EVALUATING A NOVEL BIODEGRADABLE LATTICE STRUCTURE FOR SUBTROPICAL SEAGRASS RESTORATION

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Highlights:

- Seagrass restoration is expensive and often unsuccessful.
- Traditional and novel physical restoration techniques were compared.
- Biodegradable starch (BESE) lattices yielded better growth.
- BESE may improve restoration in hydrodynamically active environments.

Abstract

While attention in coastal ecosystem restoration has increased over the last two decades, the success rate of efforts remains relatively low. To increase success rates, physical restoration techniques often utilize supporting or protective materials to provide a stable surface for transplantation, and in some cases reduce herbivory and hydrodynamic disturbances. In this study, we evaluated the effectiveness of traditional (staples, burlap) and novel (BESE elements, a biodegradable potato starch lattice) physical restoration techniques on the growth of transplanted *Halodule wrightii* seagrass. A first experiment revealed that seagrass planted in both two-stacked BESE structure without planting holes and four-stacked BESE with holes had significantly higher shoot count and blade length than four-stacked BESE without holes, with the latter design losing all seagrass shortly after deployment as shoots could not float through the structure. In a second experiment, the BESE lattice treatment (four-stacked with holes) had three times the shoot count and equal to greater blade length compared to traditional methods of physical restoration (staples and burlap), likely due to BESE providing some protection from hydrodynamic activity. However, disturbances, possibly including herbivory and hydrodynamic activity (culminating with Hurricane Irma), prevented long term study, illustrating the importance of stochastic abiotic factors in seagrass planting success. Overall our study demonstrates the effectiveness of using BESE lattice designs and similar physical techniques in the restoration of seagrass beds.

Keywords: *Halodule wrightii*; seagrass; marine; restoration; coastal; Indian River Lagoon; shoots; subtropical; success

1. Introduction

In the past two decades, greater attention on coastal ecosystem restoration (Basconi et al., 2020; Zhang et al., 2018) has better identified the challenges of this field (i.e. costs, stressors, site characteristics, etc.). While regulations attempt to improve conditions for natural regrowth (passive restoration), active restoration is often necessary to remediate environments either too damaged or too low in the desired species population to passively improve (Basconi et al., 2020; Rinkevich, 2005). As a result, active coastal ecosystem restoration is often expensive and frequently fails to achieve success (Bayraktarov et al., 2016; Zhao et al., 2016).

Restoration of seagrass ecosystems is often hindered by multiple and often elevated/unnatural physical disturbances (Castillo et al., 2000; Hauxwell et al., 2004; McFalls et al., 2010). For example, natural seedling establishment is typically low due to hydrodynamic disturbances (Infantes et al., 2011) which can dislodge, erode, or bury transplanted seagrasses before they can establish (Katwijk et al., 2009; Paulo et al., 2019). Herbivory has also been established as a significant factor in seagrass and other submerged aquatic vegetation (SAV) restoration, with many manatees, sea turtles, and fish capable of overwhelming grasses, especially in polluted systems already under stress

(Bourque & Fourqurean, 2013; Hauxwell et al., 2004; Ravaglioli et al., 2018; Tomas et al., 2005; Tuya et al., 2017). As climate change may exacerbate both hydrodynamic activity (Duarte et al., 2013) and herbivory impacts (Heck et al., 2015) on seagrass beds, finding a means to reduce these physical disturbances is an important strategy to reducing stress on seagrass and improving the success of restoration efforts.

Physical restoration techniques utilize supporting or protective materials that provide a stable surface for transplantation, and in some cases reduce herbivory and physical disturbances (K. Hammerstrom et al., 1998; Temmink et al., 2020; Wear et al., 2010). These protective materials maintain seagrass patch size/density (important for the long term survival of the plants [Maxwell et al., 2017; Silliman et al., 2015]), thereby providing seagrass transplants the time and support to overcome transplantation stress and becme established. Among physical restoration techniques applied to seagrasses, staples affixed to seagrass rhizomes have been used for decades as an anchor while the grass establishes (Bird et al., 1994; Heise & Bortone, 1999). Burlap is a another cost-effective anchoring surface for transplants, either as a stabilizing surface for sediment, or as strips facilitating natural recruitment of seedlings in a hydrodynamically active environment (Irving et al., 2010; Wear et al., 2010). Artificial seagrass (plastic strips imitating seagrass) and exclusion cages have also found success in reducing fish and turtle herbivory, giving plants a sufficient window of opportunity to establish themselves (Hammerstrom et al., 1998; Tuya et al., 2017).

The disadvantages of many physical restoration techniques are that the materials used either provide limited protection (e.g., staples and burlap do not provide aboveground protection from hydrodynamic activity or herbivory) or require regular maintenance which may result in pollution of the surrounding environment. For example, both cages and artificial grass accumulate algae and epiphytes, blocking light, and artificial seagrass is often plastic-based, persisting and polluting the environment (Tuya et al., 2017). Thus, low-maintenance biodegradable materials with aboveground structure to protect from hydrodynamic activity and herbivory are a potential solution to both maximizing resources and minimizing long-term debris accumulation at restored sites. Biodegradable Elements for Starting Ecosystems (BESE-elements, BESE BV, Culemborg, Netherlands, hereafter called BESE) are carbon neutral, biodegradable potato starch-based lattices. BESE lattices can be used belowground as an anchor for transplants and/or stacked into vertical structures aboveground to protect plants from currents and herbivory. Studies have shown promise in trials restoring oyster, mangrove, and saltmarsh habitats (*BESE-Ecosystem Restoration Products*, 2018; D'Angelo, 2018; Temmink et al., 2020), but despite this potential, only one study has been published using these structures in seagrass systems (Temmink et al., 2020). Additionally, Temmink et al. (2020) did not examine subtropical environments (conducted in temperate and tropical environments) and used *Thalassia testudinum* instead of *Halodule wrightii*, the latter being an early successional seagrass species better suited for restoration in the southern USA (Biber et al., 2013; Furman et al., 2019).

