Ecological Engineering 53 (2013) 250–256

Contents lists available at SciVerse ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Cost-effectiveness of two small-scale salt marsh restoration designs

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ARTICLE INFO

Article history:
Received 28 June 2012
Received in revised form
20 September 2012
Accepted 3 December 2012
Available online 29 December 2012

Keywords:
Juncus roemerianus
Black needlerush
Gulf of Mexico
Wetland
Morphology
Physiology
Management
Colonization
Chlorophyll fluorescence
Transplant

ABSTRACT

Two small-scale Black needlerush (*Juncus roemerianus*) marsh restoration designs were examined for cost-effectiveness by analyzing a suite of morphological and physiological metrics, along with vegetated area over time. The restoration was conducted by harvesting marsh sods from an adjacent natural marsh and planting in the restoration site. Both restoration designs are on suitable scales for private property owners to conduct, but differed in initially planted coverage area. One design was fully planted (100% coverage of planted marsh sods; termed full density design) and the other design was planted at half the density of the fully planted design (50% coverage of planted marsh sods; termed half density design). We found no consistent differences in the measured metrics between the two restoration designs and few differences between restored sites and reference natural marsh stands. These findings suggest the potential similar functionality across all treatments. The only metrics with consistent differences among treatments were increased leaf nutrient and chlorophyll content in the restored plots when compared to natural stands. These differences are potentially attributable to nutrient-rich runoff from an adjacent parking lot to the restoration site. Total vegetated coverage area for half density plots was similar to full density plots at 2.1 years after planting. Cost-effectiveness analysis of both designs across eight differing restoration scenarios (based on hiring or donation of cost categories) resulted in half density plots having higher or equal cost-effectiveness in seven of the eight scenarios. Half density plots were approximately twice as cost-effective in scenarios with donated pre-planting site construction. Based on the similar vegetated area between the two designs and lower cost and restoration effort, we suggest the half density design as a more cost-effective restoration strategy than the full density design and should be considered for small-scale Black needlerush restoration projects.

1. Introduction

Salt marshes are considered integral components of coastal ecosystems. These marshes provide valuable services, such as the provision of food and shelter for many organisms (Beck et al., 2001; Boesch and Turner, 1984; Cai et al., 2000; Phillips, 1987; Turner, 1977), carbon sequestration (Chmura et al., 2003), shoreline stabilization (King and Lester, 1995; Moeller et al., 1996) and filtration of excess nutrients prior to entering coastal waters (Tobias et al., 2001a, 2001b; Valiela and Cole, 2002; Valiela et al., 2000). Regardless of the substantial benefits marshes provide, destruction of coastal wetlands continues at alarming rates. A recent report estimates that 67% of coastal wetlands have been lost to human development in 12 of the world's largest estuaries (Lotze et al., 2006).

Research has suggested the present marsh area may not be able to provide the ecosystem services needed to sustain the well-being of coastal human populations (Bromberg-Gedan et al., 2009). For this reason, marsh restoration is now a ubiquitous practice to mitigate the loss of these important ecosystems, as well as the suite of their associated environmental and economic benefits. There is no unified salt marsh restoration protocol; therefore, different methods are employed (LaSalle, 1996; Lewis, 1982; Turner and Streever, 2002) often leading to inconsistent results. The costly nature of most restoration efforts, coupled with scant knowledge of the effectiveness and success of those efforts, present daunting challenges that hinder the use and application of restoration for coastal environmental management (Chapman and Underwood, 2000).

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0925-8574/$ – see front matter
http://dx.doi.org/10.1016/j.ecoleng.2012.12.053

Many restoration evaluations are estimates based on semi-quantitative appraisals of vegetation survival. Other morphological and physiological plant characteristics, such as density, leaf length, growth rates, and photosynthetic performance are potential useful indicators of restoration success. For instance, comparing these morphological and physiological characteristics between pre-existing and restored plants could be informative of whether the restored plants adjust to the performance of natural marsh plants. Similar performances of restored and natural marsh plants would indicate that the restored marsh might eventually provide similar ecosystems services to the ones provided by the pre-existing marsh (Christensen and Peet, 1984; Keddy, 1999).

Furthermore, most restoration projects are conducted on relatively large tracts of government owned property. However, the majority of coastal property is divided into small privately owned tracts. The techniques and scale of the government funded restorations is typically on scales too large (monetarily and spatially) to be applicable to private property scale restorations. To maximize marsh restoration, techniques for small-scale restorations targeted at individual coastal property owners need to be evaluated to determine which is the most successful and cost-effective.

