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

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1 **ABSTRACT**

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

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

20

21 **1. Introduction**

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

29 Use of living shorelines for erosion control has increased along U.S. coasts since their
30 introduction in the 1980s. In Virginia, for example, the Living Shorelines Act in 2011 deemed
31 these constructed fringing marshes the preferred shoreline management practice. While in the
32 earlier years only about 1-3% of the shoreline construction permits requested were for living
33 shorelines, since 2011 about 15% are for living shorelines (CCRM, 2019). In contrast, armoring
34 (bulkhead and riprap revetment) permit requests declined during the same time period that
35 living shoreline use increased, although armoring continues to make up the majority of
36 requested projects. The use of bulkheads has dramatically declined from highs in the 1970s and
37 1980s of about 70% of the shoreline permits requested annually, to 38% in the 1990s and
38 2000s, with further declines in recent years (2011 to 2017) to 31%. Riprap revetment, another
39 form of armoring, has also declined slightly from its peak use in the 1990s and 2000s (47% of
40 the shoreline permits requested) to 40% (2011-2017) (CCRM, 2019). The increase in living
41 shoreline construction increases the total length of estuarine coastline occupied by fringing
42 marsh.

43 Natural fringing marshes are loosely defined as wetlands up to 30 m wide (Davis et al., 2015),
44 comprising intertidal habitat between upland and open water. These narrow bands of
45 vegetated marsh account for little total area relative to expansive coastal marshes, but they are
46 prominent estuarine features (Morgan et al., 2009). In Chesapeake Bay, for example, fringing
47 marshes cover just 42 km² vs 930 km² of total tidal wetland area (CCRM online database:
48 <http://www.vims.edu/ccrm/research/inventory/index.php>). Assuming an average 15 m width,
49 however, these fringing marshes conservatively occupy roughly 2,800 km of shoreline, which is
50 15% of the total 19,000 km of the Chesapeake Bay shoreline (CCRM, 2019). Similarly, narrow
51 fringing marshes <2 m wide comprise ~13% of the New River estuary in North Carolina (Currin
52 et al., 2015), and fringing marshes are the dominant marsh type in New England (Roman et al.,
53 2000). Functionally, fringing shoreline marshes intercept nutrients from upland groundwater
54 discharge (Valiela and Cole, 2002; Bowen et al., 2007; Beck et al., 2017) and may serve to
55 “connect” other estuarine habitats and habitat complexes (Able et al., 2012; Davis et al., 2012)
56 that would otherwise be isolated by coastal development. Whether isolation from other
57 habitat complexes might affect the extent or rate at which a created living shoreline develops
58 natural marsh characteristics is unknown.

59 The science of living shoreline ecosystems still is relatively young (Bilkovic and Mitchell, 2017),
60 yet numerous earlier studies compared ecosystem components of the broader general category
61 of created wetlands with natural wetland systems. From many years of plant and soil surveys,
62 Craft et al. (1998, 1999, 2002, 2003) documented the pace of ecosystem development in
63 created wetlands, noting that living plant biomass in constructed marshes typically reached
64 equivalence with natural marsh systems within five years. Soil nutrients, however,

65 accumulated more slowly in created marshes and could take decades to centuries before
66 reaching equivalence with natural systems. For living shoreline marshes, a similar story is
67 emerging, both in terms of rapid vegetation establishment (Currin et al., 2008) and longer-term
68 carbon sequestration and nitrogen accrual (Davis et al., 2015).

69 Created fringing marshes have become a popular tool for protecting uplands from the impacts
70 of coastal erosion (Broome et al., 1992; Theuerkauf et al., 2015), but few studies to date have
71 measured the accrual or processing of nutrients in living shoreline marshes relative to nearby
72 natural fringing marshes found in similar shorescape settings (Currin et al., 2008; Davis et al.,
73 2015; Beck et al., 2017). We measured the carbon, nitrogen, and phosphorus in soils and plants
74 from 13 living shoreline marshes of different ages in Chesapeake Bay, and tested the following
75 hypotheses: 1) nutrient pools in living shoreline marshes are less than their natural marsh pairs;
76 2) nutrient accrual decreases with living marsh age and/or degree of isolation in the estuarine
77 shorescape; 3) older living shoreline soils require fewer years to reach equivalence with the
78 nutrient content of their natural marsh pairs. Our overall objective was to assess the nutrient
79 storage function of living shoreline marshes constructed as an alternative to hardened
80 shorelines in estuarine shorescapes.