Based on the potential gaps of previous studies investigating the effectiveness of physical restoration techniques, the purpose of this study was to *i)* explore the effectiveness of different BESE lattice designs on promoting *H. wrightii* growth (measured via shoot count and blade length), *ii)* compare the relatively novel BESE lattices to traditional physical restoration techniques (staples and burlap), and *iii)* to determine the mechanisms (protection from physical disturbances, herbivory, etc.) behind their success or failure in establishing a seagrass community. We also aimed to identify the fish and invertebrate communities that utilize (consume, colonize, etc.) the seagrass/structures to inform the design of future restoration efforts. We hypothesized that seagrass within the BESE lattice would have increased success relative to staples and burlap planted units due to better protection from wave action and macro-herbivores (similar to Temmink et al., 2020).

2. Materials and Methods

2.1 Site Description

This seagrass restoration study was conducted in Stuart, FL, within the Indian River Lagoon (IRL) (Figure 1). The value of seagrasses, and the consequences of their removal, have been especially relevant to the IRL. In 2009, estimates found that the IRL was worth $3.7 billion dollars in ecosystem services and revenue, with a large part of these services coming from the (historic) 72,400 acres of seagrass in the lagoon, estimated at $2 billion annually (USEPA, 2009). “Superblooms” of toxic algae (caused by poor water quality) subsequently covered tens of thousands of acres, destroying up to 95% of seagrass in the lagoon, and precipitating a phase shift of the environment into a “toxic phytoplankton-dominated system” (Barile, 2018; Lapointe et al., 2020). The seagrass and its associated communities have yet to recover (Barile, 2018; Lapointe et al., 2020). While algae and bare sediment have largely replaced seagrass and macroalgae in this area, there is a functioning seagrass bed directly across the study site, indicating that seagrass establishment was possible.

The specific location of the experiment is a permitted oyster and seagrass restoration site (27º12’33.4” N, 80º12’11.9” W) approximately 3.2 miles northwest of the St. Lucie Inlet, and is maintained by the Florida Oceanographic Society (FOS) of Stuart, FL. Efforts to restore seagrass at multiple sites in the southern IRL have been undertaken by FOS. This system is an ecotone between temperate and sub-tropical habitats, fostering above-average biodiversity (Lapointe et al., 2020). The IRL is a microtidal system, with limited transport occurring locally around inlets (Weaver et al., 2016). Due to its narrow (2-4 km wide) and shallow (average depth is 1.2 meters) characteristics, the IRL is considered a restricted lagoonal system (Lapointe et al., 2020). The currents in the IRL are wind-driven but extremely fetch limited except from the southeast or northwest (Colvin et al., 2018). In 2017, average monthly water temperatures in the area of the restoration site (Stuart, FL) ranged from 20.8 ± 0.2 ºC to 30.6 ± 0.3 ºC (mean ± standard error), salinity ranged from 18.75 ± 1.11 ppt to 37.48 ± 0.76 ppt, Secchi depth ranged from 0.70 ± 0.04 m to 1.37 ± 0.15 m, and dissolved oxygen ranged from 4.93 ± 0.16 $mg.L^{-1}$ to 6.90 ± 0.42 $mg.L^{-1}$ (Florida Oceanographic Society, 2017). The experimental site had a depth of approximately 0.61 m at mean low water (MLW).

2.2 Optimizing BESE design for seagrass restoration (Exp. 1)

The first study was an eight-week experiment (June 30th to August 22nd, 2017) to confirm the survivability of seagrass at the restoration site, as well as compare multiple BESE lattice designs (Figure 1). There were three replicates of three different designs: two-stacked (connecting two individual lattices to form a vertical structure, dimensions are approximately 1 m x 0.5 m x 4 cm, buried 4 cm in the sediment) and four-stacked with and without holes (dimensions approximately 1 m x 0.5 m x 8 cm, the lower 4 cm buried in the sediment). Four-stacked with planting holes had 25 cm circular cutouts in the top three layers of BESE so seagrass shoots could be unimpeded by the lattice. While there were no controls (seagrass not planted using physical restoration techniques), the staples approach was considered a pseudo control in this experiment, as it appeared to provide the least structural protection from hydrodynamic activity and herbivory. Twenty-five shoots of seagrass were planted in each plot. All shoots were adult plants obtained from the seagrass nursery lagoon at the FOS Coastal Center. Seagrasses were affixed to BESE lattices via 0.404 mm (26 gauge) flower wire, and the BESE lattices were buried approximately 4 cm in the sediment and anchored with 60.96 cm (24 in.) metal rods. Plants were minimally exposed to air ($x<10$ minutes) to avoid desiccation and stress. Seagrass metrics (shoot count and blade length) were taken 24 and 48 hours after deployment, as well as five additional times over an approximate two month period ($x \leq 14$ days between sampling periods). Based on the survival of two BESE designs, a larger project comparing novel BESE lattices to traditional physical restoration approaches was subsequently deployed in August 2017 (Figure 1).

2.3 Comparison of physical restoration techniques (Exp. 2)

The second study was a two-week experiment (August 17th through August 31st) to compare the BESE lattice (four-stacked with planting holes design) to staples (seagrass attached directly to staples with flower wire) and burlap approaches (seagrass attached to a burlap square with flower wire) (Figure 1). The four-stacked with planting holes BESE design was chosen based on the favorable shoot and length measurements found early in the first study (up until mid-July) versus the two-stacked and four-stacked designs. Twelve plots with seagrass of approximately 0.5 m x 1 m (BESE was slightly smaller at 0.45 m x 0.95 m) were arranged in randomized blocks approximately 0.5 m apart. Twelve plots without seagrass were placed adjacent to the restoration site acting as a control. The plot size and spacing of plots for all techniques tested was equivalent and based on that described in Duarte et al. (2015), with a compromise between restoration success and availability of seagrass plants and permitted space. We expected the plots to remain independent for the duration of the study based on the reported mean horizontal elongation rate of *H. wrightii* varying greatly in the literature, (Duarte et al., 2013; Gallegos et al., 1994), the disturbed nature of the area/site being restored, the distance between seagrass shoots (approximately 0.6 m when accounting for the space between the plants and the edge of the plot), and the short period of observation for the study.

