Ecological Engineering 42 (2012) 54–63

Contents lists available at SciVerse ScienceDirect

Ecological Engineering

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

Marsh construction techniques influence net plant carbon capture by emergent and submerged vegetation in a brackish marsh in the northwestern Gulf of Mexico

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ARTICLE INFO

Article history:
Received 26 July 2011
Received in revised form 12 January 2012
Accepted 1 February 2012
Available online 3 March 2012

Keywords:
Carbon storage and sequestration
Constructed marsh
Restoration
Net annual primary production
Net annual plant carbon capture
Gulf of Mexico

ABSTRACT

Coastal marshes play an important role in global carbon cycles, yet coastal development has led to widespread losses of marsh habitat. To address this problem, many coastal wetlands have been restored or created over the past several decades using a variety of construction techniques, but it is unclear if net plant carbon capture in constructed marshes is equal to that of reference marshes, or if rates of plant carbon capture are influenced by marsh construction techniques. To comparatively assess relative carbon capture by emergent and submerged vegetation in constructed and reference marshes, we measured standing biomass and carbon content in above- and belowground emergent plant tissue and submerged vegetation in three constructed areas (2–3 years old) and one reference area in a brackish marsh in the northwestern Gulf of Mexico in 2009 and 2010. We also used aerial photographs to construct a GIS database of emergent and submerged vegetation coverage. These data were combined to estimate net annual plant carbon capture per square meter of marsh vegetation in each constructed and reference area. This index of carbon input to wetland vegetation suggests that rates of carbon capture by emergent aboveground vegetation and submerged aquatic vegetation were similar in constructed and reference areas. However, submerged vegetation captured less carbon (0.1–0.3 kg m^{-2}) than emergent vegetation (0.2–1.7 kg m^{-2}), and constructed areas contained an order of magnitude less emergent habitat than the reference area. Consequently, the annual carbon production of entire constructed areas (emergent + submerged vegetation; 0.1–1.2 kg m^{-2}) was always less than half that of the reference area (0.8–2.5 kg m^{-2}). Therefore, although productivity of emergent and submerged vegetation in constructed and reference areas was similar, the smaller ratio of land to water in the constructed areas reduced their annual rate of plant carbon capture at a larger spatial scale. To more closely mimic rates of plant carbon capture in reference marsh habitats, constructed marsh designs should aim to replicate the ratio of land to water in adjacent reference marshes.

1. Introduction

Coastal marshes are one of the most productive ecosystems on the planet (Brevik and Homburg, 2004; Dawes, 1998) and sequester large quantities of organic carbon (~41 Tg/year; Chmura et al., 2003). Unlike freshwater inland wetlands (e.g., bogs and peatlands), saline coastal marshes generally have relatively low emissions of the potent greenhouse gas methane (Bartlett et al., 1987; Bartlett and Harris, 1993; Brevik and Homburg, 2004; Chmura et al., 2003; Connor et al., 2001; Ding et al., 2003; Pearce and Clymo, 2001; Thom et al., 2002; Poffenbarger et al., 2011). Coastal marshes thus play a vital role in the global carbon cycle (Chmura et al., 2003; Mitra et al., 2005; Sahagian and Melack, 1988), yet coastal development is causing an alarming rate of worldwide wetland loss. In the United States alone, an average of 160 acres of wetlands was lost every day between 1986 and 1997 (US Department of Agriculture, 2000a,b).

Wetland habitat loss is often mitigated through the restoration of degraded wetlands or the construction of new wetlands. In coastal areas of the Gulf of Mexico, constructed salt marshes are usually built from existing benthic sediments or dredge material that is shaped into mounds or terraces and surrounded by shallow water habitat (Costa-Pierce and Weinstein, 2002; Edwards and Proffitt, 2003; Streever, 2000; Turner and Streever, 2002). Coastal marsh restoration and construction projects are often considered

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doi:10.1016/j.ecoleng.2012.02.001

successful if their emergent vegetation can meet benchmark levels of vegetation coverage and biomass production within a given period of time (Ainslie, 1994; Kentula, 2002). When threshold levels of plant coverage are achieved, it is often assumed that the ecological function and productivity of the constructed marsh is equal to that of reference marsh areas (Adamus et al., 1991; Ainslie, 1994; Edwards and Mills, 2005; Edwards and Proffitt, 2003; Short et al., 2000; Streever, 2000). A large body of literature has explored the merits of these assumptions; the majority of studies have focused on ecosystem functions like food web support and nutrient cycling (Craft et al., 2003; Streever, 2000; Thayer and Kentula, 2005; Zedler, 2000a,b; Zedler and Callaway, 1999). More recently, the standing carbon stock and carbon sequestration potential of restored and constructed coastal marsh habitats has received more attention (e.g., Irving et al., 2011; Miller and Fujii, 2010) because constructed coastal marshes that do not replicate the important carbon storage properties of reference marshes will ultimately contribute to the loss of an important global sink of organic carbon.

Given their capacity to sequester carbon, many researchers have explored the possibility of using coastal marshes as a natural means of carbon capture and storage (Connor et al., 2001; Dixon and Krankina, 1995; Irving et al., 2011; Miller et al., 2008; Miller and Fujii, 2010; Pelley, 2008; Santin et al., 2009; Shafer and Streever, 2000; Thom et al., 2002). Analyses of plant carbon capture in constructed marshes to date indicate that they generally contain less organic carbon than reference marsh habitats (Santin et al., 2009; Shafer and Streever, 2000) and that their construction would need to achieve an industrial scale to significantly impact global levels of atmospheric carbon (Irving et al., 2011). While newly constructed coastal marsh habitats may never attain the sequestered carbon stocks of reference marshes that are thousands of years old, it should be possible to construct marshes with annual rates of net plant carbon capture that are equivalent to reference marshes. To meet this goal, it is necessary to gain a better understanding of how marsh construction design influences plant carbon capture in constructed marshes.

A basic assumption about carbon storage in constructed wetlands is that carbon will become sequestered in the soil when carbon inputs exceed carbon loss. Levels of standing carbon and rates of net annual plant carbon capture in constructed marshes should thus be equal to or greater than reference areas in order to have equivalent rates of carbon sequestration. While many investigations have examined primary productivity of emergent vegetation in constructed, restored, and reference marshes, these comparisons typically occur among marshes at different sites or of different ages (e.g., Craft et al., 2003; Dai and Wiegert, 1996; Delaney et al., 2000; Edwards and Proffitt, 2003; Miller and Fujii, 2010; Short et al., 2000; Streever, 2000; Thayer and Kentula, 2005; Zedler, 2000a; Zedler and Callaway, 1999). Furthermore, to our knowledge, there have been no previous attempts to combine measures of emergent and submerged vegetation cover in constructed habitats in order to assess annual plant carbon capture at a landscape scale that integrates both emergent and subtidal habitats.