81 **2. Materials and methods**

82 *2.1. Location and description of study area*

83 Thirteen pairs of living shoreline marshes and nearby natural fringing marshes (separation
84 distance 55-845 m, average 395 m) in the southern portion of Chesapeake Bay were included
85 for study (Fig. 1). The living shorelines were constructed with a rock sill, behind which clean

86 sand fill was planted with *Spartina alterniflora* in the low marsh and *S. patens* in the high marsh.
87 Current practice is to fertilize during planting living shoreline marshes, but we do not know
88 whether the marshes in our study were fertilized when constructed. Living shoreline marshes
89 spanned an age range (years since construction) of 2-16 years and occurred in coastal
90 environments with different coverage of surrounding land use types (Table 1). We used GIS to
91 determine the landscape setting of each living shoreline, identifying within a 1-km radius the
92 dominant surrounding land use and total land area that was agricultural, developed, or natural
93 (i.e., forest, open space). In GIS we also created an index of isolation by calculating the average
94 distance (m) to marsh for all shoreline points within 1 km of each living shoreline marsh (Table
95 1). Marshes with a lower index of isolation are surrounded more extensively by tidal wetland
96 shorelines, whereas marshes with a high index are surrounded more extensively by shoreline
97 armoring (bulkheads, rip-rap) or other shoreline development or undeveloped open space (e.g.,
98 beaches).

99 **2.2. Soil comparisons**

100 During the 2018 growing season, soil cores to 30 cm were collected along three parallel
101 transects separated by at least 4 m and oriented perpendicular the shoreline. Cores were
102 obtained from the low marsh (dominated by *S. alterniflora*) and high marsh (dominated by *S.*
103 *patens*) of each living shoreline and paired, fringing natural marsh, then sectioned 0-5, 5-10, 10-
104 20, and 20-30 cm. For living shoreline marshes, plant roots had not yet penetrated into the 20-
105 30 cm sections.

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

124 **2.3. Plant comparisons**

125 From all 26 living shoreline and natural fringing marshes, we also harvested leaves from five *S.*
126 *alterniflora* and five *S. patens* plants located in three low and three high elevation sections,
127 respectively. The leaves were oven dried at 60C, then milled. We minimized more extensive,

128 destructive sampling of aboveground vegetation to a subset of four natural fringing marshes. At
129 peak biomass in late summer, we clipped all aboveground vegetation from $\frac{1}{4}$ m² quadrats in
130 triplicate from low and high marsh elevations in these four marshes, then air-dried and milled
131 the vegetation. For leaves and for vegetation from quadrats, total carbon, nitrogen and
132 phosphorus were determined using the methods described for soils. Stem counts and average
133 stem heights at peak biomass were obtained in duplicate along six transects for *S. alterniflora*
134 and *S. patens* from low and high marsh stands in all 26 living shoreline and natural fringing
135 marshes. We then used an allometric relationship established for *Spartina* species in
136 Chesapeake Bay tidal wetlands to estimate aboveground plant biomass as a function of stem
137 density and stem height (Beck et al., 2017):

138 $S. alterniflora$ biomass = $(0.1807e^{0.0332 * \text{Stem Height}}) * \text{Stem Density}$

139 $S. patens$ biomass = $(0.0381e^{0.04 * \text{Stem Height}}) * \text{Stem Density}$

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

144 **2.4. Statistics**

145 We plotted vertical soil profiles for living shoreline and natural fringing marshes. Paired t-tests
146 compared the mean concentrations of nutrients at each depth. We used regression analysis for
147 examining 1) organic and inorganic contributions to soil bulk density, 2) soil carbon
148 relationships to soil nitrogen and phosphorus, and 3) nutrient accrual as a function of marsh

149 age. For plant comparisons, elemental contents of leaf tissues were compared by marsh type
150 and by *Spartina* species using a full factorial ANOVA design. Finally, we used generalized linear
151 models with stepwise regression to examine aboveground biomass and belowground nutrient
152 storage and accrual in living shoreline marshes as a function of developed land use and relative
153 isolation in the coastal shorescape.

154

155 **3. Results**

156 **3.1. Soil Comparisons**

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

166

167 Averaged from high and low marsh, the nutrient pools in the top 20 cm of living shoreline soils
168 were less than in natural marsh soils for 10 of the 13 marsh pairs examined (Fig. 4). The soil
169 carbon, nitrogen and phosphorus pools in living shoreline marshes tended to increase with age,
170 but the variability among sites was large. Only the soil nitrogen pool was significantly and

171 positively correlated with age ($r^2 = 0.503$; $F = 13.152$, $p = 0.004$). Neither carbon nor phosphorus
172 was correlated with living shoreline age ($p > 0.05$). Further, the concomitant, large range in
173 nutrient pool sizes among natural marshes (Fig. 4) demonstrates the variability in these
174 established, fringing wetlands used as reference to the paired living shoreline marshes.

