Comparison of Nutrient Accrual in Constructed Living Shoreline and Natural Fringing Marshes

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Recommended Citation

Chambers, Randolph; Gorsky, A. L.; Isdell, Robert E.; Mitchell, Molly; and Bilkovic, Donna Marie, "Comparison of Nutrient Accrual in Constructed Living Shoreline and Natural Fringing Marshes" (2021). *Ocean and Coastal Management*. 20.
https://doi.org/10.1016/j.ocecoaman.2020.105401

Ocean and Coastal Management 199:105401 (January 2021)

Comparison of Nutrient Accrual in Constructed Living Shoreline and Natural Fringing Marshes

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https://doi.org/10.1016/j.ocecoaman.2020.105401

ABSTRACT

Living shoreline marshes are coastal wetlands constructed as alternatives to “hardened shorelines” (e.g., bulkheads, riprap) to mitigate erosion and to allow for landward migration of intertidal habitat as sea level rises. Living shorelines are designed to mimic natural fringing marshes and over time should be sinks for carbon and other nutrients. We collected soil cores and aboveground plant material from 13 pairs of natural fringing marshes and living shoreline marshes of different ages and degree of isolation from more extensive marsh shorescapes to compare nutrient pools and accrual. Although the nutrient content of plants was similar within and between marsh types, soil nutrients were variable from both living shorelines aged 2-16 years and long-established natural marshes. Most—but not all—living shoreline marshes had lower soil organic content, higher bulk density, and lower soil % carbon, nitrogen and phosphorus than their natural marsh pair. Variation in soil nutrients from living shorelines was not strongly correlated with either marsh age or degree of isolation in the estuarine shorescape. Assuming constant accrual within individual marshes, we estimated soil nutrient levels in living shorelines would approach those observed in their paired, natural fringing marshes over timescales from less than 10 years to many decades. Living shoreline marshes are on trajectories to match natural marsh function with respect to carbon and nutrient storage in estuarine systems.

Keywords: estuaries, fringing tidal marsh, living shoreline; shorescape, soil nutrients

1. Introduction

Living shorelines are created, fringing tidal marshes that mitigate for the impacts of rising sea level and ongoing coastal erosion by promoting shoreward marsh growth (Bilkovic et al., 2017). Instead of using bulkheads or riprap that effectively preclude wetland development (Currin et al., 2010), the living shoreline consists of a rock or oyster reef “sill” in the low intertidal to subtidal zone, behind which vegetation in the created low marsh and high marsh is planted. The sill reduces wave energy and traps sediment reaching the vegetated marsh that is then able to establish and expand (Currin et al., 2017).

Use of living shorelines for erosion control has increased along U.S. coasts since their introduction in the 1980s. In Virginia, for example, the Living Shorelines Act in 2011 deemed these constructed fringing marshes the preferred shoreline management practice. While in the earlier years only about 1-3% of the shoreline construction permits requested were for living shorelines, since 2011 about 15% are for living shorelines (CCRM, 2019). In contrast, armoring (bulkhead and riprap revetment) permit requests declined during the same time period that living shoreline use increased, although armoring continues to make up the majority of requested projects. The use of bulkheads has dramatically declined from highs in the 1970s and 1980s of about 70% of the shoreline permits requested annually, to 38% in the 1990s and 2000s, with further declines in recent years (2011 to 2017) to 31%. Riprap revetment, another form of armoring, has also declined slightly from its peak use in the 1990s and 2000s (47% of the shoreline permits requested) to 40% (2011-2017) (CCRM, 2019). The increase in living shoreline construction increases the total length of estuarine coastline occupied by fringing marsh.

Natural fringing marshes are loosely defined as wetlands up to 30 m wide (Davis et al., 2015), comprising intertidal habitat between upland and open water. These narrow bands of vegetated marsh account for little total area relative to expansive coastal marshes, but they are prominent estuarine features (Morgan et al., 2009). In Chesapeake Bay, for example, fringing marshes cover just 42 km^2 vs 930 km^2 of total tidal wetland area (CCRM online database: http://www.vims.edu/ccrm/research/inventory/index.php). Assuming an average 15 m width, however, these fringing marshes conservatively occupy roughly 2,800 km of shoreline, which is 15% of the total 19,000 km of the Chesapeake Bay shoreline (CCRM, 2019). Similarly, narrow fringing marshes <2 m wide comprise ~13% of the New River estuary in North Carolina (Currin et al., 2015), and fringing marshes are the dominant marsh type in New England (Roman et al., 2000). Functionally, fringing shoreline marshes intercept nutrients from upland groundwater discharge (Valiela and Cole, 2002; Bowen et al., 2007; Beck et al., 2017) and may serve to "connect" other estuarine habitats and habitat complexes (Able et al., 2012; Davis et al., 2012) that would otherwise be isolated by coastal development. Whether isolation from other habitat complexes might affect the extent or rate at which a created living shoreline develops natural marsh characteristics is unknown.

The science of living shoreline ecosystems still is relatively young (Bilkovic and Mitchell, 2017), yet numerous earlier studies compared ecosystem components of the broader general category of created wetlands with natural wetland systems. From many years of plant and soil surveys, Craft et al. (1998, 1999, 2002, 2003) documented the pace of ecosystem development in created wetlands, noting that living plant biomass in constructed marshes typically reached equivalence with natural marsh systems within five years. Soil nutrients, however, accumulated more slowly in created marshes and could take decades to centuries before reaching equivalence with natural systems. For living shoreline marshes, a similar story is emerging, both in terms of rapid vegetation establishment (Currin et al., 2008) and longer-term carbon sequestration and nitrogen accrual (Davis et al., 2015).