To explore how constructed marsh design may influence landscape-level rates of plant carbon capture by emergent and submerged vegetation, we measured biomass, carbon content, and vegetation coverage in constructed and reference areas of a brackish marsh in the northwestern Gulf of Mexico. Rather than quantifying absolute carbon capture by measuring carbon movement into recalcitrant, "captured" form, our approach provided a relative index of carbon input that could be compared among constructed wetlands that varied in structural design. All constructed areas in our study were engineered to contain circular mounds, but they varied in soil source and surrounding water depth. Our goals were to identify which construction techniques were associated with the highest rates of primary production and plant carbon capture, and to compare how all constructed areas performed relative to an adjoining reference area.

Table 1
Soil characteristics of constructed (excavated, filled, pumped) and reference marshes in June 2009 and September 2010.

	Excavated	Filled	Pumped	Reference
% Organic carbon				
2009	4.2 ± 0.8	3.4 ± 0.4	1.2 ± 0.1	6.1 ± 0.8
2010	4.1 ± 0.7	4.3 ± 1.0	2.3 ± 0.4	5.6 ± 0.8
% Inorganic carbon				
2009	<0.1	<0.1	<0.1	0.2 ± 0.1
2010	0.1 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1
% Nitrogen				
2009	0.28 ± 0.05	0.22 ± 0.02	0.11 ± 0.01	0.42 ± 0.05
2010	0.24 ± 0.05	0.25 ± 0.06	0.15 ± 0.03	0.36 ± 0.05
% Phosphorus				
2009	0.016 ± 0.002	0.021 ± 0.002	0.024 ± 0.002	0.034 ± 0.004
2010	0.018 ± 0.004	0.019 ± 0.003	0.023 ± 0.002	0.040 ± 0.002
% Sand				
2009	47.1 ± 6.5	45.9 ± 2.9	31.3 ± 2.9	58.6 ± 5.2
2010	23.4 ± 6.0	39.1 ± 4.7	24.9 ± 2.6	48.4 ± 5.2

2. Materials and methods

2.1. Study site and marsh construction

Constructed marshes were built in fall (September–November) 2007 in the Old River Unit of the Lower Neches Wildlife Management Area (N30°00.228′, W93°51.539′) near Port Arthur, TX, USA (Fig. 1). Three different construction techniques, termed excavated mounds (Fig. 2A), filled mounds (Fig. 2B), and pumped mounds (Fig. 2C), were used to create emergent marsh habitat within terraced containment areas (Fig. 1). Excavated mounds were formed from material excavated from adjacent bottom sediment that was shaped into circular mounds with an emergent area of ~27 m^2/mound that were spaced approximately 12 m apart (Figs. 2A and 3A). Filled mounds were created by filling submerged areas surrounding excavated mounds with dredge material pumped directly from a nearby industrial canal (Figs. 2B and 3B). Filled mounds had an area of ~13 m^2/mound and were spaced ~22 m apart. Pumped mounds were created by mixing soil from an upland dredge disposal site with water and then pumping the slurry into the restoration area (Figs. 2C and 3C). The slurry was pumped directly onto existing benthic sediments to create circular mounds with an average emergent area of ~23 m^2/mound that were spaced ~14 m apart. The upland site used to create the slurry was 1.3 km to the southwest of the restoration area (Fig. 1C), and had been built from dredge spoil during periodic canal maintenance events between ca. 1980–2007. The final depth of the water surrounding filled and pumped mounds (~0.2 m) was less than around excavated mounds (~1.0 m; Fig. 2A–C). Tidal exchange occurred through multiple culverts into the area, such that all constructed and reference marsh areas experienced similar inundation frequencies and had water salinities that ranged from 1 to 6 ppt for most of the study period. Soil characteristics were similar among all constructed mound types; soils in the reference area were sandier and had higher organic and inorganic carbon, nitrogen, and phosphorus content (Table 1).

Following marsh construction, mounds were planted with *Spartina alterniflora* cv. Vermilion, a naturally occurring ecotype isolated by the Natural Resources Conservation Service that has been used extensively in marsh restoration in the northern Gulf

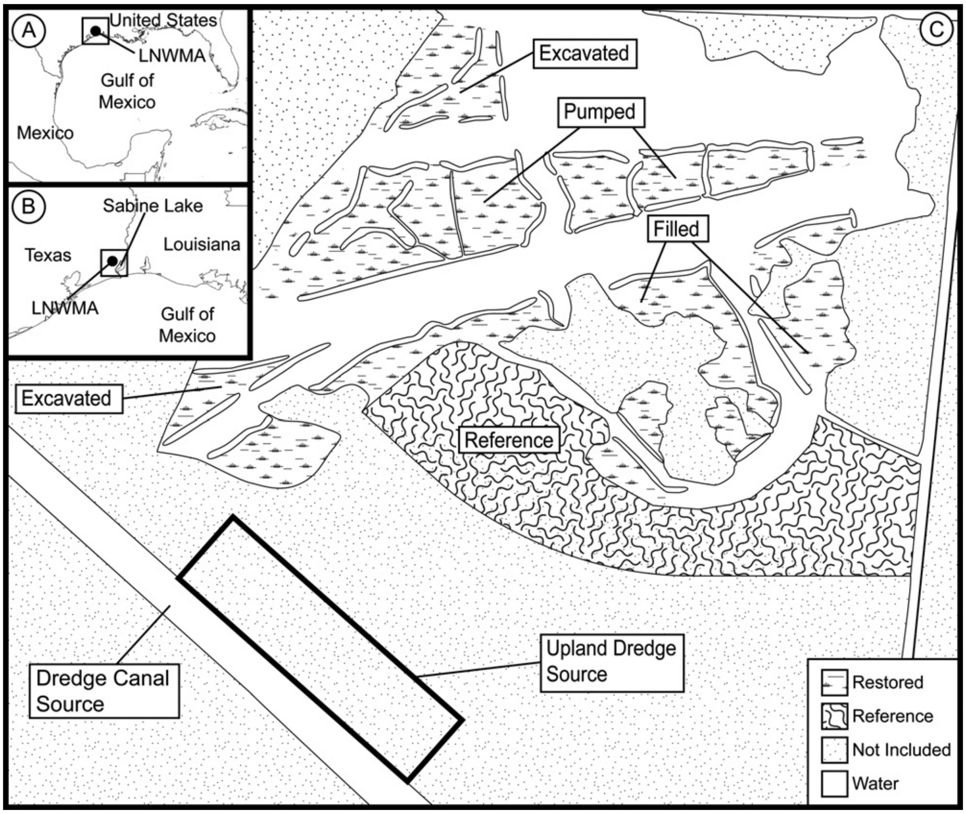

Fig. 1. The Lower Neches River Wildlife Management Area (LNWMA) is in the northwestern Gulf of Mexico (A) on the shore of Sabine Lake (B). The box in panel A surrounds the area depicted in panel B, and the area pictured in panel C is from a portion of the area surrounded by the box in panel B. Constructed and reference marsh areas in the LNWMA are indicated with shading; treatments and dredge sources are labeled. Containment terraces were built around each constructed area to protect the mounds from erosion.

of Mexico (USDA, 2000). Emergent habitat in the reference area primarily contained *S. alterniflora* and *Spartina patens*, along with small quantities of *Schoenoplectus robustus* and *Schoenoplectus californicus* (Fig. A.1). Submerged plant species in the reference and restored area included *Myriophyllum spicatum*, *Ruppia maritima*, and mats of green algae (primarily *Cladophora* sp. and *Spirogyra* sp.) (Fig. A.2).