175
176 In living shoreline soils, nutrient accrual plotted with respect to marsh age exhibited a variable
177 pattern, both among marshes and among nutrients (Fig. 5). Average carbon accrual ranged
178 from a high of $\sim 250 \text{ g m}^{-2} \text{ y}^{-1}$ in a seven year-old marsh to $< 50 \text{ g m}^{-2} \text{ y}^{-1}$ in the oldest living
179 shoreline measured (16 years), but was not significantly correlated with age. Both nitrogen and
180 phosphorus accrual in soils were negatively correlated with age ($p < 0.05$). Annual accrual of soil
181 nitrogen was highest ($21 \text{ g m}^{-2} \text{ y}^{-1}$) in the youngest living shoreline measured (two years) and
182 lowest ($6 \text{ g m}^{-2} \text{ y}^{-1}$) in the oldest marsh. Finally, phosphorus accrual was highest ($2.1 \text{ g m}^{-2} \text{ y}^{-1}$) in
183 a seven year-old marsh and lowest ($0.2 \text{ g m}^{-2} \text{ y}^{-1}$) in the oldest marsh (Fig. 5).

184
185 Based on current pool sizes and the nutrient accrual in the upper 20 cm of soil of each marsh,
186 we then estimated average number of years required to reach equivalence with the paired
187 natural marsh, assuming those rates would remain constant over time (Table 2). For two of 13
188 living shoreline marshes, the carbon and nitrogen pools were already greater than the natural
189 marsh; the phosphorus pool was already greater than the natural marsh for four of 13 living
190 shoreline marshes. The largest average number of years to equivalence was greatest for soil
191 carbon (23 y), with a range of 0-63 years. The years to equivalence were lower for soil nitrogen
192 (13 y) and lowest for soil phosphorus (6 y) (Table 2).

193

194 **3.2. Plant comparisons**

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

201

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

209

210 **3.3. Nutrient Accrual, Plant Biomass, Land Use and Marsh Isolation**

211 Finally, we considered features of the surrounding shorescape (Table 1) and how they might
212 affect plant biomass and soil nutrient accrual in living shorelines (Fig. 4, Fig. 5, Table 4). From
213 generalized linear model analysis with log transformation of the dependent variables, however,
214 none of our measures of soil nutrients (i.e., accumulated soil stocks, accumulation rates of

215 carbon, nitrogen or phosphorus) correlated significantly with any land use variables or with the
216 marsh isolation index. In contrast, aboveground biomass of *S. patens* was positively correlated
217 with the area of surrounding development in a 1-km radius ($\beta= 1.2 \times 10^{-6}$; $p = 0.021$).

218

219 **4. Discussion**

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

232 Living shoreline soils tend to lag behind older natural marsh soils because of the relative
233 absence of soil organic matter that—when present—decreases bulk density and stores carbon
234 and nitrogen (Fig. 3). Soil carbon and nitrogen are strongly correlated, whereas the correlation
235 between soil carbon and phosphorus is much weaker. In addition to incorporation into organic
236 matter in marsh soils, phosphorus can also be bound with clays (Bai et al., 2017) and with

237 different inorganic iron and calcium minerals (Hartzell et al., 2010), so that the pool of
238 phosphorus in living shoreline soils can grow more quickly over time, relative to carbon or
239 nitrogen for which organic forms dominate in soils. As a result, the average “time to
240 equivalence” for phosphorus from living shoreline soils is about half that of nitrogen, and one-
241 fourth that of carbon (Table 2).

242 The leaf tissues of *S. alterniflora* and *S. patens* have similar concentrations of carbon, nitrogen
243 and phosphorus, averaged across living shoreline and natural fringing marshes (Table 3).

244 Further, the aboveground biomass of living shoreline plants was at least as large as natural
245 marsh plants (Table 4). Thus, the aboveground growth of plants in living shoreline marshes does
246 not appear to lag behind natural marshes despite the smaller pools of nutrients belowground.

247 Many living shoreline plantings include initial applications of timed-release N and P fertilizers,
248 which would stimulate aboveground growth. Nutrients in aboveground tissues in perennial
249 plants from living shoreline marshes represent a larger percentage of the total soil nutrient pool
250 (Table 4), but the growth of plants is about the same as from natural marshes. The similarity
251 could be because: 1) the available soil nutrient pool in either abundance or stoichiometric ratio
252 (Qiao et al., 2018) may be sufficient to support similar aboveground growth (Hopkinson and
253 Schubauer, 1984); 2) the growth in both marsh types may be supported primarily by tidal
254 nutrient exchange (Steever et al., 1976) or by groundwater (Beck et al., 2017); 3) plant growth
255 in living shoreline marshes may be limited by nutrients, whereas plant growth in natural marsh
256 soils may be limited to a similar extent by other factors such as more reducing conditions and
257 elevated soil sulfide concentrations driven by higher soil carbon content (Fig. 2) that would
258 inhibit growth (Howes et al., 1986).

