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Impacts of seawalls on saltmarsh plant communities in the Great Bay Estuary, New Hampshire USA

Catherine M. Bozek and David M. Burdick*
*Department of Natural Resources, Jackson Estuarine Laboratory, University of New Hampshire, 85 Adams Point Road, Durham, NH 03824, USA; *Author for correspondence (e-mail: dburdick@cisunix.unh.edu; phone: +1-603-862-5129; fax: +1-603-862-1101)*

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Abstract

Seawalls are often built along naturally dynamic coastlines, including the upland edge of salt marshes, in order to prevent erosion or to extend properties seaward. The impacts of seawalls on fringing salt marshes were studied at five pairs of walled and natural marshes in the Great Bay Estuary of New Hampshire, USA. Marsh plant species and communities showed no difference in front of walls when compared with similar elevations at paired controls. However, seawalls eliminated the vegetative transition zone at the upper border. Not only did the plant community of the transition zone have high plant diversity relative to the low marsh, but it varied greatly from site to site in the estuary. The effects of seawall presence on other marsh processes, including sediment movement, wrack accumulation, groundwater flow, and vegetation distribution and growth, were examined. Although no statistically significant effects of seawalls were found, variation in the indicators of these processes were largely controlled by wave exposure, site-specific geomorphology and land use, and distance of the sampling station from the upland. Trends indicated there was more sediment movement close to seawalls at high energy sites and less fine grain sediment near seawalls. Both trends are consistent with an increase in energy from wave reflection. The distribution of seawalls bordering salt marshes was mapped for Great and Little Bays and their rivers. Throughout the study area, 3.54% of the marshes were bounded by shoreline armoring (5876 m of seawalls along 165.8 km of marsh shoreline). Localized areas with high population densities had up to 43% of marshes bounded by seawalls. Coastal managers should consider limiting seawall construction to preserve plant diversity at the upper borders of salt marshes and prevent marsh habitat loss due to transgression associated with sea level rise.

Introduction

Dynamic coastal features such as salt marshes and beaches exist in a natural cycle of erosion and accretion (Boorman and Hazelden 1995; Pope 1997). This cycle usually goes unnoticed by humans, until they build structures near the coast or otherwise invest in coastal resources (Jacobson 1997). As human development expands and coastal areas experience erosion due to sea level rise, seawalls will continue to be constructed along much of the coastline. State and federal laws regulate the construction of seawalls in or near salt marshes, but permits are still granted and seawalls continue to be built. The building of structures within salt marshes is regulated for good reason. Salt marshes are home to a diversity of organisms, and provide many important ecological functions and values that benefit society (Costanza et al 1997; Mitsch and Gosselink 2000). Salt marshes provide an important buffer between land and coastal waters, improving water quality (Valiela and Cole 2002) and protecting the upland from erosion (Mitsch and Gosselink 2000; Morgan 2000). As sea level rises, marshes can continue to act as a buffer, but only if they build in elevation with the rising water level. Coastal marshes can maintain their position relative to sea level by accreting mineral sediments and organic matter, and by migrating over the upland (Nuttle et al. 1997). Unfortunately coastal development, especially seawalls, will prevent marshes from migrating landward into the upland (Boorman 1992) and in many areas this will result in marsh loss. Loss of marsh at the upper transition zone, where it meets the upland, will be most pronounced along armored shorelines.

The effect of seawalls on marsh sedimentary processes has not been well studied, but some reports attribute observed marsh erosion to scour caused by waves reflecting off of seawalls and bulkheads, or to alteration of the tidal flow by seawalls (Harris 1981; Harmsworth and Long 1986). Studies of beaches have found that wave reflection off seawalls increases sediment movement, if only temporarily (Jacobson 1997; Pope 1997). However, such sediment disturbance in marshes can affect vegetation by removing fine grains and the nutrients that are associated with them, thereby lowering growth rates (Keddy 1985). Sediment movement caused by wave exposure can also prohibit seedling emergence, uproot or bury vegetation, and undermine the sediment in which the plants are rooted (Keddy 1985; Kennedy and Bruno 2000).