Including submerged and emergent areas, a total of 0.45 km^2 of marsh habitat was built. The compartment containing excavated mounds (emergent + submerged areas) was 0.05 km^2, the compartment containing pumped mounds was 0.08 km^2, and the compartment containing filled mounds was 0.07 km^2 (Fig. 1C). The remaining constructed marsh areas that were not included in this study were built with a combination of these construction techniques. We established ten sampling stations at random locations in each of the excavated, filled, and pumped mound areas and in comparable reference habitat (Fig. 1C).

2.2. GIS calculations

We calculated the size of emergent and submerged areas in constructed and reference marshes with DeLorme XMap 7 GIS software (Yarmouth, ME). Base maps of the restoration area were constructed in a Geographic Information System (GIS) database from georeferenced aerial photographs of the study site taken on December 6, 2007, October 8, 2008, August 31, 2009, and August 5, 2010 (Fig. 3). The edges of mounds and shorelines were manually traced in each photograph to create vector format layers of emergent vegetation in constructed and reference areas. The outermost boundaries of each restoration area (where they made contact with surrounding terraces) and the comparable intertidal portion of the reference area were also traced to create a vector layer of total emergent + submerged vegetation in each constructed (excavated, filled, or pumped) and reference area. The difference between the emergent (land) and the total area (land + water) of each constructed and reference area was the submerged area (water).

2.3. Plant sampling

All aboveground emergent plant tissue was harvested quarterly (April, June, September, January) from 10 cm × 20 cm (0.02 m^2) quadrats at each monitoring station from April 2009 through January 2011. Live and dead tissue was pooled and transported to the laboratory where it was rinsed, separated by species, dried at 70 °C to a constant weight, and weighed to determine biomass (kg m^{-2}). The standing biomass of emergent aboveground vegetation (SB_{EAG}) at each monitoring station was the sum of live and dead plant biomass for all plant species.

Subsamples of dried plant tissue from each species were ground with a Thomas Scientific (Swedesboro, NJ) model 3383-L10 Wiley mini-mill and analyzed for carbon (C) content with a Perkin Elmer (Waltham, Massachusetts, USA) series II CHNS/O analyzer. *S. alterniflora* leaf %C content was measured at every sampling event, but the average leaf %C content changed <0.5% among all constructed and reference areas from April 2009 to January 2011. Since this temporal and spatial deviation was so small, the average %C content of all measurements (42.11 ± 0.20; N = 347) was used in further calculations of standing carbon for *S. alterniflora*.

Measurements of %C were not obtained at every sampling event for the other plant species included in this investigation. However, we assumed that their %C content also changed little over time. %C content was thus determined from the average of ten replicate

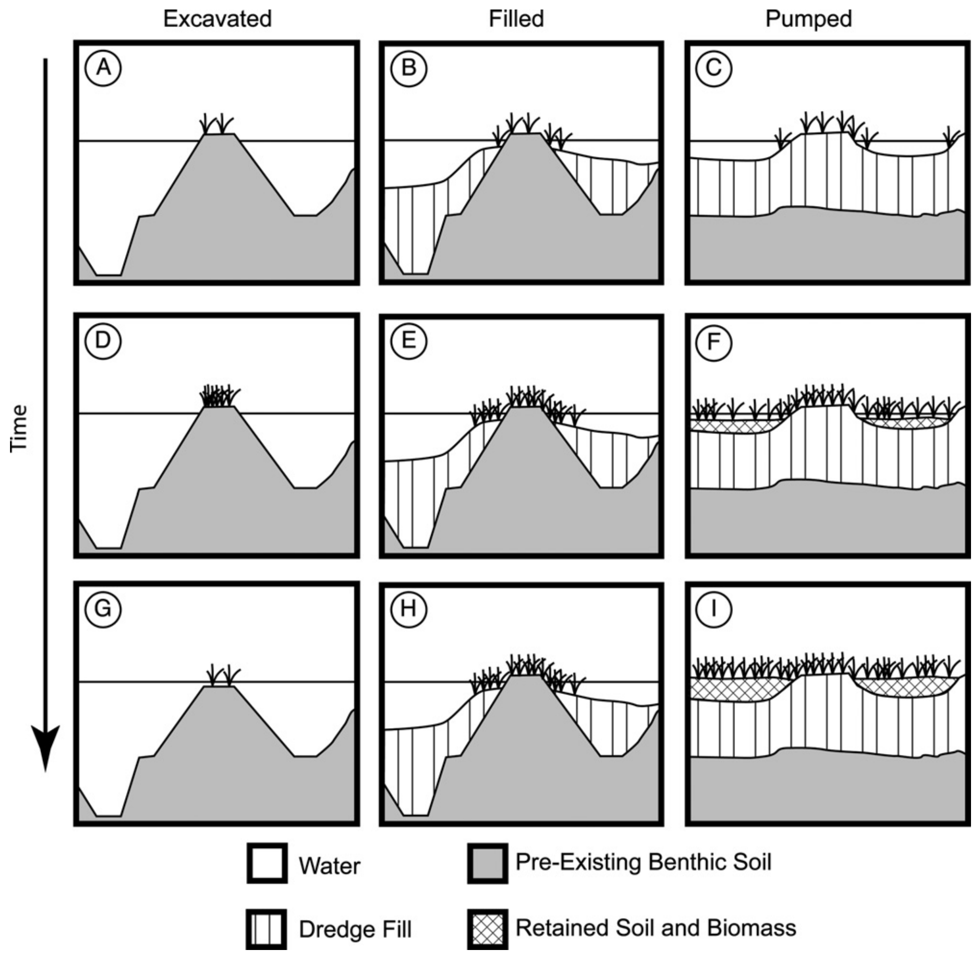

Fig. 2. Constructed mound designs. Soil source is indicated in legend and plantings of *S. alterniflora* are depicted on the mounds. The top row (A–C) depicts mounds following construction in 2007. The second and third rows depict changes over time based on data presented for the land to water ratio in Fig. 5 and net annual plant carbon capture in Fig. 6.

measurements of %C performed on dried and ground biomass samples collected in September of 2010 for *S. patens* (47.13 ± 3.09), *S. californicus* (46.43 ± 2.63), *S. robustus* (47.63 ± 5.92), *M. spicatum* (34.29 ± 0.48), *R. maritima* (33.73 ± 2.16), and algal mats (27.86 ± 0.99). The sum of the products of the standing biomass of each plant species multiplied by its corresponding %C content was the emergent standing carbon (SC_{EAG}) at each station.