The most critical aspects of salt marsh restoration are obtaining the correct elevation and substrate (Broome et al., 1988; Turner and Streever, 2002). Elevation and substrate of the restoration site should be similar to that of natural marshes for the highest chance of restoration success. After elevation and substrate are suitable for marsh restoration, several techniques can be used to vegetate the site, such as: natural seeding, sowing seed, planting of seedlings or sod transplantation. All of these techniques are associated with varying costs, effort and time required to obtain target restoration goals. We chose to evaluate different designs of the sod transplantation technique because it is more esthetically pleasing to property owners and provides a quick method to restore areas of marsh.

We focus on Black needlerush (*Juncus roemerianus*) marshes, which are dominant in the northern Gulf of Mexico (GOM) and abundant along the southeastern Atlantic coast (Eleuterius, 1976). Black needlerush marshes, similar to other marsh communities, play many ecologically important roles and have been lost at rapid rates (Turner, 1990). Black needlerush can grow in a variety of environments with contrasting physical and chemical conditions (Lin and Mendelssohn, 2009; Woerner and Hackney, 1997). Due to the predicted increase in atmospheric CO_2, this species' C_3 photosynthetic pathway may represent a competitive advantage over the C_4 pathway (Ainsworth and Long, 2005; Erickson et al., 2007; Lenssen et al., 1993; Rozema et al., 1991). These attributes render these marshes a prime candidate for long-term restoration efforts throughout the GOM and southeastern Atlantic coast. Several efforts to restore these marshes have taken place (LaSalle, 1996; Lewis, 1982; Turner and Streever, 2002), but evaluations of the success and cost-effectiveness of such efforts are rare.

In this study, we present two small-scale restoration designs that differ in cost and effort. Both designs consist of restoring 2.25 m^2 plots of marsh. In one design the plots are fully planted (full density), whereas only 50% of the plot area is planted in the second design (half density). We evaluate the cost and effort required to construct these designs, and use several metrics of plant health to compare restoration effectiveness between designs. Metrics include: shoot size, shoot percent living tissue, leaf nutrient content, leaf growth rates, leaf fluorescence and leaf chlorophyll content. We also monitored the same metrics in ambient marsh stands adjacent to the restored stands to assess how the restored marsh performed in comparison to the natural marsh. This research furthers our understanding of how to use marsh restoration in a cost-effective way to address policies and strategies for the conservation of coastal environmental health.

2. Methods

2.1. Study site and restoration site construction

The study site is located in the southeastern portion of the Grand Bay National Estuarine Research Reserve (GBNERR) in Mississippi, USA (30°24′29′N, 88°24′10′ W). The restoration site borders Bayou Heron and is adjacent to a gravel parking lot with a boat ramp and fishing pier managed by the US Fish and Wildlife Service.

The restoration site was amended to adequate elevation for Black needlerush tolerance (±0.3 m around mean water level). To do this, a 30 m long sediment wedge was constructed on top of an impervious clay layer to raise the bottom at the restored site to the suitable elevation. The wedge was then surrounded with crushed limestone rock for protection. Nine plots (1.5 m × 1.5 m) were sectioned off and subdivided into 25 cm × 25 cm squares for planting of sods. Plots were placed in a randomized block design, consisting of three blocks of three treatments. Treatments were control (no planting), half density (every other square planted), and full density (every square planted; Fig. 1).

Marsh sods were harvested from three natural marsh sites within the GBNERR in close proximity to the restoration site (<2 km). These natural sites were also used for comparison with the restoration site. Sods were harvested in cubes with a side length of 25 cm. We chose this sod size to encompass the rhizosphere of the plants, provide adequate stability once planted while being small enough to transport without heavy machinery. Each harvested sod was collected at a minimum of 3 m from another sod with no more than 30 sods collected from one area. Once 30 sods were collected in one area, we moved 50 m down the shoreline to begin harvesting again. At 1 year after harvest, natural sediment deposition had filled most harvested sod holes in the donor site and revegetation was progressing. We made an effort to ensure the harvested sods could successfully transition to the new conditions of the restoration site. To accomplish this, we left the sods submerged in in situ water for 1 day at mid distance between the collection and restoration sites, and for a second day nearby the restoration site before planting. Marsh construction and planting was completed in April 2006.

2.2. Morphological and physiological metrics

Two months after planting, 15 shoots were randomly tagged in natural stands and within the planted sods at each restored plot. Tags were constructed out of flexible, transparent plastic tubing and flagging tape. As tagged shoots died, new living shoots were tagged to replace them to ensure a consistent sample size. The total length of each leaf, length of living (i.e. green) tissue and number of leaves per shoot were recorded at each sampling period. Growth for each leaf was calculated as the increase in length between consecutive sampling times. The growth of all the leaves on the same shoot was pooled, divided by the number of days elapsed in between the sampling dates, and expressed as mg dry weight (DW) per shoot per day using the mean length-specific weight (i.e. mg DW per cm of leaf) for the sample.