From initial observations, it appears that wrack might accumulate against a structure in the marsh, such as a seawall, rather than along the gentle slope of a marsh with a natural transition to the upland. Wrack accumulation is a significant process in the salt marsh, impacting the distribution of vegetation in the area (Hartman 1988) through shading, smothering, or releasing allelopathic compounds (Valiela and Rietsma 1995).

Groundwater from the upland passes through the marsh on its path towards the estuary. Groundwater can discharge onto the marsh surface through seepage faces on the upland border, into the base of marsh soil from the underlying aquifer, or under marsh sediments and out of tidal creek bottoms (Harvey and Odum 1990; DeSimone et al. 1998; Schultz and Ruppel 2002). Low permeability sediments influence how groundwater flows along these pathways (Harvey and Odum 1990; Schultz and Ruppel 2002). If seawalls act as a low permeability layer at the upland-marsh boundary, they may reduce groundwater flow onto the marsh surface. Different plant species have varying tolerances to salinity (Bertness 1991a), so reduced groundwater flow may increase salinity and impact vegetation distribution and growth characteristics (Smart and Barko 1980; Bertness 1991a; Portnoy and Valiela 1997; Mendelssohn and Morris 2000).

In the Great Bay Estuary, it appears that many seawalls are built in the upper area of narrow fringing marshes. Fringing marshes are narrow and individually small in area (Morgan 2000) and are therefore often overlooked in surveys designed to estimate the total marsh area of a region. Jacobson et al. (1987) found that earlier studies greatly underestimated the total marsh area in the state of Maine, probably because many small marshes were missed as a result of inaccurate mapping techniques or poor quality equipment. However, fringing marshes contribute significantly to the area of northern New England salt marshes, and they provide many important functions, such as filtration and trapping of sediments, dampening of wave energy, maintenance of plant diversity, and plant production (Morgan 2000).

We investigated the type and extent of impacts that seawalls have on marsh processes that are important for maintaining health and function, (sediment movement, wrack accumulation, groundwater flow, and vegetation growth). In addition, plant communities of marshes bordered by seawalls were compared to communities with natural transitions to upland. Finally, the linear extent of marshes with walled and non-walled upland borders were surveyed throughout the Great and Little Bays and their tributaries. Understanding the extent of seawall effects in salt marshes will help managers regulate these structures to protect public resources.

Methods

Study sites

Five study sites were chosen in the Great Bay Estuary (Figure 1), with each site consisting of paired wall (marsh with a seawall at the upland border) and control (marsh with natural transition to the upland) areas. Control areas were located either adjacent to the wall or in a nearby location with similar fetch and orientation. Site location varied greatly, from NC, to the bays (BR, CP, PR), to a tidal river (TL). All of the walls were constructed of large stones; CP was the only site where the rock wall was cemented. The sites were fringing marshes dominated by *Spartina alterniflora* Loiseleur. Sites BR, CP, and NC had sand and gravel beach areas in the swash zone, PR had sparse beach areas, and TL had continuous vegetation.

Marsh processes were assessed in front of the wall, and in the corresponding area of control marsh. In the wall areas, data were collected at three horizontal distances from the wall (0.5 m from the base of the wall, 1.5 m from the wall, and half-way between the wall and the seaward edge of the marsh) along three randomly located transects (Figure 2). Three random transects were also established in the control area, with the 0.5 m distance set using a laser level at the average elevation of the 0.5 m distance samples of the wall area.

To assess vegetation diversity, additional stations were established every meter to the high tide line (determined by disappearance of salt tolerant plants) in the control areas. The high tide mark on the wall was assumed to be along its face, since there were no marsh species above the wall at any of the study sites. This set-up divided the sites into three main communities: the lower marsh in front of the wall, the lower marsh in the control area, and a transition community located between the lower marsh and the upland in the control area.