Emergent belowground plant tissue was collected at each station at the peak of aboveground production in June 2009 and September 2010. Belowground biomass was extracted from soil cores (10 cm diameter, 20 cm deep) that were placed in the center of the quadrat used to collect aboveground biomass. Cores were rinsed in the laboratory over a 2 mm mesh sieve to isolate plant material from surrounding soil, dried at 70 °C to a constant weight, and weighed to determine standing biomass (SB_{EBG}). Carbon content was determined as described above, and total SB_{EBG} was multiplied by its %C content to determine emergent belowground standing carbon (SC_{EBG}) at each station.

To estimate standing biomass of submerged aquatic vegetation (SB_{SAV}), we combined the Rapid Survey Method of Deppe and Lathrop (1993) and Trebitz et al. (1993) with the Rake Method of Hansel-Welch et al. (2003) and Spears et al. (2009). Five stations in each constructed and reference area were approached in a non-motorized boat so as to not disturb the submerged vegetation. The head of a 16-tine, 0.04 m wide metal rake was dropped in the water two meters away from the side of the boat. The rake was dragged across the bottom and towards the boat in a downward sweeping motion that collected all vegetation within a 0.08 m^2 area. Vegetation trapped in the rake was placed in a plastic bag, transported on ice to the laboratory, and stored at −20 °C until it could be processed. Once thawed, plants were separated by species, rinsed to remove adhered sediment, dried for at least four days at 70 °C to a constant weight, and weighed to determine biomass. Since submerged aquatic vegetation (SAV) biomass was relatively low, we pooled *M. spicatum*, *R. maritima*, and green algae biomass at each monitoring station to calculate standing biomass (SB_{SAV}). Carbon content and standing carbon of submerged aquatic vegetation (SC_{SAV}) was determined as described above.

2.4. Production estimates

We estimated net annual primary production (NAPP) for each type of vegetation (emergent aboveground, emergent belowground, submerged aquatic vegetation) in each of the three constructed areas and the reference area. Our estimate of emergent aboveground net annual primary production ($NAPP_{EAG}$) was modified from Milner and Hughes (1968) and Singh et al. (1975), where $NAPP_{EAG}$ was the difference between the maximum and minimum SB_{EAG} and negative values were replaced with zeros. In 2009, peak SB_{EAG} was recorded in June and end-of-season (minimum)

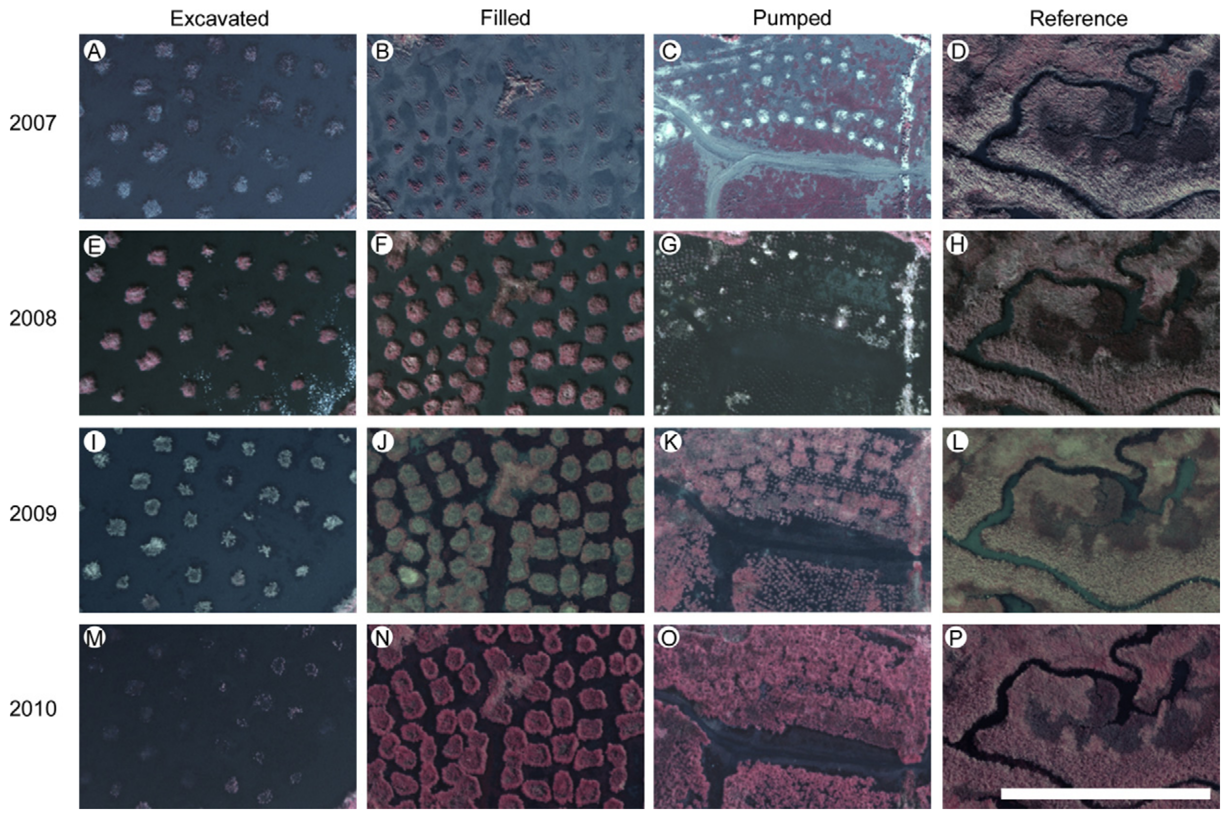

Fig. 3. A representative portion of each constructed and reference area viewed under high magnification in aerial photographs. Representative photos from excavated (A, E, I, and M), filled (B, F, J, and N), pumped (C, G, K, and O), and reference (D, H, L, and P) areas are shown over four consecutive years. Scale bar in P equals 75 m.