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

274 Aboveground biomass of *S. patens* was positively correlated with the total area of developed
275 land within a 1-km radius, suggesting a local influence on plant production.

276 The fringing natural marshes used for comparison to living shoreline marshes exhibited a broad
277 range in soil nutrient pools (Fig. 4). We had expected a smaller range because these marshes
278 are much older than their living shoreline pairs and have had time to accumulate nutrients.

279 Some of the natural marshes, however, showed evidence of erosion and were steeply scarped
280 at the water's edge, suggesting active loss of marsh owing to ongoing exposure to wave energy

281 from coastal storms and/or sea level rise. In addition, other natural marshes had evidence of
282 sand deposits from storm overwash, and others were sites of significant wrack deposits.
283 Differences in sediment characteristics might also be related to marsh elevation (Rezek et al.,
284 2017). Relative to more expansive marshes that form in more protected estuarine areas, these
285 fringing marshes are exposed to physical factors and other environmental disturbances
286 (Morgan et al., 2009) that may alter the site-specific dynamics of soil development, plant
287 growth and nutrient accumulation (Feagin et al., 2009; Miller et al., 2001; Macreadie et al.,
288 2013).

289

290 **5. Conclusion**

291 Given the observed similarities in plant growth between living shoreline and natural fringing
292 marshes sampled from a range of shorescape settings, we conclude that the plant performance
293 and soil nutrients of created living shoreline marshes are not negatively affected by isolation. In
294 other words, a living shoreline marsh surrounded by development and hardened shoreline
295 structures like bulkheads and riprap might grow and accumulate nutrients at rates similar to a
296 living shoreline created in a shorescape setting already replete with natural marsh.

297 Surrounding urbanization can affect the structure and function both restored and natural
298 marshes (Silliman and Bertness, 2004; Windham et al., 2004). For living shorelines, however,
299 the ecosystem services and functions of shoreline protection, nutrient cycling, plant growth and
300 carbon storage appear to be satisfied irrespective of shorescape setting. Other functions (e.g.,

301 habitat support for fish, invertebrates and other wildlife) may be similarly satisfied by living
302 shoreline marshes created across gradients in coastal development.

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304

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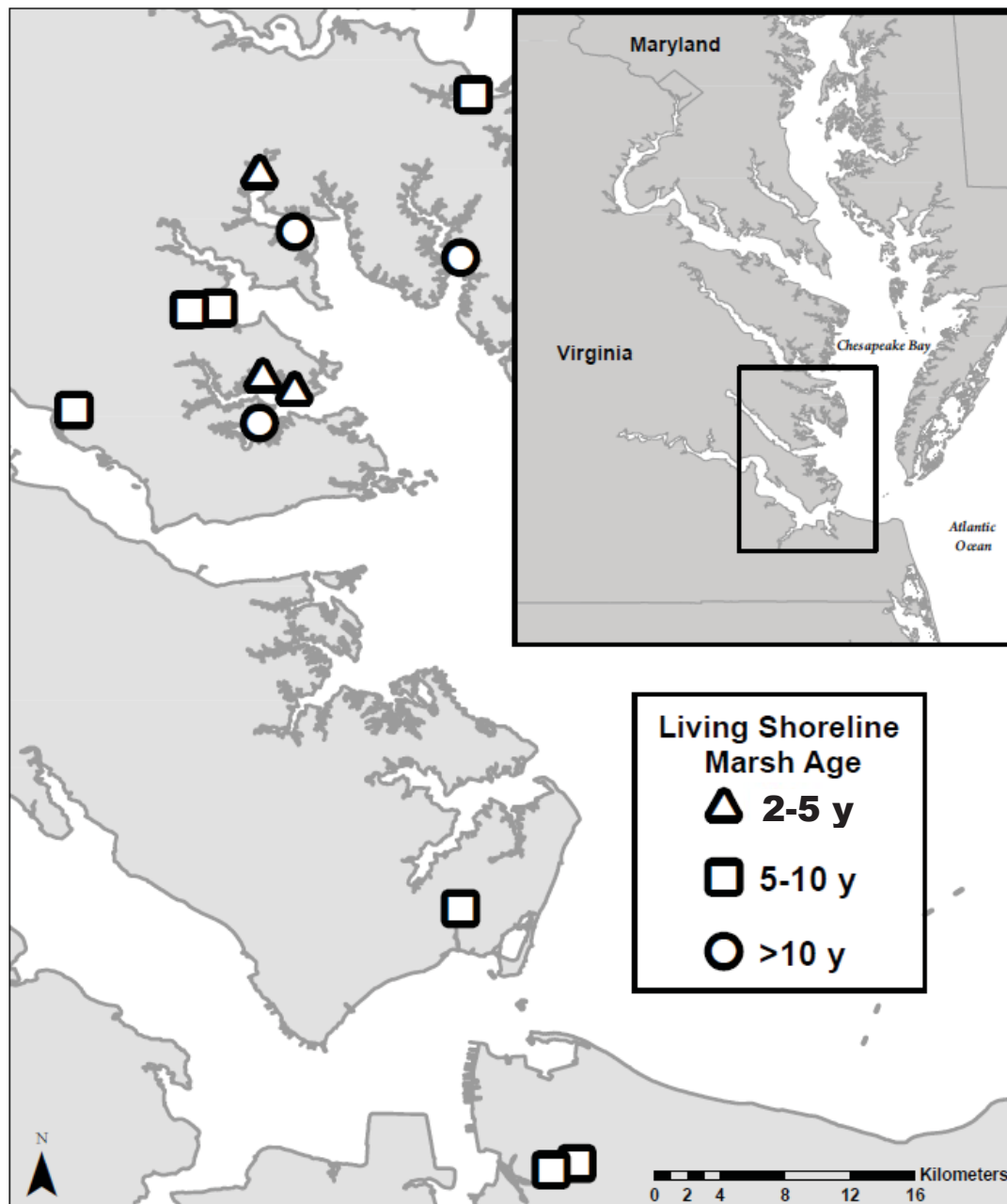