Created fringing marshes have become a popular tool for protecting uplands from the impacts of coastal erosion (Broome et al., 1992; Theuerkauf et al., 2015), but few studies to date have measured the accrual or processing of nutrients in living shoreline marshes relative to nearby natural fringing marshes found in similar shorescape settings (Currin et al., 2008; Davis et al., 2015; Beck et al., 2017). We measured the carbon, nitrogen, and phosphorus in soils and plants from 13 living shoreline marshes of different ages in Chesapeake Bay, and tested the following hypotheses: 1) nutrient pools in living shoreline marshes are less than their natural marsh pairs; 2) nutrient accrual decreases with living marsh age and/or degree of isolation in the estuarine shorescape; 3) older living shoreline soils require fewer years to reach equivalence with the nutrient content of their natural marsh pairs. Our overall objective was to assess the nutrient storage function of living shoreline marshes constructed as an alternative to hardened shorelines in estuarine shorescapes.

2. Materials and methods

2.1. Location and description of study area

Thirteen pairs of living shoreline marshes and nearby natural fringing marshes (separation distance 55-845 m, average 395 m) in the southern portion of Chesapeake Bay were included for study (Fig. 1). The living shorelines were constructed with a rock sill, behind which clean sand fill was planted with *Spartina alterniflora* in the low marsh and *S. patens* in the high marsh. Current practice is to fertilize during planting living shoreline marshes, but we do not know whether the marshes in our study were fertilized when constructed. Living shoreline marshes spanned an age range (years since construction) of 2-16 years and occurred in coastal environments with different coverage of surrounding land use types (Table 1). We used GIS to determine the landscape setting of each living shoreline, identifying within a 1-km radius the dominant surrounding land use and total land area that was agricultural, developed, or natural (i.e., forest, open space). In GIS we also created an index of isolation by calculating the average distance (m) to marsh for all shoreline points within 1 km of each living shoreline marsh (Table 1). Marshes with a lower index of isolation are surrounded more extensively by tidal wetland shorelines, whereas marshes with a high index are surrounded more extensively by shoreline armoring (bulkheads, rip-rap) or other shoreline development or undeveloped open space (e.g., beaches).

2.2. Soil comparisons

During the 2018 growing season, soil cores to 30 cm were collected along three parallel transects separated by at least 4 m and oriented perpendicular the shoreline. Cores were obtained from the low marsh (dominated by *S. alterniflora*) and high marsh (dominated by *S. patens*) of each living shoreline and paired, fringing natural marsh, then sectioned 0-5, 5-10, 10-20, and 20-30 cm. For living shoreline marshes, plant roots had not yet penetrated into the 20-30 cm sections.

All core sections were oven dried at 60C and then bulk density was determined gravimetrically. From dried sub-samples at each depth, organic content was calculated from weight loss after ashing for 4 hours at 450C. Total carbon (C) and nitrogen (N) were determined using a Perkin-Elmer 2400 elemental analyzer; total phosphorus (P) was determined using an ashing/acid hydrolysis method (Chambers and Fourqurean, 1991). Soil nutrient standing stocks to 20 cm were calculated, and for living shoreline marshes, nutrient accrual was determined by calculating the nutrient additions since marsh construction (i.e., nutrient stocks 0-20 cm, less the initial nutrient stock size in that layer, estimated by the nutrient pool measured at 20-30 cm where no roots were observed, then divided by the marsh age). With this method, we assumed that the current nutrient stocks 20-30 cm were representative of those at the time of living shoreline construction. The difference between nutrient pools 0-20 cm in each living shoreline-natural marsh pair was then divided by the nutrient accumulation rates to estimate the number of years to “equivalence”, i.e., the years that would be required for each living shoreline marsh to accrue nutrients to the level observed in its natural marsh pair. Similar to prior studies, this calculation assumes that annual plant production and subsequent nutrient accrual occurs is constant (Davis et al., 2015). For any living shoreline marsh that had nutrient pools already larger than its nearby natural marsh pair, the number of years to equivalence was considered zero.

2.3. Plant comparisons

From all 26 living shoreline and natural fringing marshes, we also harvested leaves from five *S. alterniflora* and five *S. patens* plants located in three low and three high elevation sections, respectively. The leaves were oven dried at 60C, then milled. We minimized more extensive, destructive sampling of aboveground vegetation to a subset of four natural fringing marshes. At peak biomass in late summer, we clipped all aboveground vegetation from ¼ m^2 quadrats in triplicate from low and high marsh elevations in these four marshes, then air-dried and milled the vegetation. For leaves and for vegetation from quadrats, total carbon, nitrogen and phosphorus were determined using the methods described for soils. Stem counts and average stem heights at peak biomass were obtained in duplicate along six transects for *S. alterniflora* and *S. patens* from low and high marsh stands in all 26 living shoreline and natural fringing marshes. We then used an allometric relationship established for *Spartina* species in Chesapeake Bay tidal wetlands to estimate aboveground plant biomass as a function of stem density and stem height (Beck et al., 2017):

$$\textit{S. alterniflora}\text{ biomass} = (0.1807e^{0.0332*\text{Stem Height}})*\text{Stem Density}$$

$$\textit{S. patens}\text{ biomass} = (0.0381e^{0.04*\text{Stem Height}})*\text{Stem Density}$$

Finally, peak biomass calculations for *S. patens* and *S. alterniflora*, coupled with the average measured nutrient content of aboveground plants harvested from four natural marshes were used to calculate the aboveground plant C, N and P. We compared the aboveground nutrient pools in living shoreline and natural marshes with the average belowground soil nutrient pools.

2.4. Statistics

We plotted vertical soil profiles for living shoreline and natural fringing marshes. Paired t-tests compared the mean concentrations of nutrients at each depth. We used regression analysis for examining 1) organic and inorganic contributions to soil bulk density, 2) soil carbon relationships to soil nitrogen and phosphorus, and 3) nutrient accrual as a function of marsh age. For plant comparisons, elemental contents of leaf tissues were compared by marsh type and by *Spartina* species using a full factorial ANOVA design. Finally, we used generalized linear models with stepwise regression to examine aboveground biomass and belowground nutrient storage and accrual in living shoreline marshes as a function of developed land use and relative isolation in the coastal shorescape.