SB_{EAG} was in January of 2010. In 2010, peak SB_{EAG} was recorded in September and end-of-season SB_{EAG} was in January 2011. This technique is a conservative estimate of $NAPP_{EAG}$ because it does not account for biomass turnover/loss that may have occurred before peak biomass production.

The NAPP of belowground biomass ($NAPP_{EBG}$) was the difference between peak and end-of-season SB_{EBG}. Peak SB_{EBG} was directly measured in June 2009 and September 2010. End-of-season SB_{EBG} was estimated by multiplying end-of-season SB_{EAG} by the ratio of SB_{EAG} to SB_{EBG} at the peak of the growing season.

The NAPP of submerged aquatic vegetation ($NAPP_{SAV}$) was the difference between peak and end-of-season SB_{SAV}. These collections do not account for biomass turnover and are therefore a conservative estimate of $NAPP_{SAV}$.

We estimated net annual plant carbon capture (NACC) of the emergent aboveground plant community ($NACC_{EAG}$), emergent belowground plant community ($NACC_{EBG}$), and submerged aquatic vegetation ($NACC_{SAV}$) by calculating the difference between peak and end-of-season standing carbon (SC).

To integrate data from emergent and submerged areas and estimate net annual primary production at a larger landscape level ($NAPP_{AREA}$), we summed the products of the mean $NAPP_{EAG}$, $NAPP_{EBG}$, and $NAPP_{SAV}$ and their total respective areas (we assumed that emergent vegetation was only found on land and SAV was only found in the water), and divided this number by the size of each constructed or reference area in km^2. The net annual plant carbon capture of an entire constructed or reference area ($NACC_{AREA}$) was determined with a similar calculation except that mean NACC was used in place of mean NAPP. These values ($NAPP_{AREA}$ and $NACC_{AREA}$) describe the annual plant production and plant carbon capture per square meter of constructed or reference area.

2.5. Statistical analyses

Productivity and plant carbon capture were analyzed separately in 2009 and 2010 with one-way ANOVA, in which peak SB, end-of-season SB, NAPP and NACC for emergent aboveground, emergent belowground, and submerged aquatic vegetation were dependent variables and habitat type (excavated, filled, pumped, or reference) was the fixed factor. Homogeneity of variances for all response variables were confirmed with a Welch test. Variance was homogenous for each test and did not require transformation. Each ANOVA was followed with a post hoc Tukey test.

3. Results

3.1. Species composition of emergent and submerged areas

The emergent vegetation of each constructed area was dominated by *S. alterniflora* (Fig. A.1(A)–(C)). *S. alterniflora* biomass varied seasonally, and the highest values were in June 2009 and September 2010. In the reference area, there was more *S. patens* ($\leq$2.75 kg m^{-2}) than in the constructed areas ($\leq$0.02 kg m^{-2}), but *S. alterniflora* was still the dominant species (Fig. A.1D). *S. robustus* was absent from excavated and filled mounds and *S. californicus* did not occur in any of the constructed areas, but small amounts ($\leq$1.0 kg m^{-2}) of both species were consistently found in the reference area (Fig. A.1D).

In all constructed and reference areas, *Myriophyllum* was the dominant submerged aquatic plant species (Fig. A.2). In both years, it was most abundant in late summer (August 2009 and September 2010), when it accounted for $\geq$65% of all SAV standing biomass. Algal mats accounted for 41% of SB_{SAV} in filled mounds

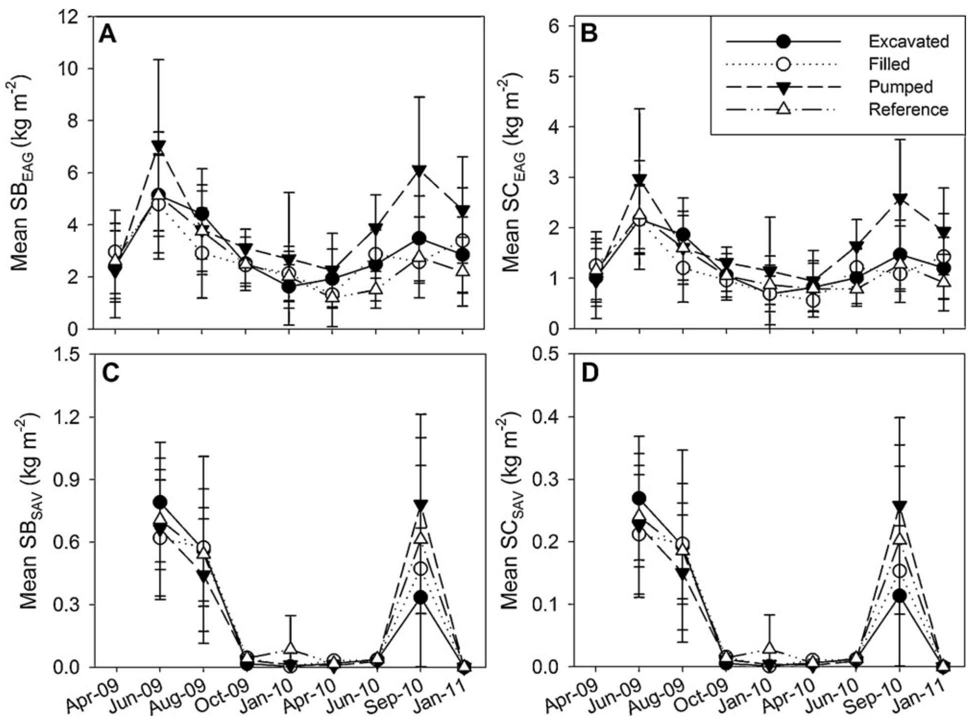

Fig. 4. Average standing biomass (A and C) and standing carbon (B and D) in emergent (A and B) and submerged (C and D) areas of constructed (excavated, filled, pumped) and reference marshes over time. Collection of emergent vegetation began in April 2009, and submerged aquatic vegetation collection began in June 2009. Error bars represent standard deviation.

in September 2010, but comprised a very small (<15%) portion of SB_{SAV} at all other sampling dates and locations (Fig. A.2).

3.2. Standing biomass and standing carbon

Mean values of peak SB_{EAG} were lower in September 2010 than in June 2009, and end-of-season mean values were slightly greater in January 2011 than in January 2010 for constructed and reference areas (Fig. 4A). Neither peak nor end-of-season mean SB_{EAG} varied significantly among habitat types in 2009 (One-way ANOVA; Peak – $P=0.171$; end-of-season – $P=0.507$; Table B.1). In 2010, peak SB_{EAG} was higher in pumped mounds relative to all other habitat types (One-way ANOVA, $P<0.001$); end-of season SB_{EAG} was higher in pumped than in reference areas (One-way ANOVA, $P=0.013$).