Fig. 1. Locations of thirteen paired living shoreline and fringing natural marshes in southern region of the Chesapeake Bay estuary. The ages of living shoreline marshes ranged from 2-16 years, and distance to the paired natural marshes was 55-845 m.

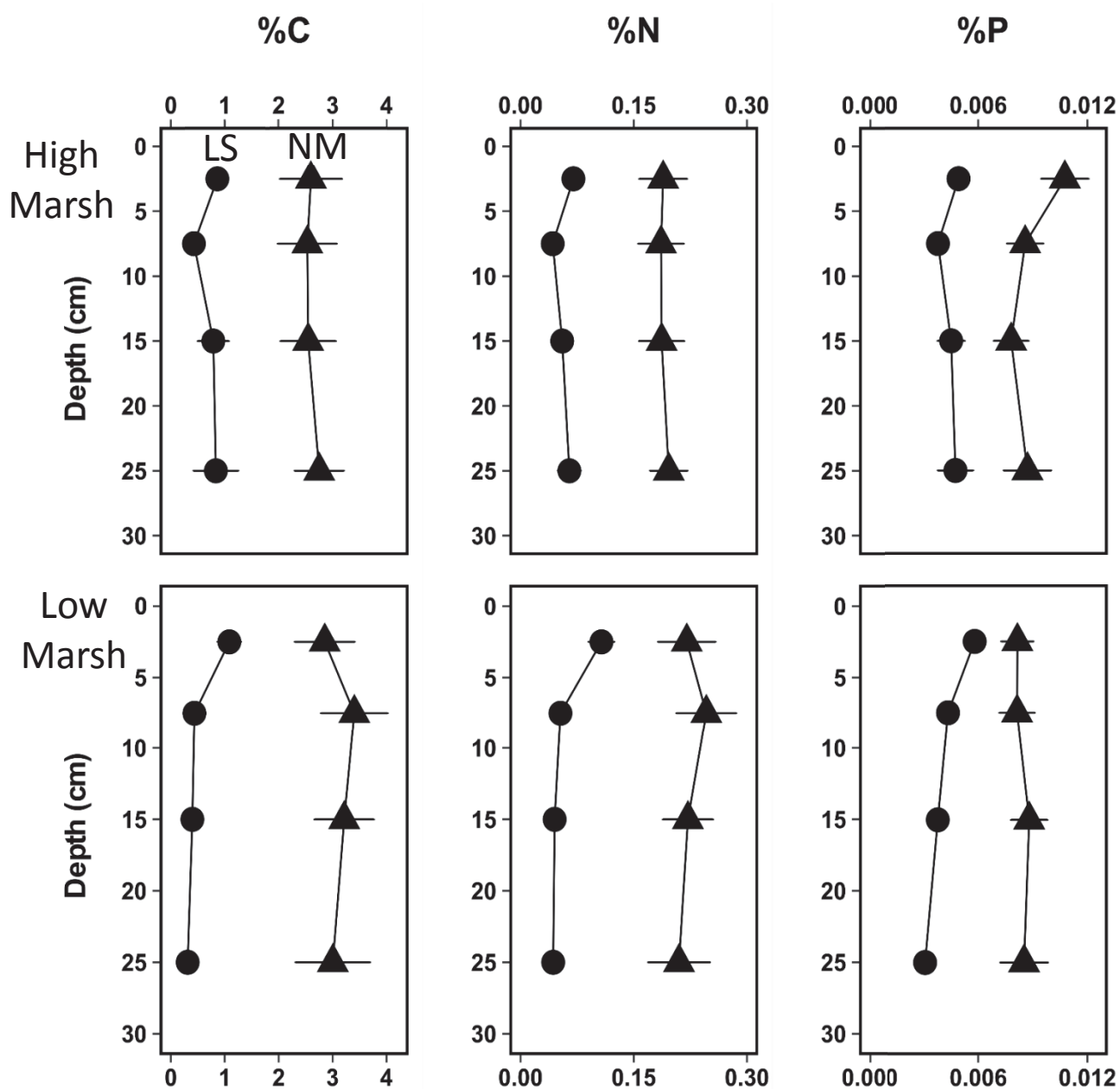


Fig. 2. Depth profiles of bulk soil nutrients (measured as a weight percent of dry soil) from high and low marsh locations of living shoreline and natural marshes. Points are averages with standard error bars (N=6).