3. Results

3.1. Soil Comparisons

Soil profiles (Fig. 2) showed the average weight percent of carbon, nitrogen and phosphorus at all depths was significantly higher from fringing natural marshes, relative to the created living shoreline marshes (t-tests, $p < 0.05$). Unlike natural marshes, the bulk density of living shoreline soils was never lighter than 0.4 g cm^{-3}; for both marsh types, however, contributions to bulk density were dominated by inorganic minerals (Figs. 3a, b). In fringing natural marshes, soil carbon ranged from 0-16 percent and was strongly correlated with soil nitrogen, whereas soil C ranged from 0-10 percent in living shoreline soils and the correlation was not as strong (Fig. 3c). In contrast, soil carbon in both living shoreline and natural marsh soils were even less strongly correlated with soil phosphorus (Fig. 3d).

Averaged from high and low marsh, the nutrient pools in the top 20 cm of living shoreline soils were less than in natural marsh soils for 10 of the 13 marsh pairs examined (Fig. 4). The soil carbon, nitrogen and phosphorus pools in living shoreline marshes tended to increase with age, but the variability among sites was large. Only the soil nitrogen pool was significantly and positively correlated with age ($r^2 = 0.503$; $F = 13.152$, $p = 0.004$). Neither carbon nor phosphorus was correlated with living shoreline age ($p > 0.05$). Further, the concomitant, large range in nutrient pool sizes among natural marshes (Fig. 4) demonstrates the variability in these established, fringing wetlands used as reference to the paired living shoreline marshes.

In living shoreline soils, nutrient accrual plotted with respect to marsh age exhibited a variable pattern, both among marshes and among nutrients (Fig. 5). Average carbon accrual ranged from a high of ~250 g m^{-2} y^{-1} in a seven year-old marsh to <50 g m^{-2} y^{-1} in the oldest living shoreline measured (16 years), but was not significantly correlated with age. Both nitrogen and phosphorus accrual in soils were negatively correlated with age ($p < 0.05$). Annual accrual of soil nitrogen was highest (21 g m^{-2} y^{-1}) in the youngest living shoreline measured (two years) and lowest (6 g m^{-2} y^{-1}) in the oldest marsh. Finally, phosphorus accrual was highest (2.1 g m^{-2} y^{-1}) in a seven year-old marsh and lowest (0.2 g m^{-2} y^{-1}) in the oldest marsh (Fig. 5).

Based on current pool sizes and the nutrient accrual in the upper 20 cm of soil of each marsh, we then estimated average number of years required to reach equivalence with the paired natural marsh, assuming those rates would remain constant over time (Table 2). For two of 13 living shoreline marshes, the carbon and nitrogen pools were already greater than the natural marsh; the phosphorus pool was already greater than the natural marsh for four of 13 living shoreline marshes. The largest average number of years to equivalence was greatest for soil carbon (23 y), with a range of 0-63 years. The years to equivalence were lower for soil nitrogen (13 y) and lowest for soil phosphorus (6 y) (Table 2).

3.2. Plant comparisons

The carbon content of *S. patens* leaves harvested from the high marsh was significantly higher than *S. alterniflora* leaves from the low marsh, but N and P content were not significantly different (Table 3). Between marsh types, the P content of leaves from living shorelines was significantly higher than from natural marshes. We did not, however, detect a significant marsh x species interaction for any nutrient, i.e., the variation in nutrient content by species was similar for both living shoreline and natural marshes.

For living shorelines, the peak biomass carbon was on average 14 and 44 percent of the high and low marsh soil carbon content, respectively, relative to one and 12 percent for natural marshes (Table 4). Likewise, nitrogen in peak biomass from high and low marshes of living shorelines was on average five and 13 percent, respectively, relative to one and six percent for natural marshes. For phosphorus, peak biomass from high and low marshes of living shorelines comprised four and 12 percent of the soil phosphorus pool, respectively, relative to one and nine percent from natural marshes (Table 4).

3.3. Nutrient Accrual, Plant Biomass, Land Use and Marsh Isolation

Finally, we considered features of the surrounding shorescape (Table 1) and how they might affect plant biomass and soil nutrient accrual in living shorelines (Fig. 4, Fig. 5, Table 4). From generalized linear model analysis with log transformation of the dependent variables, however, none of our measures of soil nutrients (i.e., accumulated soil stocks, accumulation rates of carbon, nitrogen or phosphorus) correlated significantly with any land use variables or with the marsh isolation index. In contrast, aboveground biomass of S. patens was positively correlated with the area of surrounding development in a 1-km radius ($\beta = 1.2 \times 10^{-6}$; $p = 0.021$).

4. Discussion

Similar to prior research on created tidal wetlands in general (Craft et al., 1998, 1999, 2003) and restored fringing shoreline marshes specifically (Currin et al., 2008), salt marsh plants are quick to establish and grow (Table 4), in some instances achieving aboveground biomass equivalence with adjacent natural marsh systems within fewer than 10 years. Living shoreline marshes typically are planted in clean sands that allow for rapid rhizome growth and expansion, but still the accumulation of soil carbon, nitrogen and phosphorus takes more time (Davis et al., 2015) (Fig. 2). Our study demonstrates temporal variation in the accrual of soil nutrients in living shoreline marshes, but we also show that natural fringing marshes exhibit a broad range in soil nutrient status (Fig. 4). Some living shoreline marshes accumulate soil nutrients to natural marsh levels within a few years; for others, decades are required (Table 2), either because of the slow rate of nutrient accumulation in the living shoreline marsh (Fig. 5) and/or because of the larger size of the nutrient pool in the natural marsh pair.