Three factors were used to rate study site exposure: fetch, orientation, and marsh width. The mean fetch was calculated by averaging the distance to the opposite shore perpendicular to the site and the distances to the shores located 45° from either side of the perpendicular (Knutson et al. 1981; Morgan 2000). Site

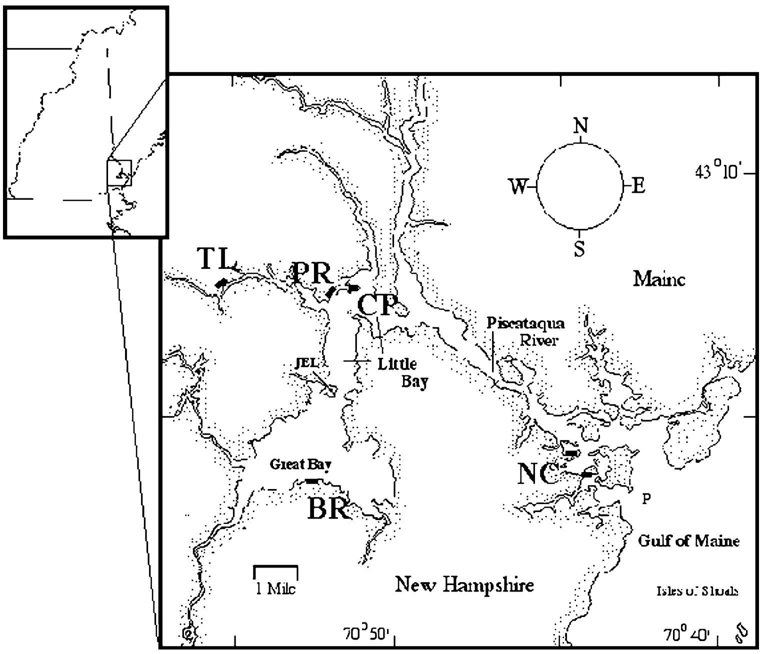

Figure 1. Study sites throughout Great Bay Estuary, NH. Sites are named for their street location. BR = Bayridge Road, Stratham; CP = Cedar Point Road, Durham; TL = Town Landing Road, Durham; NC = New Castle Avenue, Portsmouth; and PR = Piscataqua Road, Durham.

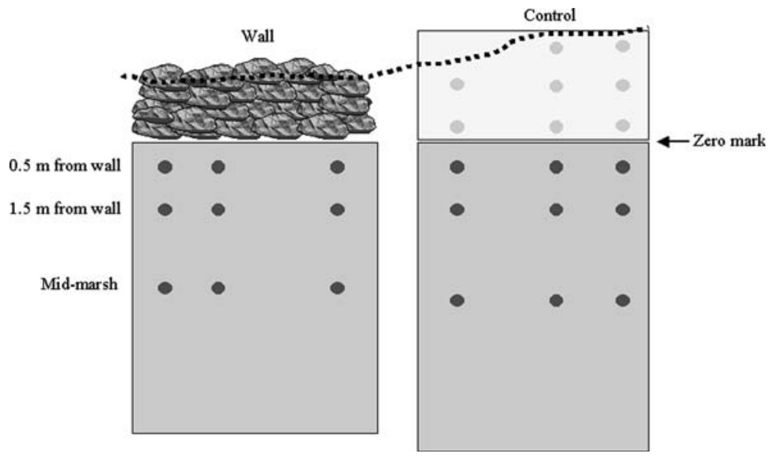

Figure 2. Typical site layout for vegetation diversity sampling. Samples are taken along three randomly located transects in both the wall and control areas. Sampling stations are located in the lower marsh at three distances from the wall or zero mark (0.5, 1.5 m and mid-marsh). In the control area, sampling stations for sampling plant diversity were located along the three transects, at every meter from the zero mark to the high tide line.

averages were ranked, with the largest fetch receiving a "1" and the shortest fetch a "5". The orientation of each site was determined. The two sites facing north received a "1," as these shores receive strong energy from northeastern storms. The south-facing site received a "5" and the remaining sites faced southeast and received a "3". The marsh width in front of the wall was measured along the three sampling transects. Wider marshes provide the upland with greater protection from wave energy (Boorman and Hazelden 1995), so the smallest mean width (5.3 m) received a rank of "1" and the largest width (17.5 m) a "5." The ranked values of fetch, orientation, and width were multiplied, giving a unique exposure value for each site, ranging from 5 (most exposed) to 30 (least exposed) (Table 1). Sites are arranged in order of exposure on the *x*-axis of figures, with the highest exposure on the left.

