant difference in the amount factor ($P = <0.001$) and the condition factor ($P = 0.006$). There was no significant difference in the location factor ($P = 0.693$). The interaction between the condition and the amount was non-significant ($P = 0.080$) but deserved some attention.

Table 2 Results of the three-way ANOVA for *P. amarum* study

Source/factors[a]	Type III sum of squares	DF	Mean squares	*F*	Sig.
Amount	1197412.0	1	1197412.0	20.667	<.001
Location	912.8	1	912.8	0.158	0.693
Condition	48295.6	1	48295.6	8.335	0.006
Amount * location	126.3	1	126.3	0.022	0.883
Location * condition	11334.3	1	11334.3	3.181	0.167
Amount * condition	18431.5	1	18431.5	1.956	0.080
Amount * location * condition	12490.9	1	12490.9	2.156	0.148
Error	324463.8	56	5794.0		
Total	1006101.5	64			
Corrected total	535797.0	63			

* Factors refers to amount (small vs. large), location (top vs. mixed) and condition (washed vs. unwashed) of sargassum used in treatments

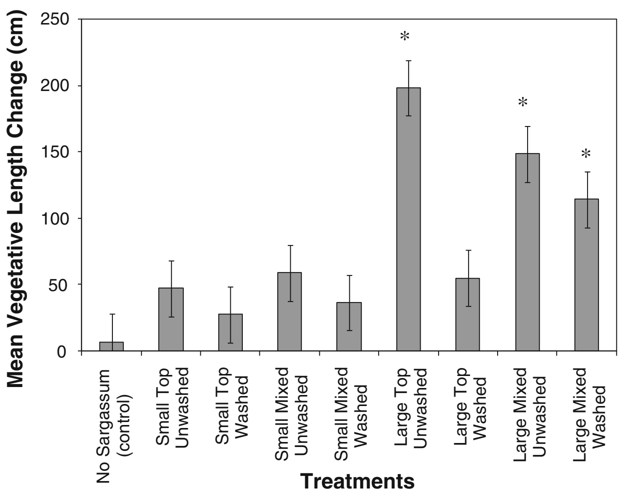

Fig. 1 Total vegetation length changes for *P. amarum*. Bars represent the average vegetative length changes in cm with error bars of ± one standard error from July to November for each of the nine treatments of plants. * Indicates significant difference between treatment and control

The results of the Post-hoc Dunnett's T (Fig. 1) showed that there was a significant increase in the Large Top Unwashed ($P < 0.001$), Large Mixed Unwashed ($P = 0.001$) and the Large Mixed Washed ($P = 0.013$) treatments versus the control treatment. None of the treatments with a small amount of sargassum were significantly different from the control of no sargassum ($P \geq 0.299$). Also, the Large Top Washed treatment did not show significant growth ($P = 0.345$). These results suggest that amount and condition factors may cause a difference in plant growth, while the location factor does not seem to make a difference as compared to the control.

For the second portion, the Post-hoc Dunnett's T results for *I. stolonifera* (log transformed values), *P. amarum* and *U. paniculata* are presented in Table 3. The Tamhane's T2 results for the original values of *S. virginicus* are presented in Table 4.

The results for *I. stolonifera* showed that when the condition was unwashed, regardless of frequency, there was a significant difference from the control, while washed treatments were not significantly different. The results for *P. amarum* and *S. virginicus* show that when the frequency of additions was multiple, regardless of the condition, there was a significant difference from the control. However, when the frequency was single there was not a significant difference from the control. The results for *U. paniculata* showed that when the condition was unwashed, regardless of frequency, and when the condition was washed with a single application of sargassum there was a significant difference from the control. However, the washed condition with multiple additions was not significantly different from the control.

Nutrient Analysis

Washing the sargassum increased the proportion of C, but significantly depleted N, Na and P (Fig. 2). For N, Na, Ca and Mg equal variances were assumed. For C, K, and P equal variances were not assumed. There was a significant change in C ($P = 0.009$), N ($P = 0.003$), Na ($P = 0.002$) and P ($P = 0.021$) between unwashed and washed sargassum.