Living shoreline soils tend to lag behind older natural marsh soils because of the relative absence of soil organic matter that—when present—decreases bulk density and stores carbon and nitrogen (Fig. 3). Soil carbon and nitrogen are strongly correlated, whereas the correlation between soil carbon and phosphorus is much weaker. In addition to incorporation into organic matter in marsh soils, phosphorus can also be bound with clays (Bai et al., 2017) and with different inorganic iron and calcium minerals (Hartzell et al., 2010), so that the pool of phosphorus in living shoreline soils can grow more quickly over time, relative to carbon or nitrogen for which organic forms dominate in soils. As a result, the average “time to equivalence” for phosphorus from living shoreline soils is about half that of nitrogen, and one-fourth that of carbon (Table 2).

The leaf tissues of *S. alterniflora* and *S. patens* have similar concentrations of carbon, nitrogen and phosphorus, averaged across living shoreline and natural fringing marshes (Table 3). Further, the aboveground biomass of living shoreline plants was at least as large as natural marsh plants (Table 4). Thus, the aboveground growth of plants in living shoreline marshes does not appear to lag behind natural marshes despite the smaller pools of nutrients belowground. Many living shoreline plantings include initial applications of timed-release N and P fertilizers, which would stimulate aboveground growth. Nutrients in aboveground tissues in perennial plants from living shoreline marshes represent a larger percentage of the total soil nutrient pool (Table 4), but the growth of plants is about the same as from natural marshes. The similarity could be because: 1) the available soil nutrient pool in either abundance or stoichiometric ratio (Qiao et al., 2018) may be sufficient to support similar aboveground growth (Hopkinson and Schubauer, 1984); 2) the growth in both marsh types may be supported primarily by tidal nutrient exchange (Steever et al., 1976) or by groundwater (Beck et al., 2017); 3) plant growth in living shoreline marshes may be limited by nutrients, whereas plant growth in natural marsh soils may be limited to a similar extent by other factors such as more reducing conditions and elevated soil sulfide concentrations driven by higher soil carbon content (Fig. 2) that would inhibit growth (Howes et al., 1986).

We found that the degree of marsh isolation in the surrounding shorescape was not significantly correlated with either pools or accrual of carbon, nitrogen and phosphorus in living shoreline soils. We had hypothesized that created marshes surrounded by a larger area of natural marsh would perhaps grow faster and accumulate more soil nutrients because local environmental conditions for marsh growth were good and because plant propagules would be readily available to enhance establishment. Instead, living shoreline marshes that had a low degree of isolation from surrounding tidal marshes (Table 1) were no higher in soil nutrients than marshes from sites that were more locally isolated. Further, the observed range in nutrients among both living shoreline and natural marsh sites was not strongly explained by age or by any other variable that we measured. Because these fringing marsh environments form a narrow interface between upland and open water, groundwater flow derived from sources immediately adjacent to the marsh might vary in the delivery of nitrogen and phosphorus for plant growth (Valiela and Cole, 2002; Currin et al., 2010; Beck et al., 2017). Groundwater subsidies from septic systems and lawn fertilizers, from agricultural fields, or other sources might affect marsh primary production and nutrient accumulation (Bowen et al., 2007). Aboveground biomass of *S. paten*s was positively correlated with the total area of developed land within a 1-km radius, suggesting a local influence on plant production.

The fringing natural marshes used for comparison to living shoreline marshes exhibited a broad range in soil nutrient pools (Fig. 4). We had expected a smaller range because these marshes are much older than their living shoreline pairs and have had time to accumulate nutrients. Some of the natural marshes, however, showed evidence of erosion and were steeply scarped at the water’s edge, suggesting active loss of marsh owing to ongoing exposure to wave energy from coastal storms and/or sea level rise. In addition, other natural marshes had evidence of sand deposits from storm overwash, and others were sites of significant wrack deposits. Differences in sediment characteristics might also be related to marsh elevation (Rezek et al., 2017). Relative to more expansive marshes that form in more protected estuarine areas, these fringing marshes are exposed to physical factors and other environmental disturbances (Morgan et al., 2009) that may alter the site-specific dynamics of soil development, plant growth and nutrient accumulation (Feagin et al., 2009; Miller et al., 2001; Macreadie et al., 2013).

5. Conclusion

Given the observed similarities in plant growth between living shoreline and natural fringing marshes sampled from a range of shorescape settings, we conclude that the plant performance and soil nutrients of created living shoreline marshes are not negatively affected by isolation. In other words, a living shoreline marsh surrounded by development and hardened shoreline structures like bulkheads and riprap might grow and accumulate nutrients at rates similar to a living shoreline created in a shorescape setting already replete with natural marsh. Surrounding urbanization can affect the structure and function both restored and natural marshes (Silliman and Bertness, 2004; Windham et al., 2004). For living shorelines, however, the ecosystem services and functions of shoreline protection, nutrient cycling, plant growth and carbon storage appear to be satisfied irrespective of shorescape setting. Other functions (e.g., habitat support for fish, invertebrates and other wildlife) may be similarly satisfied by living shoreline marshes created across gradients in coastal development.

Funding: This work was supported by National Science Foundation (grants 1600089, 1600131).

Acknowledgments

This research was completed as part of the Coastal SEES Collaborative Research Program: Sustainability in Chesapeake Bay Shorescapes, funded by NSF 1600089 and 1600131. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors thank all the homeowners who provided access to their marshes used in this study, and thank the field crew Kory Angstadt and David Stanhope for their critical assistance with sample collection. This paper is Contribution No.xxxx of the Virginia Institute of Marine Science, William & Mary.