Sediment accumulation rates and characteristics

Sediment pads were used to measure sediment accretion. The pads were constructed from Mylar discs (8 cm diameter), which were pre-weighed and pinned to squares of sheet metal, then attached flush to the marsh surface using sod staples (Morgan 2000, modified from Reed 1989). Pads were collected approximately every three weeks for five periods during summer and fall of 2002. After collection, the discs were dried at 45 °C for 2–3 days, and then weighed. The amount of sediment was calculated as grams of sediment deposited per square meter per day.

Sediment samples were collected at the 0.5 m and mid-marsh stations in the center transect of the wall and control areas of each site, using a 3.6 cm diameter corer to a depth of 5 cm. The cores were stored at 5 °C, then organic matter and salts were removed and grain size analysis was

Table 1. Fetch, orientation, and marsh width ranking, and final exposure score for all sites.

Site	Fetch ranking	Orientation ranking	Width ranking	Overall exposure ranking
BR	1	1	5	5
NC	4	1	3	12
CP	3	5	1	15
PR	2	3	4	24
TL	5	3	2	30

Lower numbers indicate higher wave exposure.

performed according to the methods of Folk (1980). Gravel, sand, silt, and clay class sizes were used in the data analysis. Duplicate cores of the samples used in grain size analysis were analyzed for bulk density and loss on ignition (LOI). Bulk density was determined by drying the core (4 days at 65 °C), then dividing the weight by the core volume. A subsample of the dried material was combusted in a muffle oven (5 h at 450 °C), then weighed to determine the percent LOI for an assessment of organic matter (Craft et al. 1991).

To collect pore water samples, wells were made from PVC pipes and inserted to a depth of 35 cm at each sampling station. A hand held, temperature-compensated refractometer was used to measure salinity on five dates in summer and fall of 2002.

Wrack accumulation and vegetation characteristics

Wrack and vegetative characteristics were measured within two 0.5 m^2 rectangular quadrats laid end to end at each sampling station. The data from the two quadrats were averaged, resulting in one number for each station. The percent of area covered by wrack within the quadrat was estimated. If there was greater than 3% cover, the thickness of the wrack at three points within each quadrat was measured using calipers, and then averaged.

For plants, the three tallest stem heights of each species were measured, and the canopy height in each quadrat was measured as the point where 80% of the plants were shorter than that height. Biomass samples were taken from clip plots in a 0.25 m^2 section of the quadrat furthest from the well and sediment pad at each station. Dead material was discarded, then the remaining plant material was dried at 60 °C for 3 days and weighed. The percent of area covered by each species was estimated at all sampling stations to the high tide line. Species were identified according to Peterson and McKenny (1968), Tiner (1987), and Gleason and Cronquist (1991).

Mapping marshes bound by seawalls

A survey of fringing marshes and seawalls was conducted by boat in Great Bay and Little Bay, as well as in the major tributary rivers leading into the bays. A study by Ward et al. (1993) outlined the marsh areas of the Great Bay Estuary on 1:2400 aerial photographs. Our survey ground-truthed marsh areas and mapped the length and type of seawalls on enlargements. Shoreline and marsh areas from the 1993 study were previously digitized into ArcView GIS (ESRI 1999), and made available by the Complex Systems Research Center at the University of New Hampshire. The border between marsh and upland and individual seawalls were mapped, and seawalls were coded as to the type of wall and marsh presence. Within ArcView, the total length of marsh and each type of wall bordered by marsh were calculated.