The SB_{SAV} reached peak levels in the same months as SB_{EAG} (Fig. 4C). Peak and end-of-season SB_{SAV} were not significantly different among constructed and reference areas in 2009 (One-way ANOVA; Peak – $P=0.808$; end-of-season – $P=0.351$; Table B.1) or 2010 (One-way ANOVA; Peak – $P=0.578$; end-of-season – $P=0.065$).

Because constructed and reference areas were dominated by the same plant species (Figs. A.1 and A.2) and differences in %C content among all plant species included in this investigation were small (see Section 2.4), the trends in SC_{EAG} and SC_{SAV} over time and among constructed and reference marsh areas (Fig. 4B and D) mirrored those observed for SB_{EAG} and SB_{SAV} (Fig. 4A and 4C).

3.3. GIS measurements

Differences in the dynamics of land expansion were clearly visible in aerial photographs of constructed and reference marsh areas from 2007 to 2010 (Fig. 3). When these images were incorporated into a GIS database, differences in the ratio of land to water in each area were quantified and the results are summarized in Table 2 and Fig. 5. The ratio of land to water in the reference area changed little from 2007 (4.96) to 2010 (5.20) and was nearly always an order of magnitude greater than the land to water ratio of any of the constructed areas (Figs. 3 and 5; Table 2). As the ratio suggests, the reference area had the greatest amount of land coverage relative to the other sites. Excavated mounds, on the other hand, had the least amount of land and the most water surrounding each mound (Figs. 3 and 5; Table 2). Excavated mounds initially gained land mass, but by fall 2010, the ratio of land to water (0.08) was less than after the initial construction of the site in 2007 (0.09). Pumped and filled mounds had intermediate levels of land and water and experienced the greatest amount of change over the study period based on the ratio of land to water in each area (Figs. 3 and 5; Table 2). Filled mounds increased in the ratio of land to water from 0.30

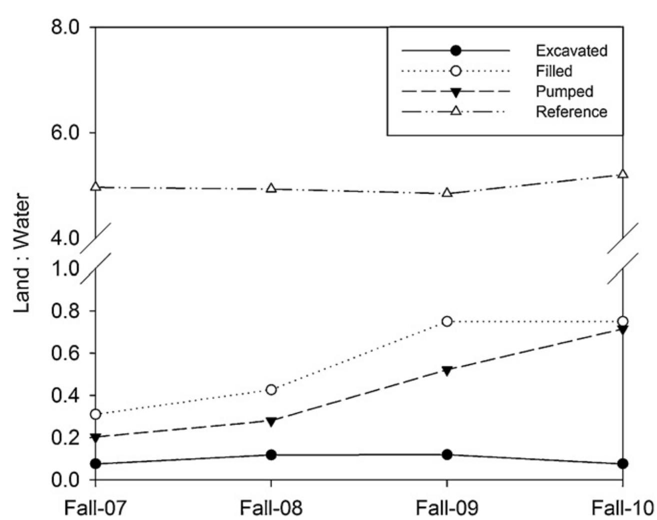

Fig. 5. Ratio of land to water within constructed (excavated, filled, pumped) and reference areas over four years after wetland construction in 2007.

Table 2
Land coverage, primary productivity, and carbon capture in constructed (excavated, filled, pumped) and reference marshes in 2009 and 2010. Each value was derived from measurements of productivity in Fig. 6 and Table A.1, and from a GIS database constructed from aerial photographs depicted in Fig. 3 and quantified in Fig. 5.

	2009				2010			
	Excavated	Filled	Pumped	Reference	Excavated	Filled	Pumped	Reference
Total area (km^2)	0.05	0.07	0.08	0.42	0.05	0.07	0.08	0.42
Total emergent area (km^2)	0.01	0.05	0.04	0.40	<0.01	0.05	0.06	0.36
Total water area (km^2)	0.04	0.02	0.04	0.01	0.05	0.02	0.02	0.06
Land: water	0.12	0.75	0.52	4.84	0.08	0.75	0.71	5.20
$NAPP_{AREA}$ (kg m^{-2})	1.61	3.57	2.96	6.75	0.33	1.96	2.17	2.96
$NACC_{AREA}$ (kg m^{-2})	0.56	1.47	1.19	2.71	0.13	0.30	0.34	0.84

in 2007 until fall of 2009 when land expansion stabilized near a ratio of 0.75. In pumped mounds, the ratio of land to water steadily increased from 0.21 in 2007 to 0.71 in 2010.

3.4. NAPP and NACC

$NAPP_{EAG}$, $NACC_{EAG}$, $NAPP_{SAV}$, and $NACC_{SAV}$ did not significantly differ among constructed and reference areas in 2009 and 2010 (Fig. 6A and C; Tables B.2 and B.3). $NAPP_{EBG}$ and $NACC_{EBG}$, however, were significantly higher in the reference area than in pumped mounds in 2009 and than in the excavated mounds in 2010 (Fig. 6B; Tables B.2 and B.3).

When the NAPP and NACC of all three kinds of vegetation (EAG, EBG, SAV) were combined with their surface area to estimate primary production and plant carbon capture of the entire constructed or reference area, large differences in $NAPP_{AREA}$ (Table 2) and $NACC_{AREA}$ (Fig. 6D; Table 2) became apparent. Both $NAPP_{AREA}$ and $NACC_{AREA}$ of the reference area were at least twice the value of any constructed area in both 2009 and 2010.

4. Discussion

4.1. Integrating landscape-level carbon storage into constructed marsh design

Although NAPP is influenced by local environmental conditions including latitude, climate, and soil chemistry (Mendelssohn and Morris, 2002), similar estimates of mean productivity have been reported in many other marshes on the Gulf of Mexico and East Coasts of the US. Mendelssohn and Morris (2002) have reviewed the productivity literature for marshes dominated by *S. alterniflora* and report a mean $NAPP_{EAG}$ of 0.8 kg m^{-2} for the northern Gulf of Mexico, which is well within the range of our estimates (0.2–1.7 kg m^{-2}). Fewer harvest-based reports of $NACC_{EBG}$ in coastal marshes are available, but our estimates of $NAPP_{EBG}$ (0.2–3.3 kg m^{-2}) are similar to those obtained in marshes on the East Coast of the US (1.7–7.6 kg m^{-2}; Dame and Kenny, 1986; Ellison et al., 1986; Schubauer and Hopkinson, 1984; Valiela et al., 1976), suggesting that our estimates of $NACC_{EBG}$ are also comparable. Submerged aquatic vegetation sometimes has a greater turnover rate than emergent vegetation (Engle et al., 2008; Miller and Fujii, 2010; Milsom et al., 2004), so our peak-season measurements may have underestimated SAV carbon capture. However, our estimates of $NACC_{SAV}$ (0.11–0.27 kg m^{-2}) are similar to previously published estimates for *Myriophyllum* spp. (0.12–0.26 kg m^{-2}; Adams and McCracken, 1974; Forsberg, 1959).