All plots contained 50 shoots inside two 0.25 m diameter circles (Figure 1), equivalent to approximately 510 shoots m^2, approximating the historic densities of *H. wrightii* seagrass in the IRL (Berninger, 2016). The total amount of seagrass used was 600 shoots. The burlap was installed with the 25.4 cm metal staples also used for the stapled plots. The BESE lattice treatment was approximately 8 cm in height (four-stacked) and had two 25 cm diameter holes cut out to the bottommost lattice (used as a point to attach the seagrass). This BESE design (four-stacked with planting holes) was chosen based on the favorable shoot and length measurements found early in the first study (up until mid-July) versus the two-stacked and four-stacked designs. BESE lattices were installed at a 4 cm sediment depth and reinforced via 0.64 cm (0.25 in.) thick, 91.44 cm (three ft.) long rebar.

Seagrass metrics (shoot count and blade length) were taken one, five, and 14 days after deployment. To assess the influence of herbivory on seagrass growth and survival during the study, seagrass blades were tethered to the benthos to imitate restored seagrasses, based on the methods of Holzer et al., (2011). Ropes with pre-measured *H. wrightii* blades attached via wooden clothespins were placed adjacent to each block (n= four strands per rope). After 24 hours, the blades were removed and compared based on their original length and proximity to an adjacent oyster reef. To assist in confirming the presence of herbivory and identity of herbivores, approximately three hours of time-lapse footage of four tethers placed parallel to each other were also recorded during daylight hours using a GoPro placed on the seabed at level with the tethers (Hero 3 Silver, GoPro, San Mateo, CA).

2.4 Seagrass Metrics and Nutrient Analyses

Seagrass shoot count (seagrass shoots defined as a unit of several leaves or blades according to Short & Coles [2001]), and blade/leaf lengths (substrate to leaf tip according to Arrington, [2008]) were quantified in both experiments. Up to five shoots were randomly selected for blade length, with the longest blade being measured. For the local site description/background data, samples of surface water were collected for total dissolved phosphorus (TDP) and sediment samples were collected for total phosphorus (TP), total nitrogen (TN), and total carbon (TC). Surface water TDP samples were collected in plastic LPDE bottles, filtered (0.45 micron), preserved with sulfuric acid to a pH to $x < 2$ and stored at 4 ºC until analysis (USEPA, 1993). Bulk sediment samples of the top 10 cm were collected via plastic corers, dried for 72 hours at 65 ºC, and ground using a ball mill.

Surface water TDP and sediment TP were measured in the University of Florida Wetland Biogeochemistry Laboratory (Gainesville, FL), while sediment total carbon (TC) and nitrogen (TN) were measured by the University of Florida Stable Isotope Mass Spectrometry Laboratory (Gainesville, FL). Water samples for TDP were digested with potassium persulfate in an autoclave and analyzed via a Shimadzu UV-1800 spectrophotometer (Shimadzu Corporation, Kyoto, Japan) using EPA method 365.1 (USEPA, 1993). TC/TN samples were run on an ECS 4010 CHN analyzer (Costech Analytical Technologies, Inc., Valencia, CA, USA) (dry combustion method) (Nevins et al., 2020). Sediment TP was determined by ashing the sample followed by dissolution with 6 M HCL (following Andersen, 1976) before an analysis of soluble P using a Shimadzu UV-1800 spectrophotometer (Shimadzu Corporation, Kyoto, Japan) (Liao et al., 2014; USEPA, 1993).

2.5 Fish Count Analysis

Fish identity and counts were conducted utilizing the full video taken of the herbivory tethers, with the recording being paused every 10 seconds to determine fish quantity and species. This approach utilizing video cameras was found to be similarly effective as direct visual observations and has been used to determine fish herbivory in past studies (Bennett et al., 2015; Eggertsen et al., 2019). The focus of the fish observations were on pinfish (*Lagodon rhomboides*), filefish (family *Monacanthidae*), and parrotfish (family *Scaridae*), common seagrass consumers in Florida (Heck et al., 2015).

2.6 Statistical Analyses

Seagrass metrics (shoot count and blade length) for both experiments were calculated using a linear mixed model. Factors included treatment type, date, and the interaction between treatment and date, with subject/plot number set as a random variable. Both seagrass shoot count and length were log and/or square root transformed as necessary to improve normality. For significant effects, multiple comparison analysis was completed via a Fishers LSD test. Tests were completed in JMP 15.2.1 (SAS Software, Cary, NC, USA) with significance set to $\alpha = 0.05$. Marginal significance was set between α= 0.05 and α= 0.10, consistent with multiple other ecology studies (Koyama et al., 2018; Nielsen et al., 2003; Stephan et al., 2000). To best determine model fit, residuals and qq plots were visually inspected. All statistical methods were accomplished in consultation with the Institute of Food and Agricultural Sciences (IFAS) Statistical Consulting Unit.

3. Results

3.1 Site Water and Sediment Characteristics

Surface water TDP during the studies fluctuated between 0.072 ± 0.002 mg.L^{-1} and 0.104 ± 0.003 mg.L^{-1}. After Hurricane Irma made landfall in southeastern Florida as a category 3 cyclone, samples were taken < 10 m from the experimental site revealed a higher surface water TDP (0.163 ± 0.013 mg.L^{-1}), likely caused by surface runoff or sewer overflow. Precipitation measurements from Cangialosi et al. (2018) confirmed the high levels of runoff, finding that the maximum precipitation reported during Irma was 55.02 cm near Fort Pierce, just north of the restoration site. Bulk sediment concentrations were 1518 ± 246 mg.kg$^{-1,}$ 121.2 ± 6.9 mg.kg^{-1}, and 48.98 ± 4.35 mg.kg^{-1}, for TC, TN, and TP, respectively. These levels are all relatively low but expected considering the nature of the site as a bare sand bed with little organic matter.