We used a pulsed amplitude modulation (PAM) fluorometer (Walz Mini-PAM) to measure the chlorophyll fluorescence yield for a subset of 10 tagged leaves seasonally in each plot. The leaves used for PAM measurements consisted of mostly green (living) tissue. To obtain the measurements, a wand was fashioned and used according to the methodology of Biber (2012) and slipped over the tagged leaf. We only measured chlorophyll fluorescence yield at one of the ports described in Biber (2012) (23 cm above the sediment surface). The timeframe for PAM measurements was typically between 0700 and 1200 h (CST), with the exact time for each measurement

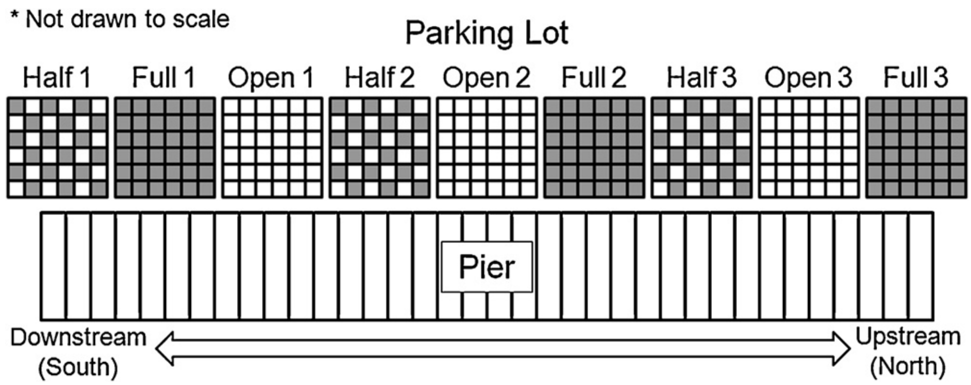

Fig. 1. Schematic of marsh construction layout with blocks 1, 2, and 3 proceeding from left (South) to right (North). Each block consist of a half density, full density and open treatment. Planted sods are indicated by shaded squares.

recorded. Ambient light conditions were measured during PAM measurements using a LI-COR (LI-192 cosine quantum sensor and LI-1000 data logger). Most PAM measurements were conducted on sunny days.

Furthermore on each sampling date, three green leaves were harvested from both the upper and lower sides of each restored plot as well as three green leaves from each of the three natural stands for carbon and nitrogen content (CN) as well as chlorophyll analyses. The section of the leaf that corresponds to the PAM measurement port (23 cm from sediment surface) was removed and kept for chlorophyll analysis. The basal portion of the clipped leaf was kept for CN analysis. Leaf clippings were kept on ice in the field and samples for chlorophyll analysis promptly frozen upon return to the lab. Samples for CN analysis were dried, ground then analyzed using a Costech ECS 410 CHNSO Analyzer. Samples for chlorophyll analysis were ground with a ceramic mortar and pestle using 90% acetone as a solvent and dried sand (250–500 μm grain size) as a grinding agent. The samples were rinsed into a plastic centrifuge tube and total volume of solvent recorded. After extraction overnight at 4 °C, the samples were centrifuged at 1500 rpm for 10 min before reading the absorbance of the sample. For reading, the solute was transferred to a 1 cm quartz cuvette and the absorbance at 664 nm and 647 nm read on a dual beam spectrophotometer (Shimadzu Pharmaspec UV-1700) referenced against 90% acetone. Absorbance values were converted to concentrations using the dichromatic equations of Jeffrey and Humphrey (1975). For each sampling round, all morphological, growth and physiological measurements were conducted during a 2–3 day interval to ensure environmental conditions remained similar.

2.3. Colonization patterns

Seasonally we counted the total number of new shoots that had appeared on the outward side of each of the bordering 25 cm × 25 cm squares in the plot. We stopped these counts whenever one of the outer squares in any of the plots reached 50 shoots, because at that point it was no longer possible to distinguish the plot the shoots originated from (i.e. shoots protruding outward from neighboring plots started to coalesce). This limit was reached approximately 1.5 years since planting. We also randomly selected and monitored five non-planted squares within each half-density plot and counted the number of shoots present in the square on each visit.