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Figure

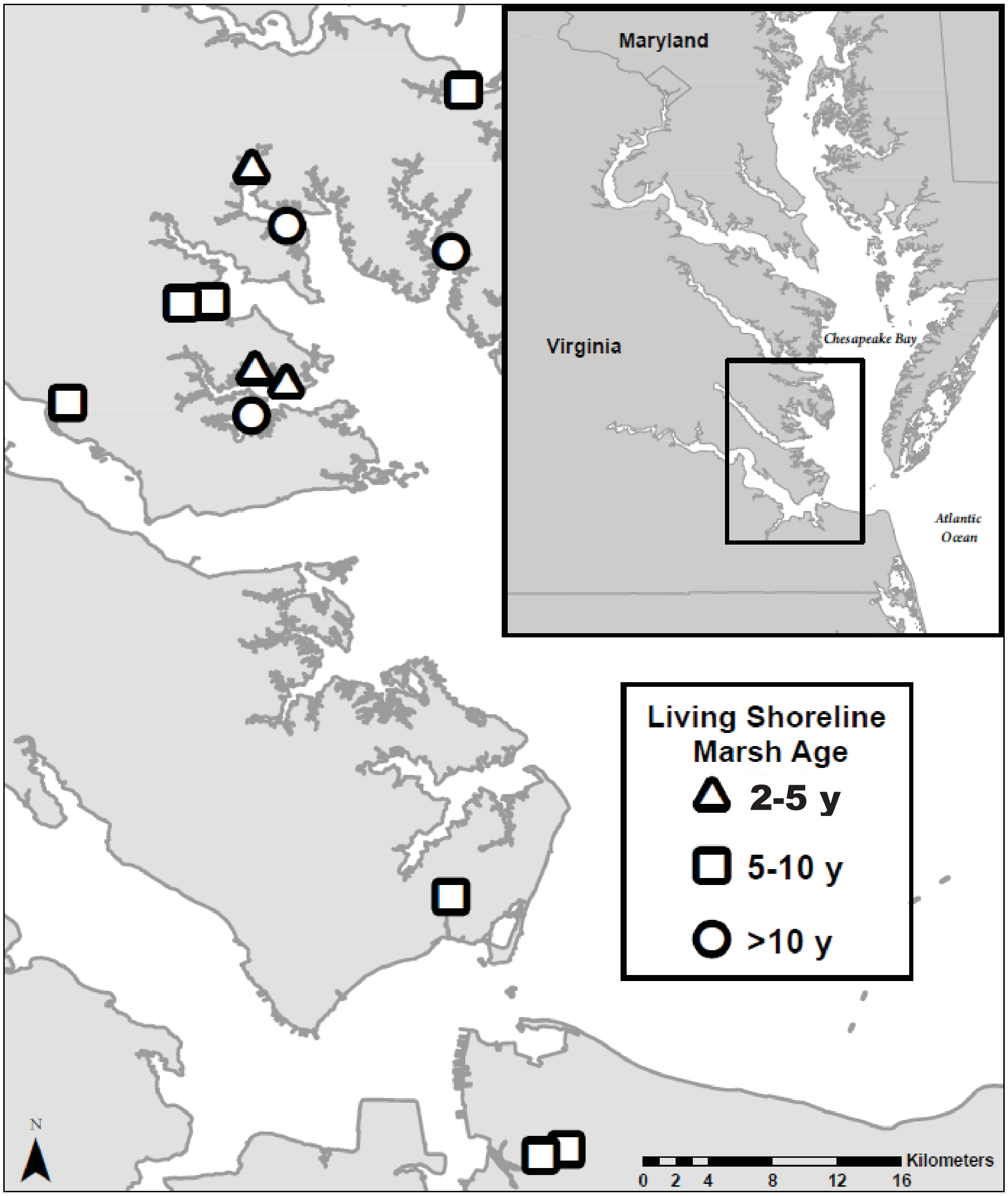

Fig. 1. Locations of thirteen paired living shoreline and fringing natural marshes in southern region of the Chesapeake Bay estuary. The ages of living shoreline marshes ranged from 2-16 years, and distance to the paired natural marshes was 55-845 m.