3.2 Optimizing BESE design for seagrass restoration (Exp. 1)

The effects of design type, date, and the interaction between type and date were significant for shoot count (Table 1). The four-stacked plots rapidly declined in shoots, with most shoots absent during and after the first sampling period (Figure 2). The two-stacked design initially decreased in shoot count until late July, subsequently increasing until August 22nd (54 days after deployment), while the four-stacked with planting holes design steadily decreased over the study period. However, the two-stacked design did not exhibit significantly higher shoot counts than the four-stacked with planting holes design until 54 days after deployment (*t*= 5.16, *p* < 0.0001). At the end of the study, mean shoot counts were 0 shoots in the four-stacked design, 2.3 ± 1. 5 shoots for the four-stacked with planting holes design, and 25.0 ± 9.3 shoots in the two-stacked design. By 54 days post deployment, all designs had lost the majority of their shoots, likely due to increased hydrodynamic activity.

Over time, the mean blade length of all plots declined from 14.8 ± 3.9 cm after deployment to 3.8 ± 1.0 cm in mid-July (Figure 3). Mean blade lengths were 0 cm for the four-stacked design (due to an absence of shoots), 2.3 ± 0.3 cm for the four-stacked with planting holes, and 3.2 ± 0.3 cm for the two-stacked design during the last date length was measured (54 days after deployment). The effects of design type, date, and type x date were significant for blade length (Table 1). Blade length was initially significantly higher in the four-stacked with planting holes design than the two-stacked design (*t*= 3.18, *p*= 0.0031; and *t*= 3.12, *p*= 0.0037 for one and two days after deployment, respectively) (Figure 3). After two days post deployment, the differences in length became insignificant.

Despite substantial declines in blade length, there was still survival and growth of seagrass shoots in multiple plots at the restoration site. For example, one plot of two-stacked BESE increased the number of shoots from 20 to 43 shoots, almost 50% increase over a two-month period. Due to this observed survival and growth, the second experiment was deployed to compare BESE to the traditionally used physical restoration techniques (staples and burlap).

3.3 Comparison of physical restoration techniques (Exp. 2)

Seagrass shoot count and blade length declined for all treatments over the course of the two weeks, likely due to transplant stress and wave action (Figures 3). Direct observations showed rhizome exposure in multiple plots, including almost all plots in the burlap treatment. This elevated exposure in the burlap treatment likely contributed to significant differences in shoot count and length between the staples, burlap, and BESE treatments during the two weeks of observation. The effects of treatment, date, and the interaction between treatment and date were significant for shoot count, while the effects of date and treatment (marginally significant at p= 0.0934, Table 2) were significant for blade length. The BESE treatment had significantly higher shoot count than both burlap (t= 5.35, p= 0.0002) and staples (t= 3.35, p= 0.0070). BESE also had a significantly higher blade length than burlap (t= 2.24, p=0.0492), with marginal significance for blade length compared to staples (t= 2.01, p= 0.0721). By the last sampling period, the BESE treatment contained 64 shoots (totaling 70% of the total shoots observed), or three times as many shoots as the staples and eight times as many as the burlap treatment. Within two weeks of this last sampling period, Hurricane Irma made landfall and subsequent observations in December revealed a complete loss of seagrass in all plots, likely due to observed burial and high hydrodynamic activity at the site.

In the time-lapse footage, over 600 fish, a majority (> 90%) pinfish (*Lagodon rhomboides*), were observed passing by the tethers, not appearing to interact with the seagrass. There were fish interactions such as apparent feeding on the macroalgae attached to the BESE lattices. Measurements of herbivory via blade length of grass over 24 hours (to account for nighttime herbivory) did not suggest herbivory as a significant factor. Losses did appear to be related to distance from the adjacent oyster reefs (Figure

4). The herbivory tethers placed at approximately one to three meters from the reef had significantly lower blade lengths after 24 hours (t= 3.17, p= 0.0020; t= 5.44, p < 0.0001; and t= 3.13, p= 0.0022 for one, two, and three meters, respectively), while tethers four and five meters from the reef were not significantly lower after 24 hours. However, these results were not consistent with observations of shoot counts or blade lengths between plots.

4. Discussion

4.1 Comparison of Methods and Abiotic Factors

While brief in length, the results of both experiments suggest the effectiveness of BESE lattices as a physical restoration technique enhanced the survival of *H. wrightii* seagrasses in the IRL. The first experiment demonstrated that the two-stacked BESE lattices appeared to be more effective than other designs over time. The aboveground BESE may have physically abraded the grass blades due to its relatively sharp structure (Temmink et al 2020). The four-stacked plots that did not have planting holes were not an adequate design for *H. wrightii*, as it did not allow the shoots to float and move through the lattice and all plants quickly died off (due to burying/smothering). BESE designs that did not smother *H. wrightii* may not completely prevent direct herbivory of shoots, especially in environments where small fish or crustaceans are the primary concern. However, the four-stacked with planting holes design could theoretically provide some protection from macro-herbivores like manatees. Instead, the BESE lattices do appear to provide a surface that accumulates sediment and/or prevents erosion. This sediment accumulation/erosion protection effect was also found in the single published study evaluating BESE lattices in seagrass, where it was determined that the BESE mimicked a mature seagrass rooting mat, improving productivity compared to stapled controls (Temmink et al., 2020).