Statistics and analyses

The statistical analyses for sediment accumulation, grain size, salinity, wrack, vegetation cover, height, and biomass used a split plot design. Data were analyzed using site (main plot), treatment (subplot), and distance into the marsh as main effects in ANOVA, using JMP software (SAS Institute 1997). The interactions between site and treatment and between treatment and distance were also tested. For the bulk density and LOI analyses where only one value per treatment was used in the analysis, a factorial design was used. Statistical significance was set at $\alpha = 0.05$. Tukey–Kramer ($\alpha = 0.05$) was used as a *post hoc* test for comparisons of means.

Data were examined to ensure they met the assumptions of least squares analysis (homogeneity of error variance and normality). Vegetation percent cover, wrack (thickness and percent cover), and LOI data were transformed by taking the arcsine of the square root of the data. Sediment pad weight, grain size, and biomass data were log transformed, and salinity data were squared. The same transformations were used when data were analyzed with a covariate (exposure) in ANCOVA. Untransformed data are shown in tables and figures. Spearman rank correlation analyses were used because most data set populations were not normally distributed.

Plant diversity was analyzed using species richness and the Shannon Diversity Index. The average species richness and Shannon Diversity Index were calculated for the three main communities within each site (Kent and Coker 1992) and analyzed using site and community type as main effects in ANOVA (after ensuring the data met assumptions). An additive tree based on the Bray–Curtis Dissimilarity Index matrix comparing the percent cover data was constructed in SYSTAT (SPSS 2000).

Results

Sediment accumulation rates and characteristics

Since the date of collection was not a significant factor in determining the weight of sediment on the sediment pads (ANOVA, $p = 0.1485$), the data from the five dates were averaged. There was a significant interaction between exposure and distance (ANCOVA, $p = 0.0098$). At higher energy sites (BR, NC, CP, and PR), the weight of sediment deposited on the sediment pads generally decreased with increasing distance from the upland. At TL, the site with the lowest exposure, sediment weight increased with increasing distance into the marsh (Figure 3a). Furthermore, at the 0.5 m and 1.5 m distances, sediment weight decreased with decreasing exposure, but at the mid-marsh stations, sediment weight increased with decreasing exposure. There was no significant effect of the wall treatment ($p = 0.1772$), but four of the five sites had a higher sediment weight at the wall than at the control at the 0.5 m distance (Figure 3b).

Gravel and sand size classes behaved similarly, as did clay and silt fractions, so the like classes were combined for analysis. The wall and control areas had similar grain size trends, with no significant difference between treatments. Distance significantly influenced grain size (ANOVA, $p = 0.0238$); with 60% gravel and sand at the 0.5 m distance compared to 38% at the middle of the marsh. Exposure was also an important factor in determining grain size. At the 0.5 m distance, the three sites with the highest exposure had the highest percent of gravel and sand (Figure 3c, ANOVA, $p = 0.0075$). When the total percent of gravel and sand at mid-marsh was subtracted from that of the 0.5 m distance (Figure 3d), the difference was greater in front of walls at every site except for BR (where sediment at both distances was primarily sand and gravel).

Distance and exposure (but not seawalls) significantly influenced soil bulk density and LOI (Figure 3e, f). The 0.5 m distance had higher bulk density and lower LOI than the mid-marsh. Exposure score was correlated with bulk density and LOI ($p < 0.0001$ for both), indicating that sites with greater exposure (lower score) had greater bulk density and less organic matter.

Groundwater salinity readings were taken on five dates, but data from only three dates were used because of dry or damaged wells. Predicted values determined from ANOVA were substituted for 14 missing data points to ensure unbiased results. Salinity varied according to the site's position in the estuary ($p = 0.0367$), with sites closest to the ocean having greater salinity (Figs. 1 and 3g). There was a significant interaction between site and treatment (ANOVA, $p < 0.0001$). BR had significantly higher salinity at the control, while TL had significantly higher salinity at the wall (t-test, $\alpha = 0.05$).

Wrack accumulation and vegetation characteristics

The only significant effect for wrack cover and thickness was a significant interaction between site and treatment at the 0.5 m distance (Figure 3h, ANOVA, $p < 0.0001$), though no trends emerged. At the 1.5 m distance, wrack cover and thickness were negatively correlated with vegetation cover (Spearman $\rho = -0.78$, $p = 0.0072$; $\rho = -0.74$, $p = 0.0148$, respectively), but were not correlated with the weight of sediment deposited on the sediment pads.