Figure 2

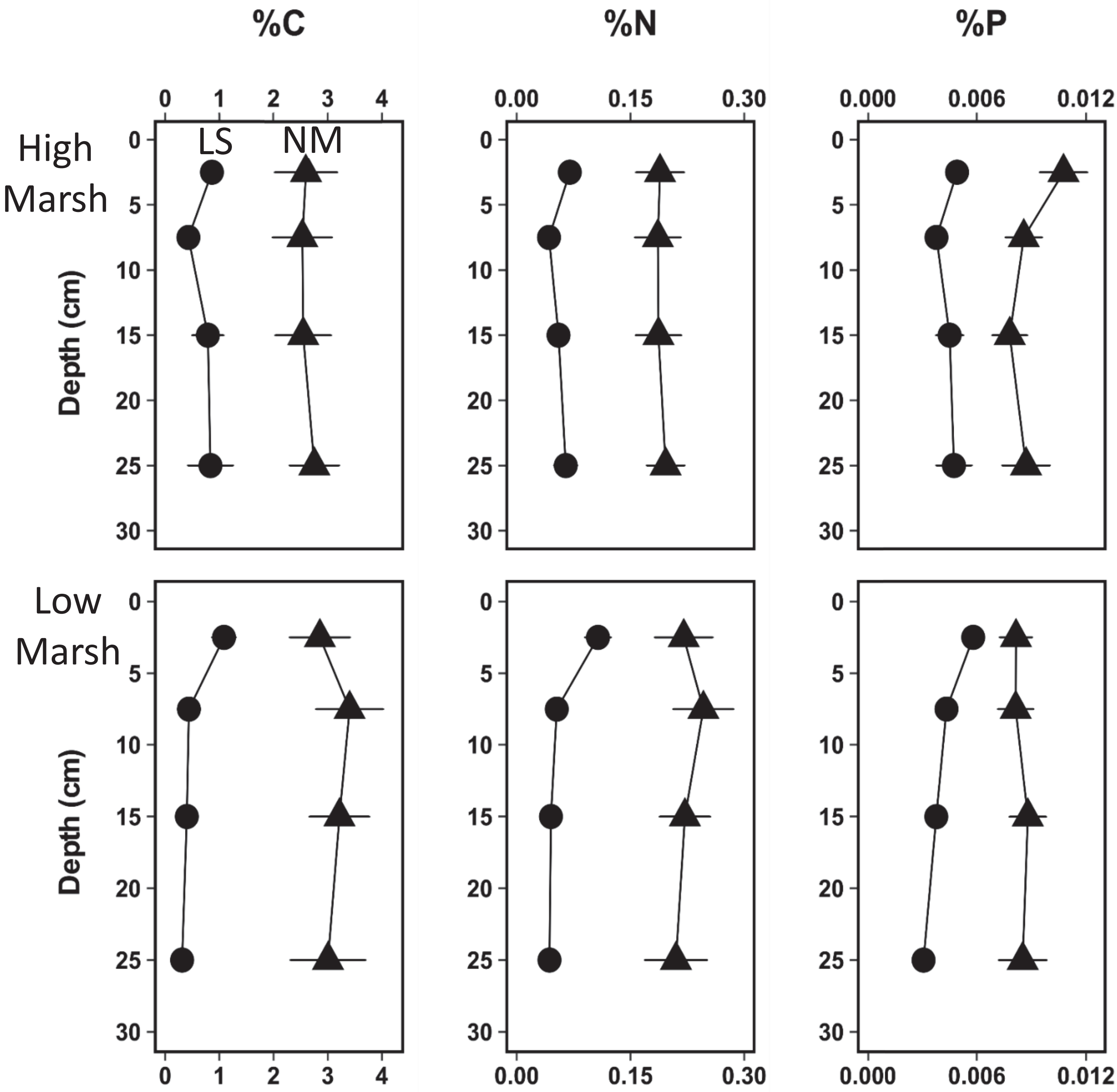

Fig. 2. Depth profiles of bulk soil nutrients (measured as a weight percent of dry soil) from high and low marsh locations of living shoreline and natural marshes. Points are averages with standard error bars (N=6).

Figure 3

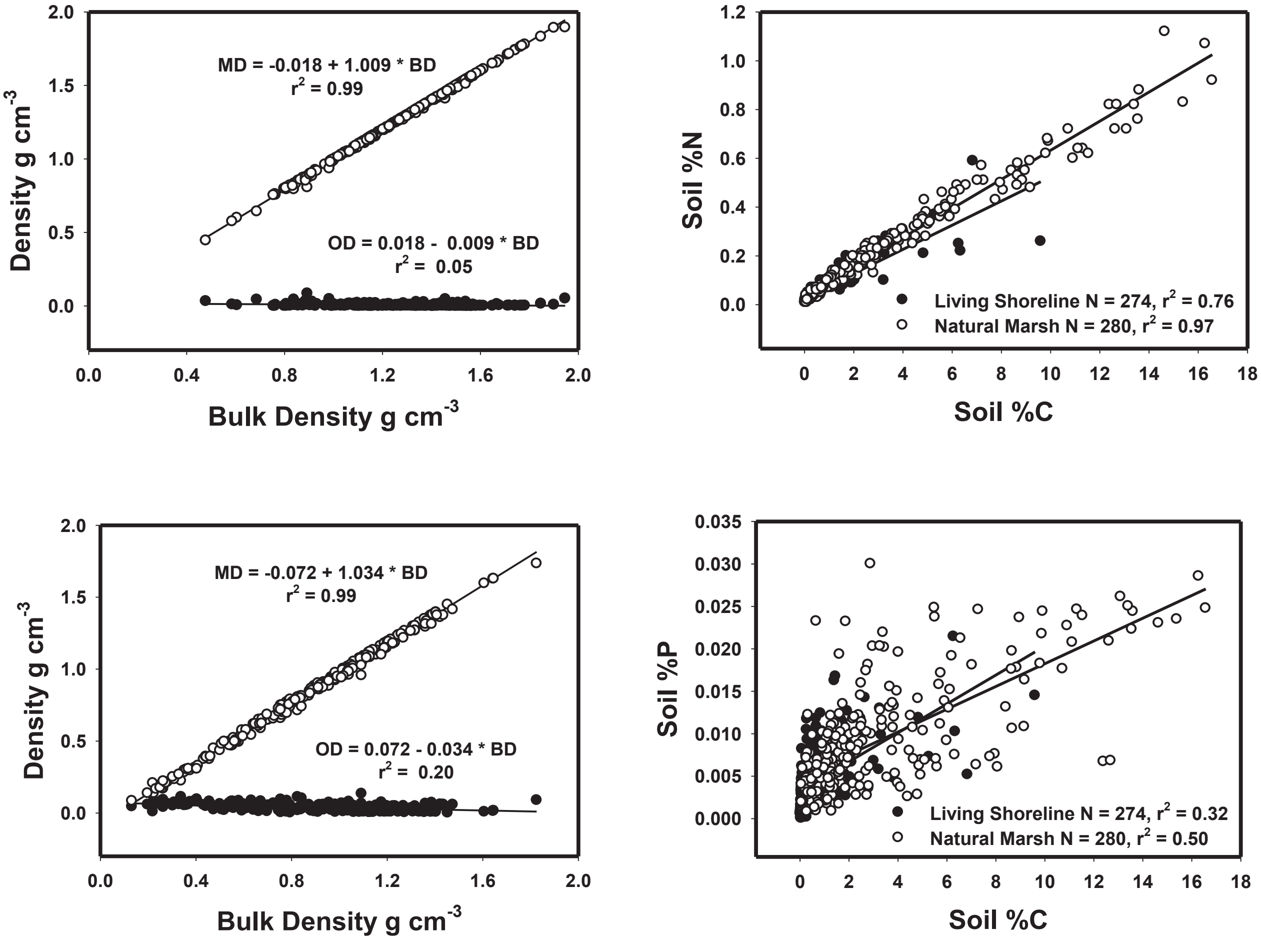

Fig. 3. Contributions of mineral density (MD) and organic density (OD) to bulk density (BD) in a) living shoreline, and b) natural marsh soils. Relationships between c) carbon and nitrogen, and d) carbon and phosphorus in living shoreline and natural marsh soils. All regressions shown are significant ($p < 0.05$).