Overall, emergent marsh vegetation is more productive and less labile than submerged vegetation (Miller and Fujii, 2010) in many marshes on the Gulf of Mexico and East Coasts of the US. Under these conditions, the ratio of land to water in constructed marshes plays an important role in their capacity for plant carbon capture, which will be maximized in marshes with more emergent than submerged vegetation. However, under different conditions, submerged vegetation could contribute the same or more carbon to $NACC_{AREA}$ as emergent vegetation. Therefore, we do not call for a default increase in the ratio of land to water in constructed marshes, but stress the importance of duplicating the land to water ratio of references marshes in constructed marsh design.

Restoring rates of plant carbon capture is only one facet of the complex challenges associated with ecological restoration of coastal marshes (e.g., Biebighauser, 2007; Zedler, 2000b). Marshes that are built solely to duplicate the ratio of land to water in adjoining reference habitat may be at odds with other ecological goals. For example, marsh edge habitat increases nekton output in constructed marshes and consequently augments their fishery value (Minello and Rozas, 2002). However, the incorporation of edge habitat into constructed marshes typically results in more submerged marsh area that would lower the ratio of land to water. In brackish areas similar to the one we investigated, this would decrease the $NACC_{AREA}$. The need to restore plant carbon capture potential must be balanced with other ecological requirements, and continued integrative research like this study will help to identify construction designs that maximize both plant carbon capture and other ecological functions such as fishery value.

The capacity of emergent plants in constructed marshes to capture carbon is likely to change as the site develops over time. Our study occurred over a relatively short time period (three years) that immediately followed marsh construction, and may have therefore underestimated plant carbon capture potential in the constructed areas. Vegetation is often the fastest to develop in restored or constructed areas, often achieving cover and biomass comparable to reference areas in less than five years, particularly in temperate habitats like the Gulf of Mexico that do not have prolonged senescence periods (Craft et al., 2003; Edwards and Proffitt, 2003). However, recovery trajectories in coastal marshes are not always linear or predictable (Zedler and Callaway, 1999), and this is reflected in the different development patterns demonstrated in our constructed areas. The emergent habitat in pumped and filled mounds expanded substantially over the study period, but excavated mounds developed much more slowly (Figs. 3 and 5). Although the plant carbon capture potential in all of these habitats is likely to continue changing over time, our study clearly demonstrated the critical link between the ratio of land to water and the plant carbon capture potential in constructed marshes.

The absolute potential for plant carbon capture in brackish marshes like our study site may be somewhat offset by the production of the potent greenhouse gas methane. Methane emissions generally vary with salinity, with lowest production rates in saline (>18 ppt) wetlands (Bartlett et al., 1987; Bartlett and Harris, 1993; Ding et al., 2003; Pearce and Clymo, 2001; Poffenbarger et al., 2011). Brackish wetlands tend to have variable but relatively high methane emissions (Poffenbarger et al., 2011). However, our study focused the influence of constructed marsh design on landscape-level plant carbon capture, which is independent of marsh salinity. This study and previous works have demonstrated that emergent vegetation usually has a much higher net plant carbon capture

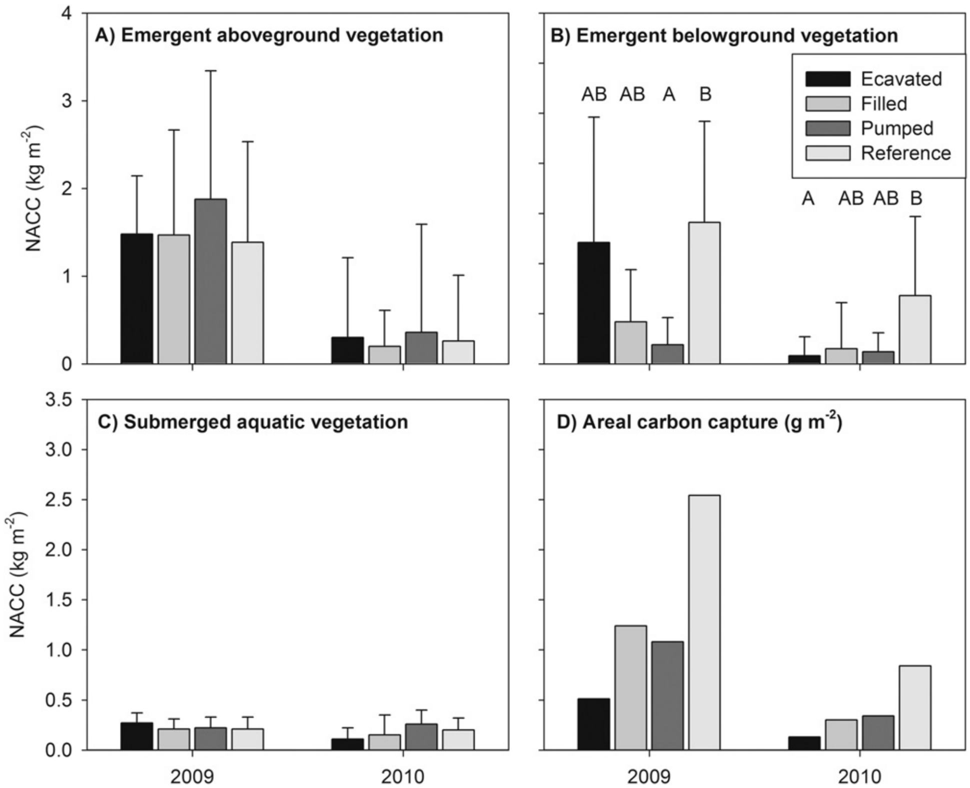

Fig. 6. Net annual plant carbon capture (NACC in kg m^{-2}) of emergent aboveground vegetation (A), emergent belowground vegetation (B), and submerged aquatic vegetation (C) in constructed (excavated, filled, pumped) and reference marshes. Homogenous subsets from Tukey tests are indicated with letters where significant. Error bars represent standard deviation. Panel (D) depicts the total areal carbon capture in g m^{-2} of each habitat type, including both emergent and submerged habitat, based on the values reported in Table 2.

rate than submerged vegetation (Adams and McCracken, 1974; Mendelssohn and Morris, 2002), and this relative difference may hold true across a range of salinities. Salt marsh restoration projects in Galveston Bay and other Gulf of Mexico estuaries often incorporate heterogeneous designs such as mounds or terraces (Rozas et al., 2005) that include a substantial amount of subtidal habitat. However, submerged aquatic vegetation such as seagrass in these habitats has declined substantially in the last 30 years, resulting in very low SAV biomass in these areas (Sheridan et al., 1998). Therefore, the difference in submerged and emergent plant biomass is pronounced in saline wetlands, and the impact of marsh design on plant carbon capture may be even more pronounced in salt marshes than in fresh or brackish marshes.