Characteristics of the vascular marsh plants indicated that both salinity and exposure influenced vegetation, but no seawall effect was found. Analysis of the three tallest *S. alterniflora* stems revealed only a significant site effect (Figure 4a, ANOVA, $p = 0.0001$), with taller plants found at sites with lower salinity (Spearman $\rho = -1.00$, $p < 0.0001$). Similarly, site was significant in determining total biomass per station area (Figure 4c, ANOVA, $p = 0.0099$), with higher biomass found at sites with lower salinity. Canopy height differed only according to distance; the 0.5 m and 1.5 m distance canopy heights were lower than the mid-marsh canopy height (Figure 4b, $p = 0.0196$). Percent cover of vegetation was significantly affected by site only

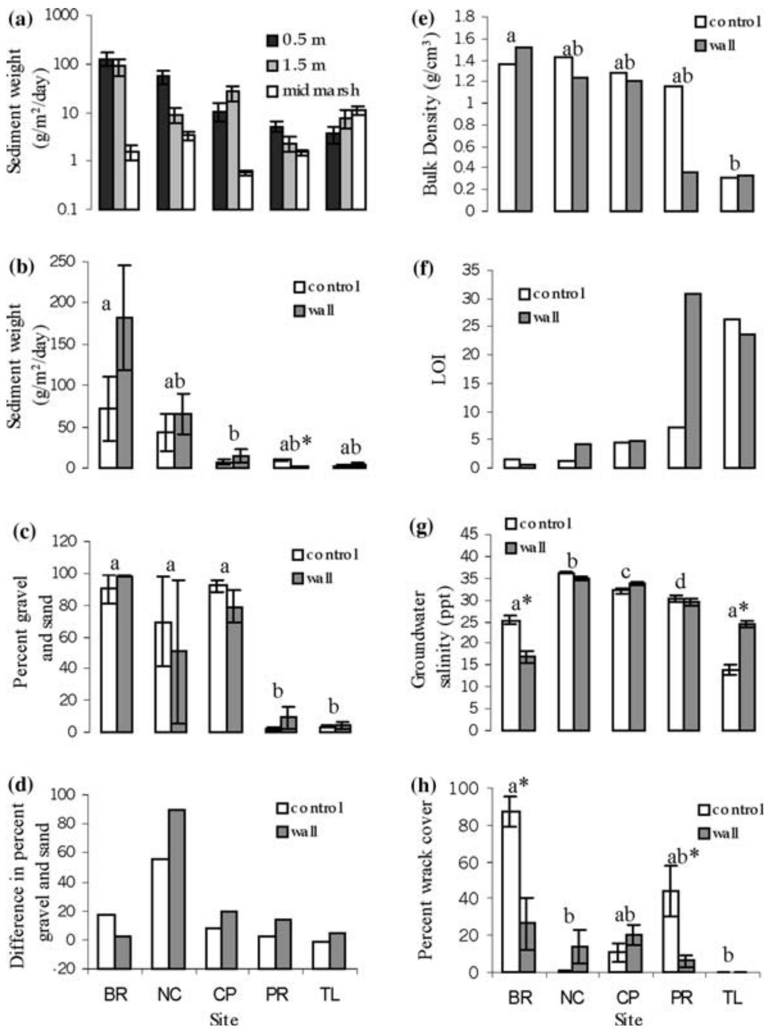

Figure 3. Sediment, salinity and wrack characteristics at five paired seawall and control marshes in the Great Bay Estuary. Error bars are +/−1 standard error from the means. Different letters indicate site means are significantly different (Tukey–Kramer *post hoc* test, $\alpha = 0.05$), and asterisks (*) indicate that wall and control are significantly different at that site (*t*-test, $\alpha = 0.05$). (a) Mean sediment weight deposited on the sediment pads for the three distances (0.5 m, 1.5 m, and mid-marsh) at each site. (b) Mean sediment weight deposited on the sediment pads at 0.5 m distance. (c) Total percent gravel and sand at the 0.5 m distance. The total gravel and sand is significantly different between the two distances (0.5 M and mid-marsh; ANOVA, $p = 0.0238$). (d) The difference in percent gravel and sand between the 0.5 m distance and the mid-marsh at the wall and control areas for each site. (NSD, ANOVA, $p = 0.2401$). (e) Bulk density for the 0.5 m distance. There is a significant difference between the bulk densities at the two distances (ANOVA, $p = 0.0173$). (f) LOI for the 0.5 m distance. There is a significant difference between the organic content of the two distances (ANCOVA, $p = 0.0485$). (g) Mean salinity at the wall and control area of the five sites at all three distances combined. There is a significant interaction between site and treatment (ANOVA, $p < 0.0001$). (h) Mean wrack percent cover 0.5 m distance only. There is a significant interaction between site and treatment (ANOVA, $p < 0.0001$).