Counts were transformed into square meters of vegetated area using the mean shoot density of the initially planted sods (i.e. 45 shoots per planted square or 720 shoots per square meter). Colonization rates were expressed as m^2 of vegetated area gained as the plot expanded outwards ("periphery colonization") or inwards onto the non-planted squares ("interior colonization," calculated only for half-density plots). We also expressed interior colonization as the percent of initially unplanted plot area (i.e. 1.125 m^2) filled with vegetation. Total marsh area per plot was calculated as the sum of the marsh area initially planted (2.25 m^2 per full density plot and 1.125 m^2 per half density plot) and the new marsh area gained through periphery (both full and half density plots) and interior (only half density plots) colonization.

2.4. Cost-effectiveness

To assess the effectiveness of our restoration designs, we primarily used the area of total marsh per plot of the two designs 2.1 years since planting. We divided the cost of the plots in three categories: (1) pre-planting site construction, (2) personnel for harvesting and planting, and (3) boat usage for transportation of personnel and marsh sods. We paid 13,500 USD ($) to an environmental restoration company for the purchase, transportation, dumping and leveling of the sediment fill and crushed limestone around the sediment. Therefore, the construction cost per plot can be estimated as $1500 (i.e. $13,500 divided by the 9 plots fitted in the restored area). Non-planted areas were left between plots (see Section 2.1). We made no effort to assign a construction cost to those areas since most restoration efforts leave such areas around the newly planted marsh to allow for future growth and expansion. A total of 35.3 personnel hours were required for the transportation and planting of sods necessary to complete one full-density plot, and a total of 17.7 personnel hours to complete a half-density plot. We converted personnel-hours into dollars using an estimate of local wages typical for this type of work (i.e. $15 personnel hour^{-1}, with $13 being base wage and $2 being benefits). Finally, approximately 2 full days of boat time (i.e. assuming 8 working hours per day) per full density plot and 1 full day per half density plot of boat use was needed to transport (i.e. including the acclimation efforts, see above) the sods. Boat usage time was converted into dollars using standard boat rental fees (i.e. $150 day^{-1}, this fee typically includes captain and gas). Restoration costs are often covered in part with donations obtained from other sources. Therefore, we built different cost-effectiveness scenarios where the three cost categories are hired or donated.

2.5. Statistical analyses

We used two way repeated measures ANOVA (RMANOVA) to examine marsh morphological and physiological differences among treatments (full-density, half-density and natural) through

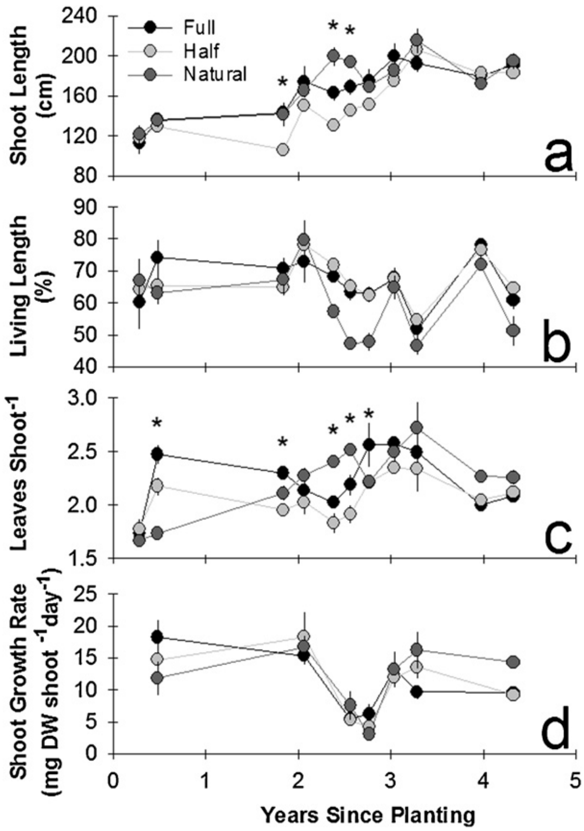

Fig. 2. Measured morphological and physiological variables through time for full density, half density and natural shoots. Variables include (a) shoot length, (b) percentage living tissue length, (c) number of leaves per shoot and (d) shoot growth rate. Asterisk (*) indicates a date with significant differences between treatments as indicated by Tukey tests. Each tick mark on the *x*-axis (years since planting) corresponds to April of the respective year. Error bars indicate ±1 SE.