Temmink et al. (2020) used designs similar to the two-stacked and four-stacked with holes from the present study, finding that the two-stacked design (which is belowground) was equal or superior to aboveground designs. The aboveground BESE treatment in Temmink et al. (2020) also had similar limitations to the four-stacked with holes treatment used here, where for example, their lattice was 6 cm thick (three-stacked) but only provided a 10 cm diameter circle for the thicker *T. testudinum* blades to freely grow. While mean maximum lateral growth was still 36 ± 12 cm over the course of 22 months in the study by Temmink et al. (2020), both growth and shoot counts were significantly lower than the belowground BESE plots. Given the similar lack of shoots of the thinner and more flexible *H. wrightii* in the current study, it appears that aboveground BESE lattices may inhibit *H. wrightii* growth. However, it has also been demonstrated that 80% of flow velocity is attenuated within and downstream of an aboveground BESE lattice design, possibly capturing sediments and organic matter (D’Angelo, 2018). Thus, having a primarily belowground design with limited aboveground lattice (perhaps a three-stacked design, with two-stacks underground and one stack above the sediment) could optimize sediment capture without limiting/damaging aboveground growth (as the aboveground lattice would not cut/directly smother the grass).

The second experiment of this current study demonstrated the effectiveness of BESE, and to a lesser extent staples, over burlap in reducing the mortality of *H. wrightii* transplants. Burlap buried at 2 cm did not perform well in this environment, with the belowground biomass becoming quickly exposed, killing the seagrass, possibly due to the burial depth being too shallow, or the currents/wave action being too high for the technique. This observation is similar to the study of Katwijk et al., (2009) who suggested this as a potential disadvantage of netting or fabric in high hydrodynamic environments. Planting the burlap deeper in the sediment would assist in reducing the potential negative effects of using burlap and other cloth/netting in further applications. While the staples and burlap may not have performed better than the BESE lattice in this environment, their accessibility and low cost necessitates further study in environments with lower levels of physical disturbance.

The relatively shallow depth of the restoration site may have exacerbated the impacts of wave and wind action on the seagrasses. The improvements in the shoot count and length could be the result of the BESE lattice buffering wave action, anchoring and protecting the grass. Wind patterns may have contributed to the accelerated decline of seagrasses in the second experiment. Higher wind velocity (taken at NOAA station TRDF1 in Trident Pier, approximately 70 miles north of the field site) was observed during the second experiment (2.91 ± 0.08 m s^{-1} for the trial/first experiment, 3.47 ± 0.24 m s^{-1} during the second experiment) combined with a northeast direction (average of 156 degrees, facing the restoration site) indicating a potentially higher level of physical disturbance at the field site later in the summer. Wind-driven disturbance has also been identified as a potential issue in the restoration of Tampa Bay seagrass beds (Yates et al., 2011). Therefore, it appears that wind driven disturbance, and perhaps the structure of the BESE lattice (which could have buffered hydrodynamic activity), may have been major factors in the differences of shoot count and blade length between the different restoration techniques.

4.2 Effects of Herbivory

As previously stated, herbivory is often found to significantly affect aquatic vegetation restoration attempts (Bourque & Fourqurean, 2013; Hauxwell et al., 2004; Paulo et al., 2019; Ravaglioli et al., 2018; Tomas et al., 2005; Tuya et al., 2017). In this present study, attempts to observe herbivory via the tethers and time-lapse footage yielded no conclusive results, perhaps indicating herbivory was not a significant factor compared to other physical disturbances. This conclusion is somewhat puzzling as known seagrass consumers were present in large numbers (i.e. pinfish). There was a possibility that resident herbivores in the adjacent oyster reef may have fed on the seagrass at night, or that the oyster reef itself might have reduced blade lengths by increasing hydrodynamic activity, given the significant decline in the length of herbivory tethers (Figure 4). However, Gruninger (2019) found that nearby oyster reefs did not have a significant effect on seagrass grazing pressure within the same proximity as our experiments. The nearby seagrass bed may have reduced herbivory for the study site, where comparatively there were far fewer seagrass shoots for a shorter period of time. However, other locations in the southern IRL may face grazing pressures (Gilmore, 1995), and herbivory should still be considered as a potential factor in future restoration efforts.

4.3 Recommendations for Application and Future Studies

Based on the positive performance of BESE in this study, it is recommended that lattices of this or similar type be applied to restoration efforts in areas with limited erosive hydrodynamic activity, including seagrass scars and fringing seagrass plots (plots at the edge of seagrass environments or restoration efforts). Smaller scale projects ($x < 1000$ shoots) could especially benefit from BESE as they lack some of the positive geomorphological feedbacks (i.e. sediment stabilization, improvement to local water quality) inherent to larger efforts (Katwijk et al., 2016; Maxwell et al., 2017). However, based on the observations of rapid burial at multiple plots in this study, prevailing winds and shifting sand deposits should be included in future site considerations for BESE applications. For example, in Florida, it is recommended to select sites on the central Gulf coast or protected banks on the Atlantic coast that will avoid dominant wind patterns that can damage plants and shift sediments at the site. The central Gulf coast of Florida is an environment “favorable to seagrasses” and is home to one of the largest seagrass communities in the US (Barry et al., 2017). However, extensive boat scarring in the Gulf threatens otherwise healthy seagrass beds, a disturbance that produces environments of elevated hydrodynamic activity that can erode adjacent healthy seagrass beds if not otherwise remediated (Hammerstrom et al., 2007). Therefore, conducting studies of seagrass scars in this region of Florida provides ample opportunities for the testing of BESE in a subtropical environment relatively isolated from the effects of eutrophication and other confounding variables/disturbances.

BESE and other physical restoration approaches should also be combined with other common restoration techniques to improve the survivability of seagrasses introduced to new environments. Seagrass is especially vulnerable to stressors during transplantation, where the composition of the local sediment may be nutrient limiting, reducing the probability of a successful restoration effort. Fertilization is a popular restoration technique used to ameliorate issues caused by nutrient limitation (Armitage & Fourqurean, 2016; Peralta et al., 2003). Combining the possible protective effects of BESE lattices and the supplemental nutrients of fertilizers could increase the growth of seagrass (especially in the low sediment TN and TP observed at the site) and improve survivability during disturbance events. However, it is also important to remember that the root cause of the much seagrass decline (i.e., urban waterways/estuaries) centers around eutrophication. Until this core issue is resolved, seagrasses will likely continue to decline, and thus, restoration will remain difficult regardless of the deployment of different active restoration approaches.