The rinsed water showed a significant increase in all the nutrients analyzed (N, K, Na, Ca, Mg and P) when compared to the standard tap water ($P \leq 0.001$).

Discussion

Beach and dune ecosystems are nutrient poor and studies have shown that many dune plants have adapted by capitalizing on natural subsidies to the environment (Allaway and Ashford 1984; Bouchard and Bjorndal 2000; Hannan and others 2007). This study has further indicated that dune plant growth is positively influenced by the presence of sargassum, a natural marine subsidy.

Table 3 Dunnett's T results of individual species compared to the control group

Dunnett's T results: did treatments grow more than the controls?					
Compare control with:		Mean difference	N	Standard error	Sig.
Condition	Frequency				
I. stolonifera[a]		Control: $N = 4$, Mean $= -0.505$ Levene's stat: 2.072, $P = .127$			
Washed	Once	−0.105	4	0.210	0.914
	Multiple	0.167	4	0.210	0.459
Unwashed	Once	0.609	6	0.192	0.009
	Multiple	0.661	58	0.200	0.006
P. amarum		Control: $N = 6$, Mean $= -24.38$ Levene's stat: 0.654, $P = 0.628$			
Washed	Once	−11.279	8	46.547	0.855
	Multiple	146.321	8	46.547	0.006
Unwashed	Once	−89.817	2	49.761	0.997
	Multiple	258.746	8	46.547	<0.001
U. paniculata		Control: $N = 6$, Mean $= -267.33$ Levene's stat: 0.959, $P = 0.447$			
Washed	Once	358.083	4	112.484	0.007
	Multiple	200.083	4	112.484	0.127
Unwashed	Once	304.708	8	94.111	0.006
	Multiple	513.833	8	94.111	<0.001

[a] Values were log transformed to meet the requirements for homogeneity of variance

Table 4 Tamhane's T2 results of for *S. virginicus* treatments as compared to the control group

Tamhane's T2 results for *S. virginicus*[a]					
Compare control with:		Mean difference	N	Standard error	Sig.
Condition	Frequency				
Washed	Once	3.357	5	2.581	0.936
	Multiple	−17.464	8	3.108	0.003
Unwashed	Once	−11.413	8	4.380	0.224
	Multiple	−13.373	5	3.318	0.037
Control: $N = 4$, Mean $= -11.06$		Levene's stat: 4.886, $P = 0.005$			

[a] Equal variances not assumed

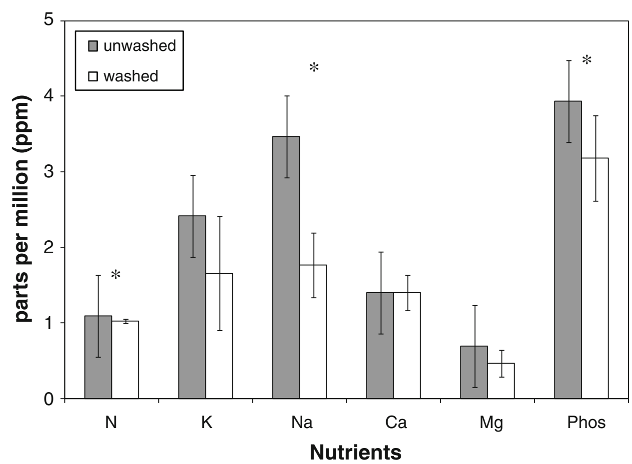

Fig. 2 Sargassum nutrients. Bars represent the average nutrient amount (in ppm) with error bars represent ± one standard error. * Indicates significant difference in the *T*-test between washed and unwashed Sargassum. Results for C have been removed from the graph

In the first experiment, *P. amarum* showed significant enhancement of growth with the addition of sargassum to the sand. In the second experiment, each species responded slightly differently between the sargassum treatments, however none were significantly impaired by the addition of sargassum as compared to plants grown without sargassum. The addition of sargassum appears to positively benefit multiple dune species even though specific functional traits may have caused different responses to treatments by different species (Álvarez-Rogel and others 2007; Gilbert 2008).