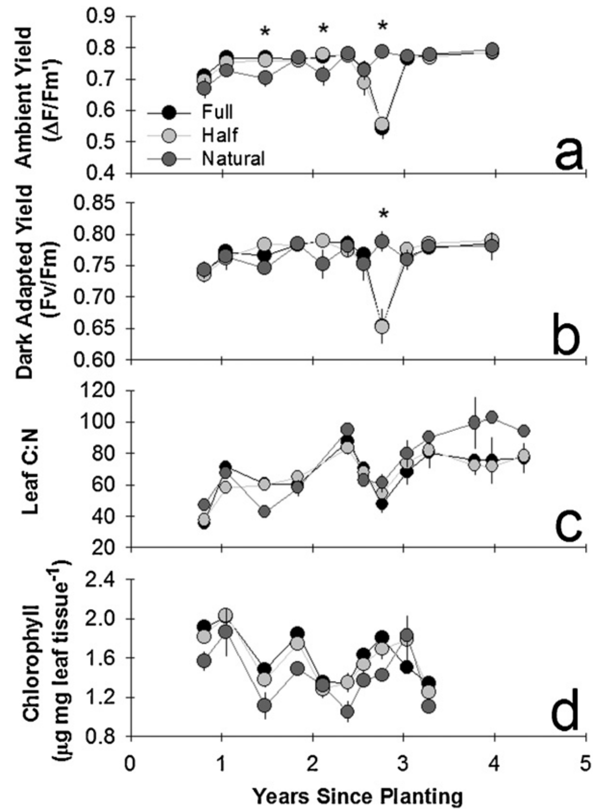

Fig. 3. Measured morphological and physiological variables through time for full density, half density and natural treatments. Variables include (a) ambient chlorophyll fluorescence yield, (b) dark adapted chlorophyll fluorescence yield, (c) leaf tissue C:N and (d) chlorophyll concentration. Asterisks (*) indicate a date with significant Tukey test differences between treatments. Error bars indicate ±1 SE.

time because we repeatedly sampled the same plots and, frequently, the same shoots (Quinn and Keough, 2002). If a significant interaction between treatment and time occurred, pairwise post hoc Tukey tests between treatments were run separately for each sampling date. If the interaction term was not significant, all sampling dates were pooled together for Tukey tests. Chlorophyll concentrations and C:N did not differ ($p > 0.05$) by location within the plot (top or bottom); thus, samples from each plot were pooled together yielding one value per plot. Colonization pattern models were adjusted with least-square regression and used to project future coverage. Significant values were considered at $p \leq 0.05$.

3. Results

3.1. Morphological and physiological metrics

Black needlerush colonization did not occur in control (i.e. non-planted) plots, thus, from here on, we focus on the full density plots, half density plots and natural marsh stands. Significant differences in shoot length among treatments were only found in three out of the eleven sampling dates during our monitoring period (significant time × treatment interaction). Those differences, however, were not consistent (Fig. 2a). Close to completion of the second year after planting we found higher lengths at the natural stands (N) and full density plots (F) than at the half density (H) plots (1.8 years since planting; $N = F > H$). On one date during the third year since planting (2.4 years since planting) we found shoot lengths to decrease from natural stands to full density plots to half density plots ($N > F > H$). On a second date during the third year since planting (2.6 years since planting) we found higher shoot lengths at the natural stands than at half density plots ($N > H$). We found no significant differences among treatments from approximately 2.5 years since planting to the end of our monitoring period (4.3 years since planting). Despite some transient differences in shoot length among treatments, we did not find any significant differences in percentage living (green) tissue in the shoots between treatments throughout our monitoring period (Fig. 2b; main treatment effect, $p > 0.05$; interaction time × treatment, $p > 0.05$).

Differences in number of leaves per shoot among treatments were found on five sampling dates (significant time × treatment interaction). The differences were inconsistent among dates (Fig. 2c); on one date (0.5 years since planting) we found more leaves per shoot in the full and half density plots than in natural stands ($F = H > N$). On two other dates (1.8 and 2.8 years since planting) we found more leaves per shoot in full density plots than in half density plots, but no significant differences between restored plots and natural stands ($F > H$, $F = N$, $H = N$). Furthermore, we found more leaves per shoot in natural stands than in full and half density plots ($N > F = H$) on two other dates (2.4 and 2.6 years since planting), although the differences between natural stands and half density plots were only marginal ($p = 0.07$) for one of those dates. We did not find any significant differences among treatments over the final 1.3 years of the monitoring period. Leaf growth rates did not differ among treatments throughout our monitoring period (Fig. 2d; main treatment effect, $p > 0.05$; interaction time × treatment, $p > 0.05$).