5. Summary and Conclusions

Human disturbances are degrading seagrass ecosystems, and current attempts to restore these coastal habitats are expensive and often unsuccessful. This study investigated the effectiveness of multiple physical restoration techniques on a pioneer seagrass species in a disturbed subtropical coastal system. While the study here was not a long-term comparison among techniques, initial results found that novel BESE lattices could reduce the rate of decline in seagrass shoot count and blade length relative to traditional (staples and burlap) restoration techniques. Herbivory and hydrodynamic activity (dominant wind and wave patterns) both may have made the local environment unsuitable for seagrass establishment by the end of the study (based on declines in shoots and length in all plots). However, the differences in seagrass parameters even in such a relatively harsh environment reveal the promise of BESE in protecting seagrass from wind and wave action. Future studies should investigate the effectiveness of other BESE designs (i.e. wider or rounder lattices more compatible with seagrass) across a wider range of systems and conditions, and in concert with other methods used to improve restoration success (i.e. fertilization) over longer periods of time. The application of staples and burlap should be further tested in different hydrodynamic environments to determine which technique is more suitable in varying levels of wave and current disturbance. By taking these steps, it may be possible to add new physical restoration techniques to the portfolio of management options to effectively re-establish seagrass and other coastal ecosystems and begin reversing their overall decline.

Funding Sources:

This work was supported by the Soil and Water Sciences Biogeochemistry Laboratory and Florida Seagrant. Seagrass restoration by the Florida Oceanographic Society was supported by the South Florida Water Management District Indian River Lagoon License Plate funding.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments:

A special thanks to Dr. C. Angelini for her assistance in the experimental design and assistance with writing. The authors acknowledge Sophia Barbour and Devin Leonard from the University of Florida’s Wetland Biogeochemistry Laboratory for assistance with the analysis of surface water and soil nutrients. Special thanks to James Colee from the IFAS statistical consulting unit for confirming the quality of the data and the subsequent analyses. Many thanks to the staff and volunteers at the Florida

Oceanographic Society, for permission to use their site and their seagrass nursery, and for support in the deployment of the experiments. We also thank Lori Morris from the St. Johns River Water Management District for help in seagrass identification and monitoring techniques.

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Table 1. Mixed model effect test results for shoot count and blade length measured during the BESE design/first experiment.

Variable						
	Shoot			Length		
Source	Count			cm		
Parameter	DF	F statistic	P value	DF	F statistic	P value
Treatment	2	54.90	< 0.0001	2	1069	< 0.0001
Date	7	14.25	< 0.0001	5	128.9	< 0.0001
Treatment x Date	14	4.461	< 0.0001	10	34.52	< 0.0001

Table 2. Mixed model effect test results for shoot count and blade length measured during the physical restoration comparison/second experiment.

Variable						
	Shoot			Length		
Source	Count			cm		
Parameter	DF	F statistic	P value	DF	F statistic	P value
Treatment	2	189.1	< 0.0001	2	134.9	< 0.0001
Date	2	9.841	0.0043	2	3.034	0.0934
Treatment x Date	4	4.722	0.0045	4	1.880	0.1398