In the first experiment, the significant change of total vegetative length of *P. amarum* when subjected to increasing amounts of sargassum indicates that the more sargassum that is placed on the vegetation, the more growth will occur. In the second experiment, *P. amarum* responded best to the multiple frequency factor of sargassum whether the condition was washed or unwashed. *P. amarum* is a very versatile plant that is able to grow easily in many disturbed environments. This species likely has developed adaptations that allow it to capitalize on any additional nutrients, despite the condition (washed or unwashed) of the subsidy. Future studies are needed to test whether there is a threshold for the amount that is beneficial (Jones and others 2004).

The first experiment also determined that there was no difference in *P. amarum* growth based on the location of the sargassum. Thus, the process of mechanical raking, which mixes the sargassum with sand and then places it on the dunes, should not prevent the sargassum from increasing the growth of *P. amarum*. Therefore, this factor was not tested in the second experiment. However, further investigation is needed to determine other ways that the mechanical process of raking may affect the natural environment (Nordstrom and others 2009).

The first experiment indicated a significant difference in the growth of *P. amarum* between the condition factors. *P. amarum* grew better when the condition of the sargassum was unwashed. In the second experiment, the unwashed condition of sargassum also produced the most positive effects on *I. stolonifera* and *U. paniculata* regardless of frequency of addition. None of the plants seemed to respond best to the washed condition of sargassum, which represent how sargassum would normally be used in gardens by local residents. Therefore, placing sargassum on the dune plants directly from the ocean, without needing additional steps and money to clean it, should be considered by coastal managers as a potential raking procedure.

It is interesting that these plants had a similar response to the condition factor even though they are not usually found in the same location of the beach (Britton and Morton 1989; Tiner 1993). *I. stolonifera*, typically found along the base of the dunes and in the embryonic dunes, may be adapted to handle the material that is deposited directly from the sea as it would encounter this subsidy in nature. *U. paniculata* and *P. amarum*, both found on the top of the dunes, may find it necessary to be able to capitalize on any types of subsidies they can come into contact with. Due to some overlapping of territories, all three of these plants may have adapted to oceanic subsidies and developed ways to capitalize on the added nutrients in similar manners in order to survive in the field. Additionally, *S. virginicus,* typically found on embryonic dunes and beach fronts, responded in a similar manner as *P. amarum* which grows on the top of the dunes to the multiple additions of sargassum. Due to difference in location, they may be able to both utilize the same subsidies.

The nutrient analysis results show that N, Na and P were significantly depleted from the sargassum when it was washed. Dune plants are typically limited by N, K and P availability (Hester and Mendelssohn 1990; Kachi and Hirose 1983; Van den Berg and others 2005). Washing the sargassum caused some portion of the N and P subsidy to be mobilized and lost. Other nutrients (K, Mg, and Ca) and micronutrients in the sargassum may enhance plant growth as well (Jobbagy and Jackson 2004), but they are unlikely to be responsible for the significant differences between the condition of sargassum, nor as the primary mechanism affecting dune plant growth in general (Hester and Mendelssohn 1990). Also, since the plants were not affected negatively by unwashed sargassum which adds Na to the sediment, beach managers do not seem to need to worry about adding salinity to the dunes.

Therefore, this depletion of N, Na and P could explain why *I. stolonifera* was unable to significantly benefit from washed treatments. Dune plants that were able to benefit from washed treatments of sargassum, such as *P. amarum and S. virginicus*, may be better at using a variety of nutrients, or to the limited amount of nutrients introduced in such treatments.

Thus, results suggest that the primary mechanism of enhanced growth in our experiments is from the additional subsidy of N and P. By washing the sargassum, some portion of this N and P subsidy is mobilized and lost. We suspect that Na may actually enhance growth of dune plants as well. Dune plants grow in an environment where they encounter salt-spray and salt water inundation. They are known to be salt tolerant (Greaver and Sternberg 2006), but future work needs to be conducted as to whether Na addition may be beneficial up to a given threshold (Howard and Mendelssohn 1999; La Peyre and others 2001). Therefore, the loss of Na from the washed sargassum may have also caused less positive growth. Future work could focus upon specific nutrient additions, where each nutrient type is singularly applied to the different dune species.