We found some transient differences in ambient chlorophyll fluorescence yield among treatments (Fig. 3a, significant

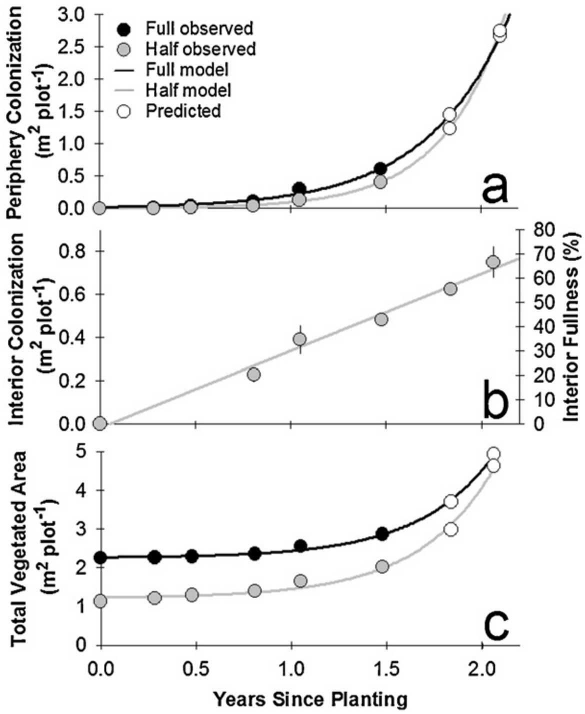

Fig. 4. Colonization patterns in full and half density plots through 2.1 years since planting. Panels represent (a) periphery colonization, (b) interior colonization for half density plots and (c) total vegetated area. Values after 1.5 years since planting for periphery colonization correspond to model predictions depicted in white circles. Values for total vegetated area have been calculated as the sum of the initially planted area plus the area gained through periphery colonization (using mean values measured through 1.5 years since planting and predicted values thereafter) plus the area gained through interior colonization (only for half density plots using the mean values measured through 2.1 years since planting). Lines depict the fitted model. Error bars on mean measured values indicate ±1 SE.

time × treatment interaction). On one date within the second year of monitoring (1.5 years since planting) leaves at the full density plots displayed higher yields than at the natural stands ($F > N$). During the third year of monitoring, we found higher yields in half-density plots than in natural stands on one date (2.1 years since planting; $H > N$), and higher yields in natural stands than in half and full density plots ($N > F = H$) on another date (2.8 years since planting). This last date was the only instance where we found significant differences in dark-adapted chlorophyll fluorescence yield among treatments throughout our monitoring period (Fig. 3b, significant time × treatment interaction), which coincided with the differences found in ambient yield ($N > F = H$). Leaf carbon to nitrogen ratio (C:N; Fig. 3c) and chlorophyll content (Fig. 3d) varied among treatments. Those aforementioned differences persisted rather consistently throughout the monitoring period (Fig. 3c and d, main treatment effect, $p < 0.05$; interaction time × treatment, $p > 0.05$ for both metrics). Namely, leaves in natural stands tended to have higher C:N (driven by lower N content) and lower chlorophyll content than leaves in the restored plots ($N > F = H$ for C:N; $N < F = H$ for chlorophyll content), although the differences in chlorophyll content between natural stands and half-density plots were only marginally significant ($p = 0.06$).

3.2. Colonization patterns

Full density plots showed more periphery colonization than half density plots, over the duration of the measurements (Fig. 4a). These results were expected because full density plots had twice the number of planted sods along each side of the plot than half density plots. However, model projections to 2.1 years since planting indicate half and full-density plots reach similar levels of periphery vegetated area (2.75 and 2.67 m^2, respectively). The adjusted models are $y = 0.020e^{(2.335x)}$, $R^2 = 0.975$ for periphery colonization in full density plots and $y = 0.004e^{(3.065x)}$, $R^2 = 0.994$ for periphery colonization in half density plots, where y = vegetated area increase per plot (m^2 per plot) and x = years since planting (Fig. 4a). Interior colonization in half-density plots (i.e. colonization of non-planted squares) increased linearly with time since planting (model fit of $y = 0.357x - 0.019$, $R^2 = 0.985$; Fig. 4b). At 2.1 years since planting, half density plots had produced on average 0.75 m^2 of newly vegetated area within the plots (i.e. on initially non-planted squares), which corresponds to approximately 66% of the initially non-planted area (1.125 m^2) within half-density plots. If the model is projected, half density plots would be fully covered with Black needlerush approximately 3.2 years since planting. By 2.1 years since planting, the combination of interior and periphery colonization in half density plots nearly compensated for their reduced initial planting density in relation to full density plots. The model fits for total vegetated area (full density $y = 0.014e^{(2.538x)} + 2.252$, $R^2 = 0.997$; half density $y = 0.018e^{(2.529x)} + 1.219$, $R^2 = 0.991$) yielded an average half density plot attaining 4.62 m^2 of vegetated marsh and full density plot attaining 4.92 m^2, 2.1 years since planting (Fig. 4c).