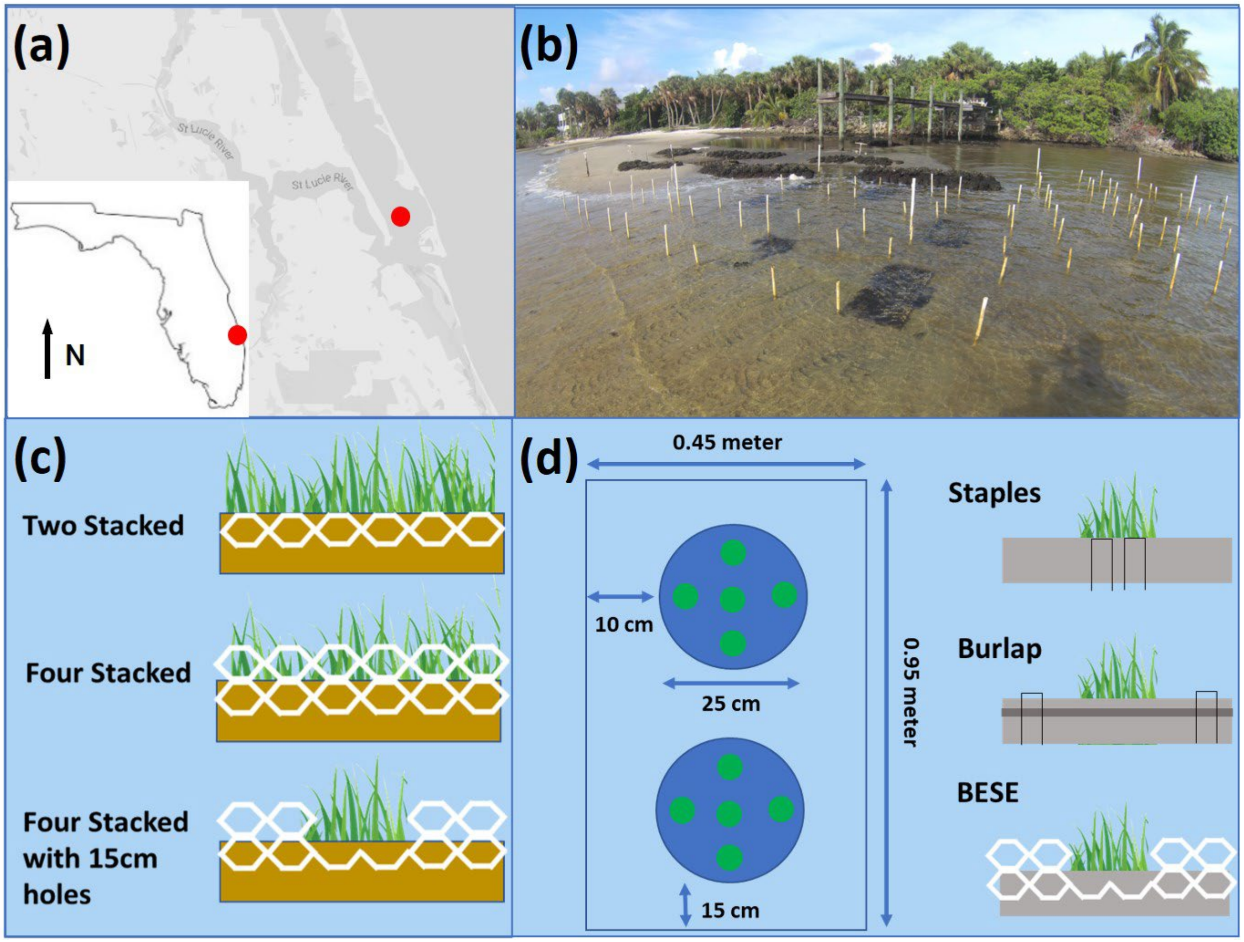

Figure 1. Location of field site (a), deployment of BESE design experiment at low tide (b), designs for BESE design/first experiment (c), and design for the physical restoration comparison/second experiment (d).

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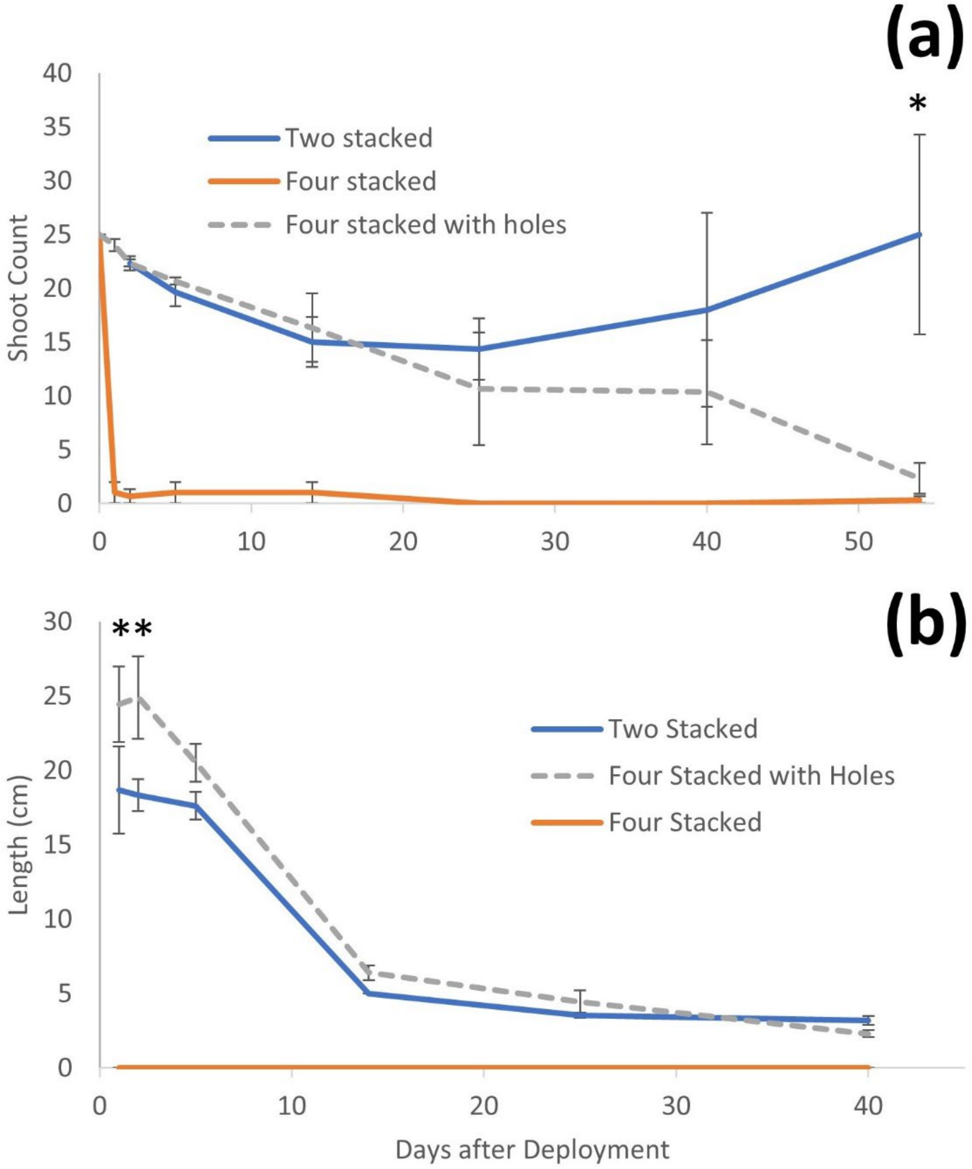

Figure 2. Average shoot count (a) (initial 25 shoots) and blade length (b) from the BESE design/first experiment. Asterisk designates the significant difference between the two-stacked and four-stacked with holes designs, points represent the mean of three replicates (± SE).