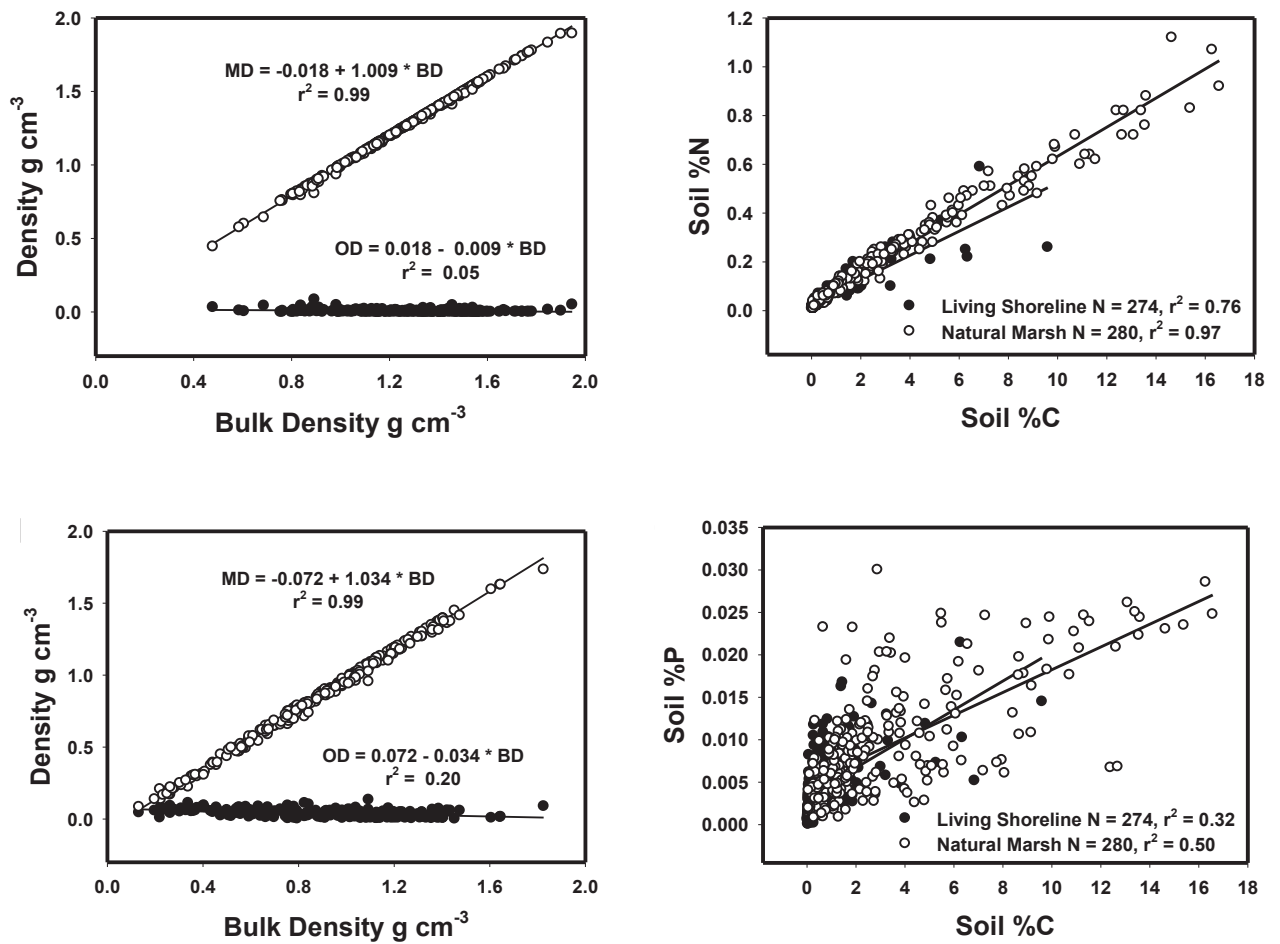


Fig. 3. Contributions of mineral density (MD) and organic density (OD) to bulk density (BD) in a) living shoreline, and b) natural marsh soils. Relationships between c) carbon and nitrogen, and d) carbon and phosphorus in living shoreline and natural marsh soils. All regressions shown are significant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