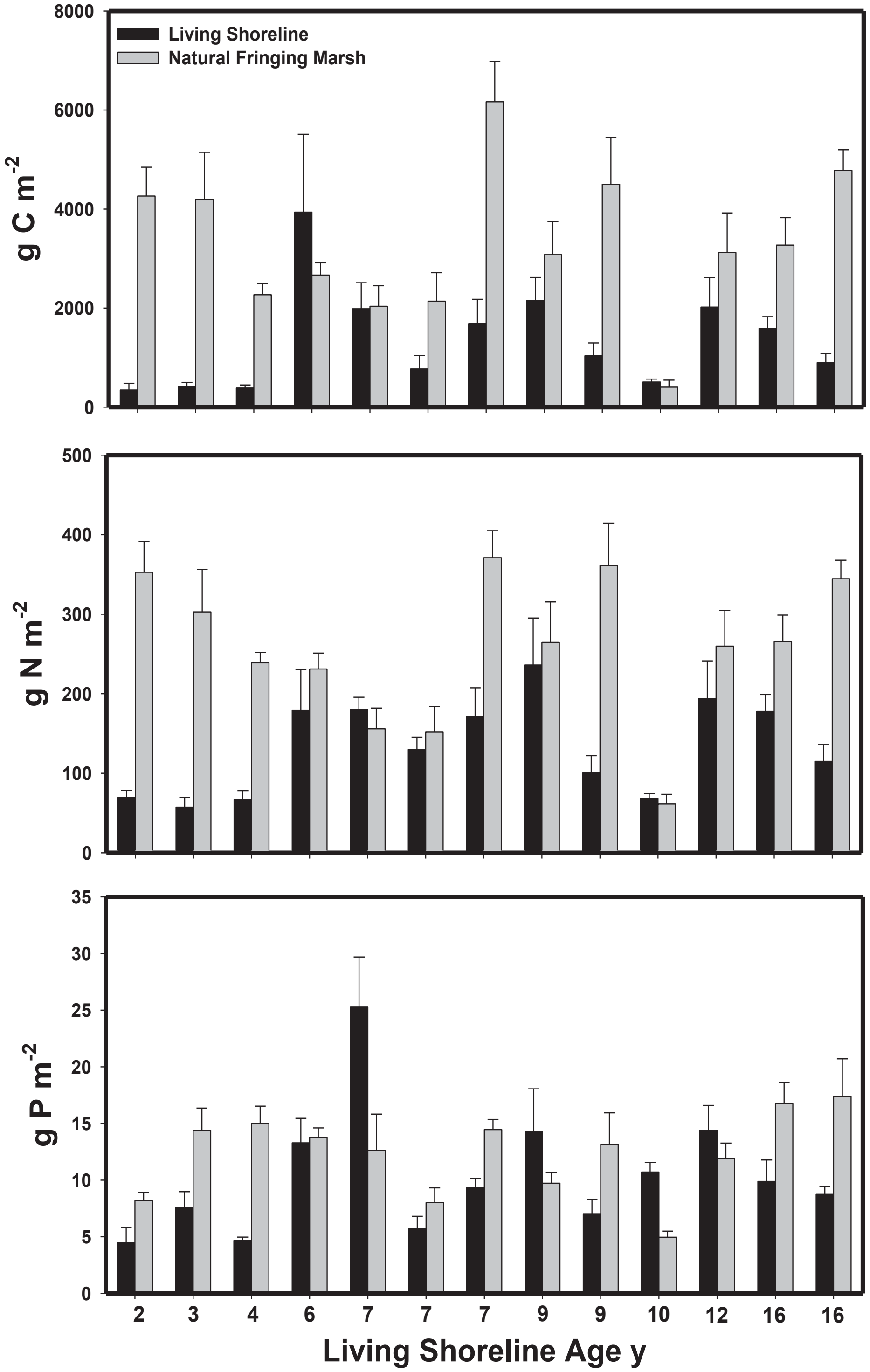

Fig. 4. Carbon, nitrogen and phosphorus in the top 0-20 cm of soil in living shoreline marshes and their natural fringing marsh pairs, with respect to living shoreline age. Bars are averages with standard errors (N=6).