3.3. Cost-effectiveness analyses

The half density design is more cost-effective (i.e. less $ per m^2 of vegetated area) than the full density design regardless of whether costs are hired or donated except when both personnel and boat costs are donated (Table 1). When the site construction is donated, the half density design is twice as cost-effective as the full density design regardless of whether the other costs are hired or donated (Table 1).

4. Discussion

Our study is the first to the best of our knowledge to evaluate plant performance and cost-effectiveness of multiple Black needlerush restoration designs on scales (monetarily and spatially) suitable for private property owners to conduct. Interestingly, we found no consistent differences for any measured morphological and physiological metric between the two restoration designs. This suggests plants in half- and full-planted plots had similar attributes and, possibly, similar functionality (Ehrenfeld, 2000; Hilderbrand et al., 2005). The only metrics that differed between restored plots and natural stands was C:N (lower in restored plots) and leaf chlorophyll concentration (higher in restored plots), although those differences were not substantial. Lower C:N values in the restoration site were due to higher N content, since C contents did not differ between that site and the natural stands. The restoration site borders a gravel parking lot heavily used by recreational fishermen and boaters, and runoff from the parking lot often pours into the restored marsh. This could account for the higher N contents, and thus lower C:N, found in plants growing in the restoration site in relation to plants growing in the natural stands. Higher nitrogen availability could perhaps allow for higher leaf chlorophyll concentrations, since one of the primary building blocks for chlorophyll is nitrogen.

Higher rates of outward expansion observed in half density plots (on a per planted unit basis) is likely due to reduced resource competition among expanding shoots. Based on the initial planting densities and designs the surface area of surrounding bare sediment available for expansion relative to the amount of bordering

Table 1
Cost-effectiveness analysis for average full and half density plot at 2.1 years post-planting.

Cost category	Scenario							
Personnel (harvesting and planting)	Hired	Donated	Hired	Donated	Hired	Donated	Hired	Donated
Boat (harvested planting unit transport)	Hired	Hired	Donated	Donated	Hired	Hired	Donated	Donated
Pre-planting site construction	Hired	Hired	Hired	Hired	Donated	Donated	Donated	Donated
Full density cost ($)	$2330	$1800	$2030	$1500	$830	$300	$530	$0
Half density cost ($)	$1915	$1650	$1765	$1500	$415	$150	$265	$0
Full density vegetated area (m^2)	4.92	4.92	4.92	4.92	4.92	4.92	4.92	4.92
Half density vegetated area (m^2)	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62
Full density cost-effectiveness ($\$ m^{-2}$)	$474	$366	$413	$305	$169	$61	$108	$0
Half density cost-effectiveness ($\$ m^{-2}$)	$415	$357	$382	$325	$90	$32	$57	$0

shoots (i.e. shoots along the plot sides) is 2-fold higher for half- than for full-density plots. Thus, we would expect less competition for light and nutrients among expanding rhizomes in half- than in full-density plots, and thus higher colonization rates for the former until the two kinds of plots reach similar shoot densities along their edges. When combining interior and periphery colonization, half density plots nearly compensate for half the initial planting density to obtain similar total vegetated area as full density plots (4.62 m^2 for half density and 4.92 m^2 for full density).

Our cost-effectiveness analysis ($ per m^2 of vegetated area at 2.1 years since planting) shows the half density design is more cost-effective than the full density design in seven of eight scenarios evaluated. The degree of increased cost-effectiveness in the half density design is highly dependent on whether the cost of the planting site construction was hired or donated. The half density design is slightly more cost-effective than the full density design when the construction cost is hired in all but one scenario (i.e. when both the costs of personnel and boat usage are donated), and when the construction cost is donated the half density design is nearly twice as cost-effective as the full density design. Construction of the planting site is the most costly aspect in our restoration work. In addition, the cost of the planting site is identical for full and half density plots, whereas the cost of the other efforts (personnel and boat usage) is less for half than for full density plots. Consequently, whether the cost of the site construction is hired or donated has an important bearing on the magnitude of elevated cost-effectiveness in half density plots than full density plots. These results could be applicable to other locations where the planting site has to be constructed before the actual planting occurs, since construction costs are usually higher than any other costs in restoration efforts (LaSalle, 1996; Lewis, 1982; Turner and Streever, 2002; Vittor et al., 1987). If a planting site were already adequate for Black needlerush planting, restoring the site with the half density design would be much more cost-effective than the full density design.