Figure 4

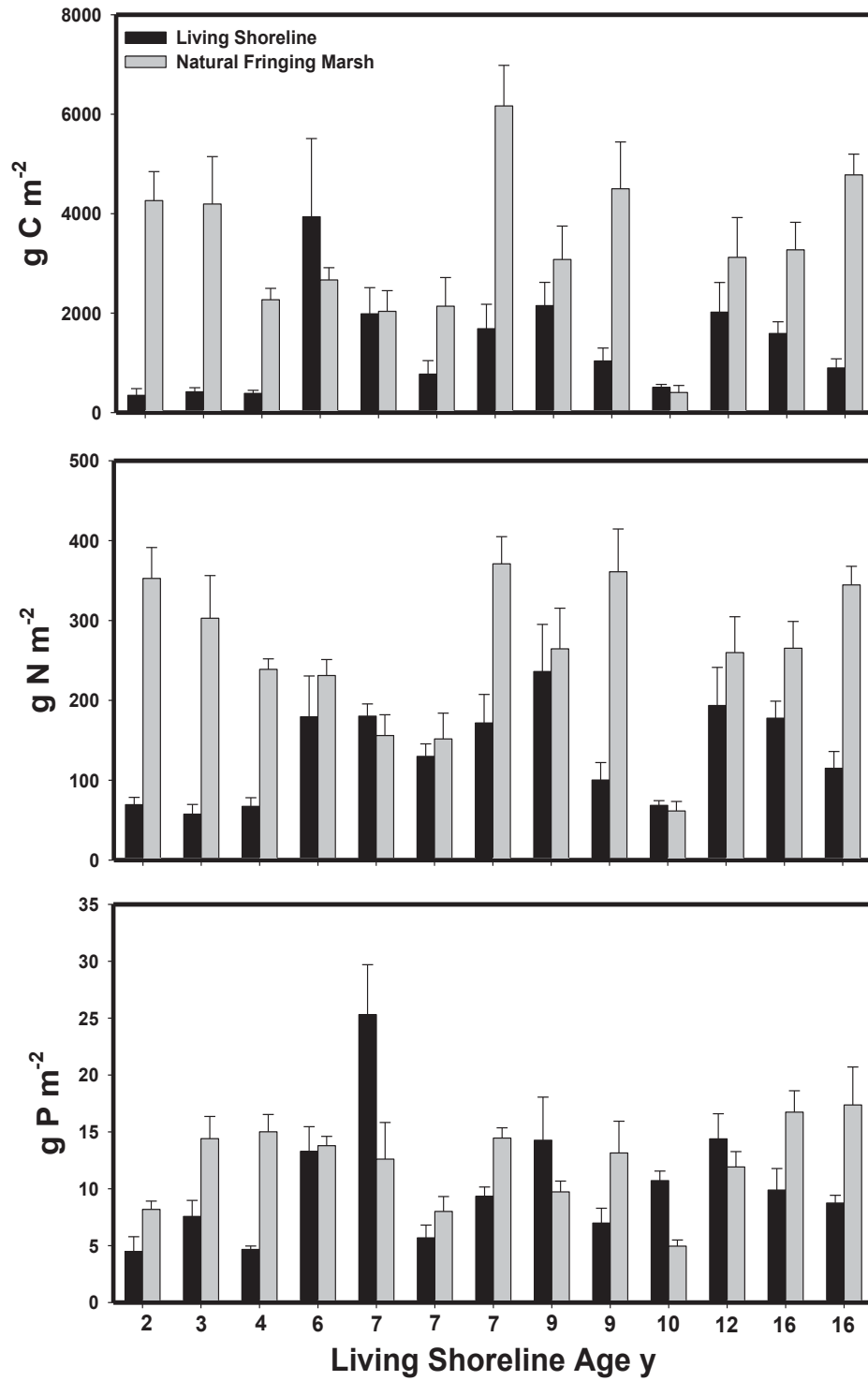


Fig. 4. Carbon, nitrogen and phosphorus in the top 0-20 cm of soil in living shoreline marshes and their natural fringing marsh pairs, with respect to living shoreline age. Bars are averages with standard errors (N=6).