Figure 5

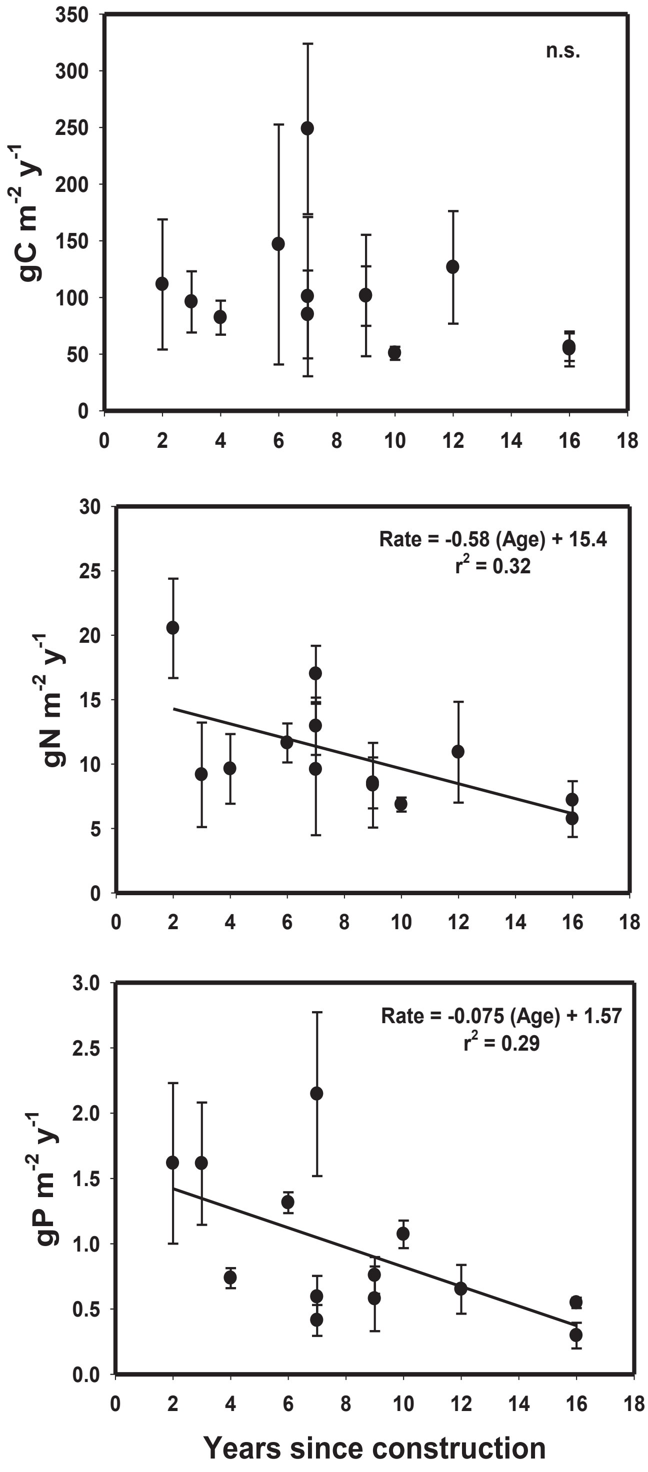

Fig. 5. Nutrient accrual in living shoreline marshes as a function of marsh age. Points are average accrual with standard error bars (N=6 measurements per marsh). Linear regression equations included for N and P; C accrual was not significantly correlated with age ($p > 0.05$).

Table 1. Location, age, land use characteristics surrounding each living shoreline marsh, and calculated isolation index. Developed, Agriculture and Natural categories refer to the number of square meters of each landuse type within a 1-km radius of the living shoreline. The index of isolation is a measure of the degree to which living shorelines are surrounded by other marshes in the shorescape.

Marsh	Lat	Long	Age y	Dominant Land cover	Developed (m^2)	Agriculture (m^2)	Natural (m^2)	Isolation Index (m)
BAHA	37.305569	-76.447000	16	Natural	113161	174387	2930140	3.99
CASI	37.324514	-76.427520	2	Natural	40143	27130	2986140	3.61
CEBU	37.312639	-76.549229	7	Ag/Mix	94663	870997	1696100	6.76
CHEN	37.486662	-76.329000	7	Ag/Mix	207183	352958	1542100	28.40
JOPO	37.331888	-76.445065	4	Ag/Mix	88227	522774	2101070	6.72
LAWS	36.896978	-76.271794	7	Developed	1063940	0	1204900	11.21
MART	36.893529	-76.285970	10	Developed	1349630	0	927144	28.73
OAHA	37.411058	-76.427266	12	Ag/Mix	85851	603660	2172420	8.02
TEAG	37.396954	-76.335979	16	Ag/Mix	168060	430037	1489860	14.45
USRY	37.037700	-76.335930	6	Developed	1171480	0	699941	29.52
WAVE	37.444115	-76.446810	3	Ag/Mix	95919	700849	2021680	4.24
WHHA	37.368960	-76.469700	9	Ag/Mix	90945	411775	2285550	8.67
WICR	37.368075	-76.485509	9	Ag/Mix	72256	380434	2513000	5.40

Table 2. Average (SE) nutrient accrual in the upper 20 cm of the thirteen living shoreline marshes, and years to reach equivalence with the paired natural marsh.

Nutrient	Accrual g/m2/y	Years to Equivalence	Range (y)
Carbon	104.7	23.7	0-63
	(14.9)	(5.8)	
Nitrogen	10.6	12.9	0-31
	(1.2)	(2.8)	
Phosphorus	1.0	6.2	0-23
	(0.2)	(2.1)	

Table 3. Elemental analysis of *Spartina* leaf tissue from living shoreline and natural marshes compared by marsh type and by species in a full factorial ANOVA design. Table data are average weight percent (SE) for marsh (N=78) and for species (N=39), with significant statistical comparisons noted with *. All marsh x species interactions were not significant (n.s.).

Element	Marsh Type			Species			Marsh x Species Interaction
	Living Shoreline	Natural Marsh	P	*S. patens*	*S. alterniflora*	P	
Carbon	44.920 (0.122)	44.696 (0.133)	0.212	45.282 (0.134)	44.332 (0.120)	<0.001*	n.s.
Nitrogen	2.320 (0.089)	2.135 (0.098)	0.166	2.164 (0.099)	2.291 (0.088)	0.340	n.s.
Phosphorus	0.082 (0.003)	0.072 (0.003)	0.035*	0.081 (0.003)	0.073 (0.003)	0.081	n.s.

Table 4. Comparison of average (SE) carbon, nitrogen and phosphorus pools in peak aboveground biomass and the upper 20 cm of soil from living shoreline and natural marshes.

	Living Shoreline		Natural Marsh	
	S. patens	*S. alterniflora*	*S. patens*	*S. alterniflora*
Aboveground	517	1389	114	1065
Biomass g/m^2	(126)	(293)	(57)	(407)
Plant %C	40.5	39.1	40.5	39.1
Plant C g/m^2	209	543	46	416
	(51)	(115)	(23)	(159)
Soil C g/m^2	1527	1230	3135	3462
Plant C:Soil C	0.14	0.44	0.01	0.12
Plant %N	1.18	1.39	1.18	1.39
Plant N g/m^2	6.1	19.3	1.3	14.8
	(1.5)	(4.1)	(0.7)	(5.6)
Soil N g/m^2	132	144	254	263
Plant N:Soil N	0.05	0.13	0.01	0.06
Plant %P	0.080	0.098	0.080	0.098
Plant P g/m^2	0.41	1.36	0.09	1.04
	(0.10)	(0.29)	(0.05)	(0.40)
Soil P g/m^2	10.7	10.9	13.3	11.4
Plant P:Soil P	0.04	0.12	0.01	0.09