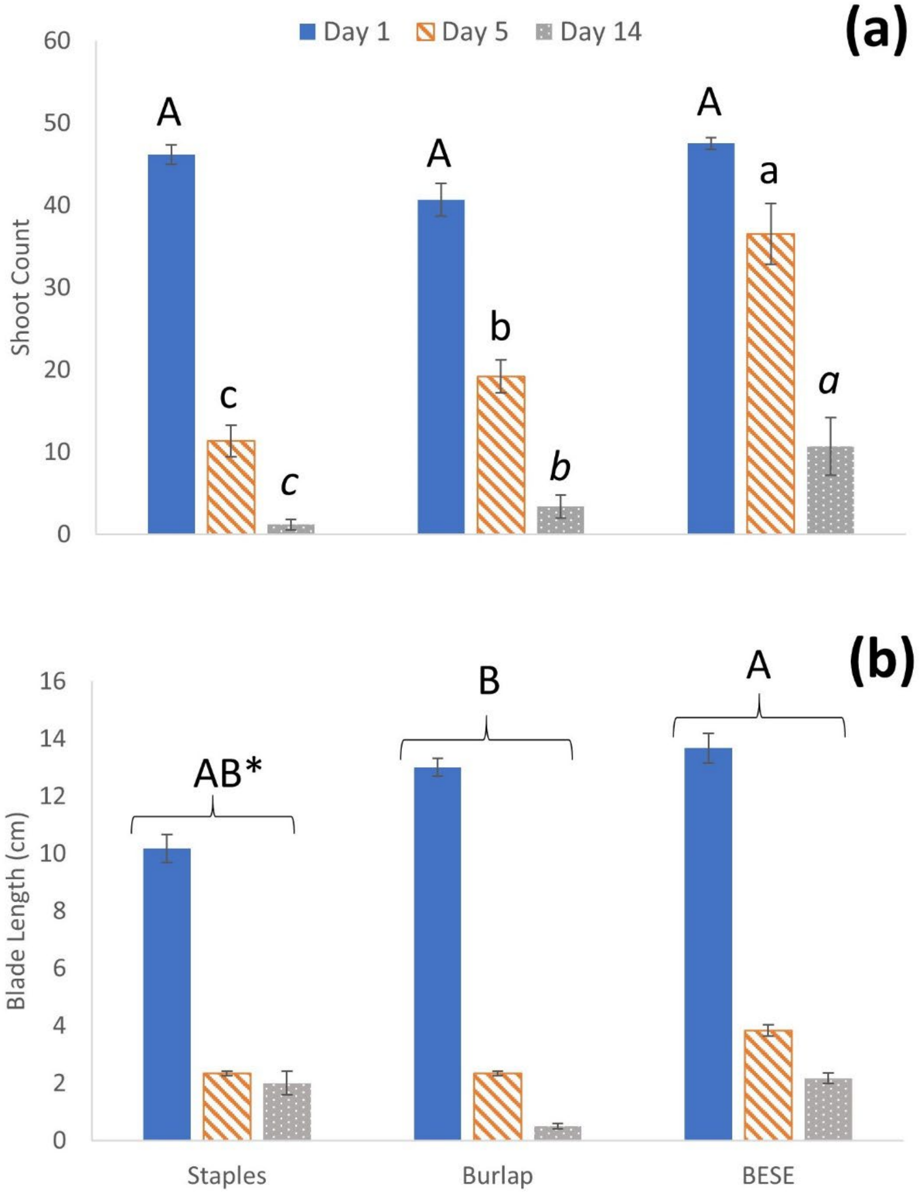

Figure 3. Average shoot count (a) (initial 50 shoots per plot) and blade length (b) during the physical restoration comparison/second experiment. Letters designate significant differences between treatments for the same sample dates, points represent the mean of six replicates (± SE). Blade length in the BESE treatment was marginally significant (longer blade length with *t*= 2.01 and *p*= 0.0721) versus staples, designated with an asterisk.

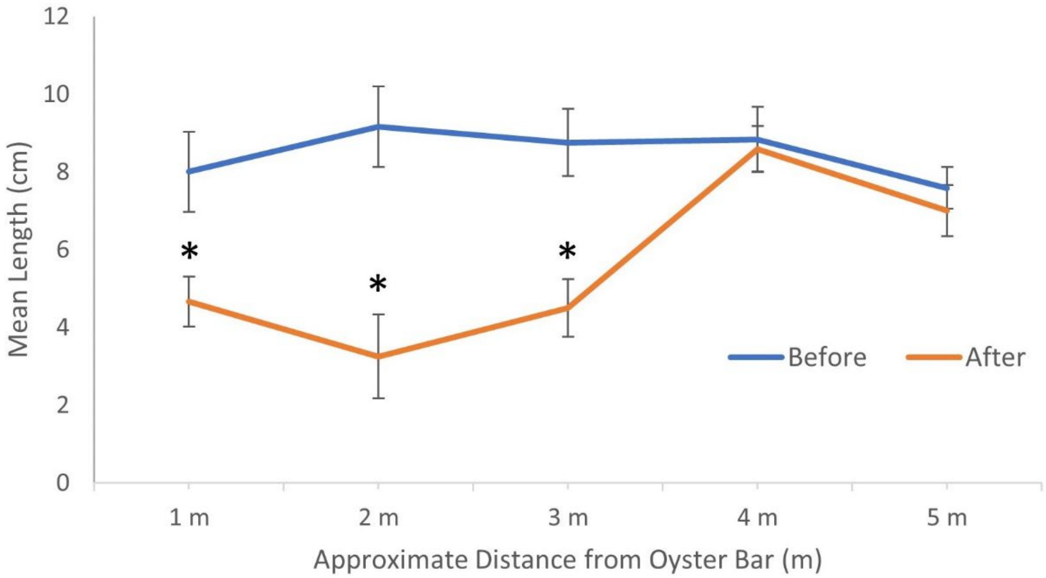

Figure 4. Average blade length of herbivory tethers based on approximate distance from the nearest restored oyster bar (labeled "approximate distance" due to the approximately 0.5 meter length of the tether) during the last sampling period of the physical restoration comparison/second study. Asterisks designate tethers that were significantly lower in length after deployment versus before deployment, points represent the mean of four replicates (± SE).