Studies have indicated that sargassum-based tannins have enhanced seedling growth (Sivasankari and others 2006) and liquid fertilizers have increased the germination of seeds (Trono Jr 1999). While this study looked at already established plants in a greenhouse setting, it is possible that in the field sargassum may help plants to germinate and reproduce asexually by clones. However, this would need to be tested in the field through additional studies. Though sargassum has an economic value in many parts of the world, such as cosmetics, medical uses and food products (Ina and others 2007; Marinho-Soriano and others 2006; Trono Jr 1999), its value as a natural fertilizer on beaches has not been capitalized upon or adequately studied. Future studies on the specific mechanisms attributed to plant growth would be needed to determine sargassum's potential as a commercial fertilizer.

The results of this study have the potential to improve coastal practices to better manage the natural ecosystem while providing aesthetically pleasing beaches. In communities where the managers choose to rake, keeping the sargassum on the beach and using it as a natural fertilizer by distributing it along the dune line rather than in large piles as is often currently done could provide a natural fertilizer for the dune plants, help stabilize the dune system and ultimately help maintain the natural coastal resources while still providing a recreational area for tourists. While this study has been focused on the Texas coast, many environmental aspects of beach raking and dune plants are applicable to a broader range of coastal systems. This practice should help to promote a variety of species' growth on the dunes, thereby creating a more diverse and resilient ecosystem rather than a monoculture ecosystem seen in some dune restoration projects when only one species is used (i.e *P. amarum*). Since sargassum is naturally deposited on the coast, it does not have the same risks as the use of chemical fertilizers (Willis and Hester 2010) and is easily accessible for dune restoration projects.

While greenhouse studies are often more practical and allow for more control (Willis and Hester 2010), future field studies are needed in order to determine if these results can be extrapolate the results to nature due to complicating factors such as sediment nutrients, organic matter, soil moisture, sea spray, and salt (Allison 2007; Lane and others 2008; Wilson and Sykes 1999). Additionally, future studies of interactions between different species in the field would be needed to determine how specific plants would respond to sargassum in a community environment. However, this study provides a basis of understanding how sargassum can benefit dune plants and is crucial in proceeding with further investigative studies for coastal researchers and managers.

Conclusion

Though different plants responded differently to the sargassum treatments, this study indicates that sargassum does positively increase growth for these dune plants. Sargassum deposits add a subsidy to the nutrient poor dune environments. All plants responded positively to some form of sargassum treatment. Overall, plants seemed to respond well to unwashed sargassum and also to multiple additions of sargassum. The amounts of sargassum that can beneficially be added to the soil and plants would need to be tested further to see if there is still some threshold where the sargassum would cause negative effects. Both caution and future studies should be taken when extrapolating this research to the field as greenhouse studies can not control for the natural conditions of the environment.

Anthropogenic activities strongly influence landscape alterations along the coasts, such as housing developments, groins, seawalls and raking for aesthetic purposes (Matias and others 2005; Nordstrom and others 2009). The environment is not only altered by these forces, but also by global climate change, sea level rise and hurricanes (Claudino-Sales and others 2008; Houser and Hamilton 2009; Morton 2002; Tilman 1996). Alternative methods to current beach management practices that help to minimize the destructive affects of these forces must begin to be investigated and implemented so that we do not lose the resources that initially attracted humans to the coast (Nordstrom and others 2004; Smith and others 2007). These results are critical to begin understanding the positive interactions and feedback loops between marine and coastal environments. Many coastal ecosystems are nutrient poor and have historically relied on constant or sporadic natural subsidies to the ecosystem.

This research provides insight into the mechanisms of how dune plants react to natural deposits of sargassum and leads to suggestions on how to alter current management practices to provide coastal stability and vegetation along with aesthetically pleasing recreation areas for tourists. Piles of sargassum could be spread out along the base of the dunes to help fertilize and establish embryonic dune systems. The benefits for landward protection would outweigh the minimum additional costs to the current maintenance practices. This study indicates that there are positive aspects of sargassum to dune plants. Overall, coastal managers should recognize the potential positive, natural and efficient alternatives of dealing with the accumulation of wrack on the beach in order to increase the stability and functionality of the coastal ecosystem.

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