Figure 5

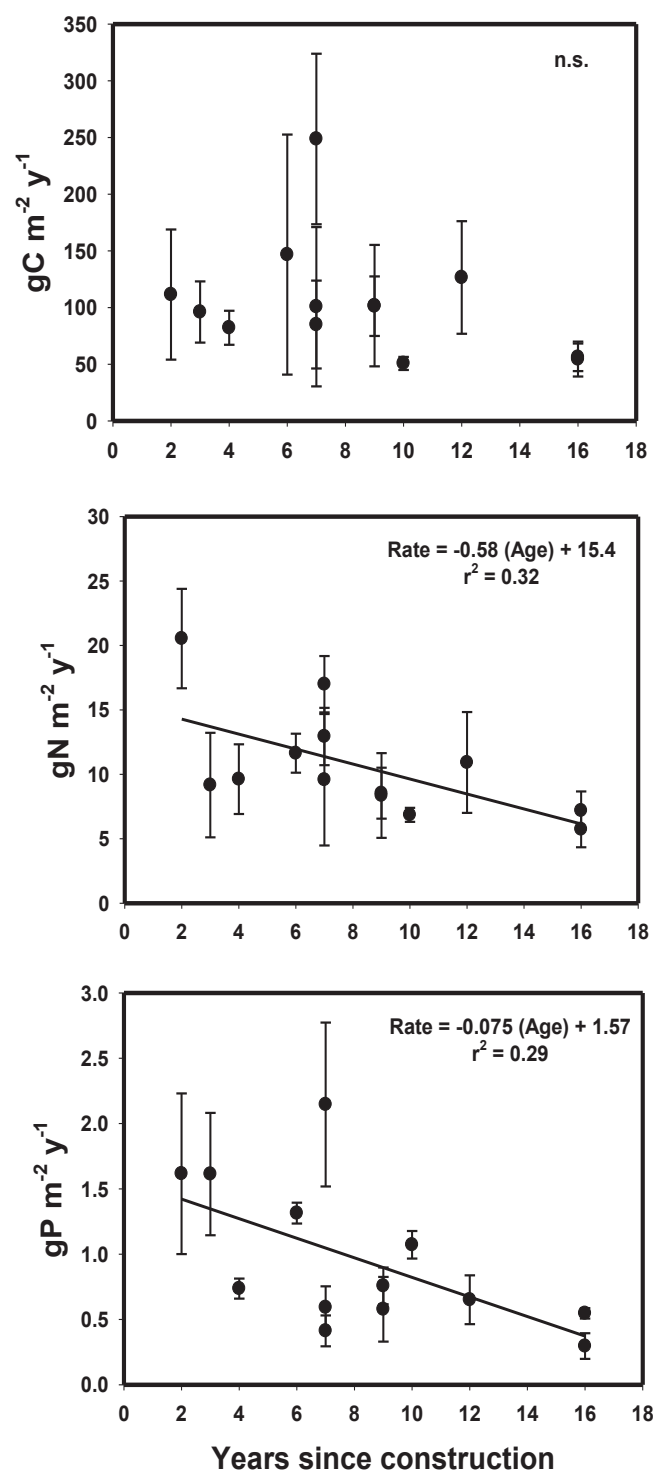


Fig. 5. Nutrient accretion in living shoreline marshes as a function of marsh age. Points are average accretion with standard error bars (N=6 measurements per marsh). Linear regression equations included for N and P; C accretion was not significantly correlated with age ($p > 0.05$).

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/m ² /y | Years to Equivalence | Range (y) |
|------------|--------------------------------|-------------------------|-----------|
| Carbon | 104.7 (14.9) | 23.7 (5.8) | 0-63 |
| Nitrogen | 10.6 (1.2) | 12.9 (2.8) | 0-31 |
| Phosphorus | 1.0 (0.2) | 6.2 (2.1) | 0-23 |

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 | Natural | P | <i>S. patens</i> | <i>S. alterniflora</i> | P | |
| | Shoreline | Marsh | | | | | |
| 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 | |
|--------------------------------------|------------------|------------------------|------------------|------------------------|
| | <i>S. patens</i> | <i>S. alterniflora</i> | <i>S. patens</i> | <i>S. alterniflora</i> |
| Aboveground Biomass g/m ² | 517 (126) | 1389 (293) | 114 (57) | 1065 (407) |
| Plant %C | 40.5 | 39.1 | 40.5 | 39.1 |
| Plant C g/m ² | 209 (51) | 543 (115) | 46 (23) | 416 (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 (1.5) | 19.3 (4.1) | 1.3 (0.7) | 14.8 (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 (0.10) | 1.36 (0.29) | 0.09 (0.05) | 1.04 (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 |