We could not extend our cost-effectiveness analyses beyond 2.1 years since planting because we inevitably trampled some areas in the plots while doing other experiments and could not continue our measurements of interior colonization. However, if we had continued our measurements to the time where the total vegetated area of full and half density plots had been virtually identical (a result expected based on the colonization trajectories observed), our conclusions regarding our cost-effectiveness analyses would have remained qualitatively unaltered.

We recognize the use and application of our restoration designs and recommendations obtained from the cost-effectiveness analysis may be limited because our approach of marsh sod transportation is labor intensive and sometimes unfeasible. Indeed, many restoration practitioners have chosen to utilize techniques other than sod transplantation from donor marshes (Bergen et al., 2000), such as natural seeding, sowing of seed and planting of seedlings.

Natural seeding has no associated cost; however, there must be an adequate seed bank present for this technique to be feasible. Sowing purchased seed is slightly more expensive than natural seeding because of the minimal effort required and low cost of seed. Planting of seedlings and transplantation of sods would be the most expensive options. Seedlings are typically purchased from nurseries with cost varying depending upon plant species and location. Sod transplantation is more labor intensive than the aforementioned techniques and can be difficult when donor sites are not in close proximity to the restoration site and/or permits for sod harvest are difficult to acquire.

The use of these other techniques can theoretically be less costly than sod transplantation, however, they come with disadvantages, such as decreased plant resiliency, high mortality and longer time spans to achieve target vegetated coverage area. Sod transplantation is the only technique that brings a well-established rhizosphere to the restoration site; thereby increasing resiliency and stabilizing the plants. Marsh plant rhizospheres trap and store nutrients from degrading organic matter (Teal et al., 1979; Valiela et al., 1978). These nutrients help plants grow and withstand periods of unfavorable conditions as well as anchoring the plants into the sediment. Consequently, uprooting of plants by waves and currents is more prevalent when using techniques other than sod transplantation. Decreased resiliency and increased uprooting leads to higher mortality for non-sod transplantation techniques. Time necessary to achieve a target vegetated coverage area would be longer for the non-sod transplantation techniques due to the time necessary for seeds and seedlings to grow and stabilize the site with their rhizosphere.

Since site construction comprises the majority of cost for a restoration project (ex. 64% for full density and 78% for half density in our project), we consider the marginal increase in cost required for the sod transplantation technique to be warranted because of the benefits it has over other techniques, particularly the half density design. However, when minimal site construction is necessary and esthetics are not a concern for the property owner, other techniques could potentially be more cost-effective if the seeds or seedlings establish quickly. Extending our cost-effectiveness analysis to more designs varying in technique used, initial planting density, effort, monetary cost and plant species would make our conclusions more globally appealing and useful to restoration practitioners with a need to maximize the impact of their efforts given budget and other limitations.

5. Conclusion

In summary, we used a suite of morphological and physiological metrics, along with vegetated area, to examine the cost-effectiveness of two private property scale restoration designs for Black needlerush, one involving 100% planted density plots and the other involving 50% planted density plots. We did not find any consistent differences in the metrics measured between the two types of plots, suggesting similar functionality. Interestingly, the restored plots had higher leaf nutrient and chlorophyll contents than reference natural stands, possibly due to nutrient-rich runoff from an adjacent parking lot. Half density plots had almost reached the total vegetated cover of full density plots by 2.1 years since planting, in part due to greater expansion rates into the bare surroundings of the plots. When total vegetated area at 2.1 years since planting is combined with the lower cost and effort required for the half density design, half density plots were overall more cost-effective than full density plots. This is particularly so if the cost of site construction can be waived or avoided, because the cost of site construction is higher than all other costs and similar for full and half-density plots. Based on our findings we recommend that, if using sods from donor sites to restore small-scale marshes, planting the sods at 50% density is a more cost-effective strategy than planting the sods at 100% density, particularly if an area adequate for Black needlerush exists already and the planting site does not need to be constructed. Future research including additional restoration techniques (i.e. seed, seedlings or sod), designs (i.e. wider range of initial planting cover) and plant species could supplement recommendations of best restoration practices under varying needs and budget constraints scenarios.

Acknowledgments

The U.S. Department of Commerce's National Oceanic and Atmospheric Administration under NOAA Award NA10OAR4170078, the Mississippi-Alabama Sea Grant Consortium (Project number R/CEH-24), the Grand Bay NERR and the Dauphin Island Sea Lab financially supported this work. The Grand Bay NERR and Dauphin Island Sea Lab also provided vehicle and boat transportation as well as additional field and lab support. The Gulf Coast Research Laboratory also provided field support. The views expressed herein do not necessarily reflect the views of any of those organizations.

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