4.2. *NACC was similar among constructed and reference marsh vegetation*

Our approach provided a relative comparison of plant carbon capture among constructed wetlands that varied in design. Previously published analyses of constructed marsh performance typically include data from restored or constructed marshes that were engineered to have similar structural designs (Kuhn et al., 1999; Thom et al., 2004; Valiela et al., 1975). Comparisons among different construction designs are usually restricted to marshes at different sites that were built at different times (Craft et al., 2003; Delaney et al., 2000; Edwards and Mills, 2005; Edwards and Proffitt, 2003; Shafer and Streever, 2000). Our study was unique in that the constructed areas we examined were built within three months of each other and were in close proximity. Atmospheric conditions, tidal influence, anthropogenic disturbance, and freshwater inflow were similar in each constructed area and the reference area, allowing for systematic comparisons among marsh construction designs and soil sources.

We expected NAPP and NACC of emergent and submerged vegetation in each marsh to be different. Instead, NACC was generally the same among constructed and reference marsh areas. Although we did not quantify absolute carbon capture by measuring carbon movement into recalcitrant forms in the sediment, we had expected that plant biomass and carbon content would vary among our wetland areas. The excavated, filled and pumped mounds were built from different soil sources (Figs. 1 and 2), and soil characteristics are usually an important determinant of restored and constructed marsh success, particularly in terms of plant biomass and productivity (Boyer and Zedler, 1998; Mitsch and Cronk, 1992). Aspects of the marsh construction effort that likely contributed to these similarities include: (i) the emergent portions of each area had roughly the same elevation, (ii) the emergent portions were planted with the same Vermilion clone of *S. alterniflora*, and (iii) even though the soil from the upland site used to create pumped mounds had been removed from the industrial canal up to 40 years ago, it was ultimately from the same source as the dredge spoil used to create the filled mounds, and ongoing monitoring at the site suggests that sediment grain size, nutrient concentrations, and organic content in dredge, upland, and existing bottom sediment are similar among all soil sources (A.R. Armitage, unpublished data). This homogeneity in elevation, plant composition, and soil composition likely contributed to the similar primary production and rate of carbon capture among emergent vegetation in constructed and reference areas.

$NACC_{SAV}$ was also similar among sites (Fig. 6C; Table A.1). This was unexpected because submerged plants were naturally recruited from the reference area and each constructed area was a different distance from the source population. For example, the shortest distance between the northernmost plot of excavated mounds and the reference area was 0.79 km, while filled mounds were only 0.16 km from the reference area (Fig. 1). Both *Myriophyllum* and *Ruppia* apparently have rapid rates of dispersion that allowed for quick colonization of constructed areas.

4.3. The future dynamics of the land to water ratio may depend on water depth

Given the key importance of land to water ratio in $NACC_{AREA}$, it is important to understand why the ratio of land to water changed in each constructed area. We hypothesize that these changes were driven in large part by the depth of water surrounding each emergent mound. Emergent vegetation is capable of trapping sediment from surrounding water and creating soil through turnover of its own biomass (Castellanos et al., 1994; van Hulzen et al., 2007), which over time can contribute to the formation of emergent marsh. The brackish marshes we monitored in this investigation were dominated by *S. alterniflora*, which can grow in water-saturated soils but cannot survive long periods of submergence (Mendelssohn and Morris, 2002). If we assume that increases in emergent marsh area are from *S. alterniflora* expanding into surrounding submerged areas and creating emergent marsh habitat, then we would expect areas with shallow water habitat to gain land faster than areas with deeper water. This is exactly what we observed in the constructed areas.

Excavated and pumped mounds represent extremes of construction design in terms of water depth (Fig. 2A and C) and they also experienced the most disparate changes in the ratio of land to water from 2007 to 2010 (Fig. 5). Pumped mounds were surrounded by shallow water (Fig. 2C) and the ratio of land to water increased every year in the pumped mound area (Figs. 3 and 5). The shallow water surrounding pumped mounds likely provided ideal habitat for the creation of new land through the colonization of shallow water areas by *S. alterniflora* (Fig. 2F and I). In the case of excavated mounds, water depth was greater (Fig. 2A) and newly emergent areas did not develop (Fig. 3). Instead, the growth of *S. alterniflora* was constrained and the ratio of land to water gradually decreased over the course of this study, most likely due to sediment compaction that reduced emergent habitat (Figs. 2D, G, 5). In filled mounds, where water depth was intermediate (Fig. 2B), *S. alterniflora* appeared to expand into shallow water areas that were habitable but eventually these areas became occupied (Fig. 2E and H) and the ratio of land to water stabilized (Fig. 5). Over the next several years, we expect the ratio of land to water in both pumped and filled mounds to increase, but for this transition to occur more quickly in pumped mounds.

Between 2009 and 2010, the ratio of land to water increased by 0.19 in pumped mounds. If we assume that the conversion of submerged to emergent vegetation continues to increase at this same rate, then the ratio of land to water in pumped mounds will be equivalent to that of the reference area in 2033, an elapsed time of 24 years since construction. An interesting goal of future studies would be to identify the threshold water depth that determines if emergent vegetation will be able to lead to the production of new areas of emergent marsh habitat and consequently impact the $NACC_{AREA}$.

5. Conclusions

A large body of scientific literature has shown that constructed and reference marshes can obtain similar levels of emergent aboveground primary production (Costa-Pierce and Weinstein, 2002; Kentula, 2002; Shafer and Streever, 2000; Turner and Streever, 2002; Zedler, 2000a; Zedler and Callaway, 1999). However, the present investigation demonstrates that even when the productivity of a single species of vegetation is comparable between constructed and reference areas, the constructed site as a whole may not be performing as well on a landscape scale that integrates emergent and subtidal habitat. It is important for constructed and reference marshes to have comparable rates of plant carbon capture, and marsh construction designs should aim to duplicate the ratio of land to water in adjacent reference marshes to meet or exceed this goal.

Acknowledgements

This research was funded by the Oil Spill Prevention and Response Division of the Texas General Land Office (B. Martin, Research & Development Director) with additional support from the TGLO Coastal Management Program. Logistical support and access to the study site was provided by the Wildlife Division of the Texas Parks and Wildlife Department, under Wildlife Division Director Clayton Wolf, with additional thanks to J. Sutherlin, A. Peters, and M. Rezsutek. Marsh construction was performed by Chevron, with valuable logistical support and advice from J. Myers and J. Hall. We thank M. Bell for data on aquatic plant biomass and A. Thronson, C. Valinoti, C. Hales, and C.-K. Ho for field assistance.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecoleng.2012.02.001.

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