(Figure 4d, ANOVA, $p = 0.0330$). There was a strong correlation between vegetative cover and exposure ranking, but only at the 0.5 m distance (Spearman $\rho = 1.00$, $p < 0.0001$); sites with high wave exposure had lower vegetation cover. These data also showed a negative correlation between vegetative cover and sediment pad deposition (Spearman $\rho = -0.94$, $p < 0.0001$).

The phytosociological table (Table 2) shows that lower marshes of wall and control areas had low species numbers and several species in common among the five study sites. Also, the

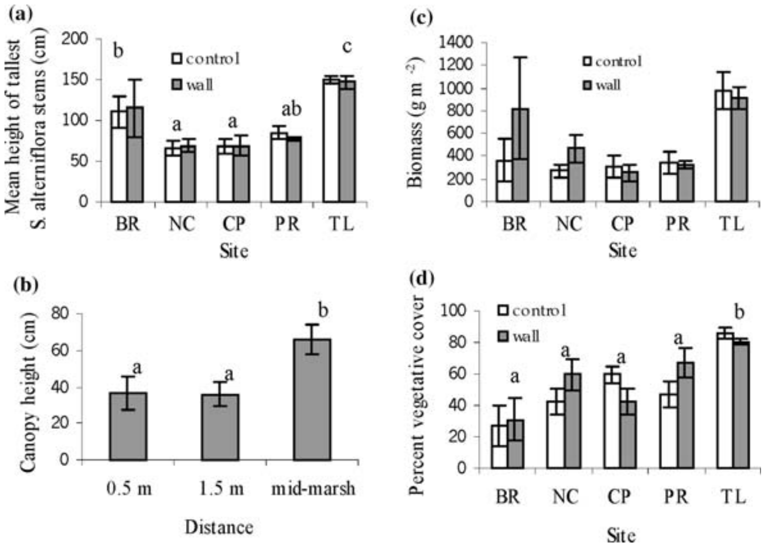

Figure 4. Vegetation characteristics at five paired seawall and control marshes in the Great Bay Estuary. Error bars are +/−1 standard error from the means. Different letters indicate means are significantly different (Tukey–Kramer *post hoc* test, $\alpha = 0.05$), and asterisks (*) indicate that wall and control are significantly different at that site (*t*-test, $\alpha = 0.05$). (a) The mean of the three tallest stems of *Spartina alterniflora* at the wall and control with all distances averaged. (b) Canopy height at all distances. (c) Mean total biomass with all distances averaged. (d) Mean percent vegetative cover at all distances combined.

transition zone communities had more species within each site and had fewer species in common between sites. When site was used as a blocking factor, the transition community had a higher species richness (mean = 7.0) than lower marsh communities (mean = 3.5; ANOVA, $p = 0.0295$). Similarly, the mean Shannon Diversity Index of the transition zone (1.38) was significantly higher than the lower marshes in wall (0.57) and control (0.43) areas (ANOVA, $p = 0.0050$).

The average Bray–Curtis Dissimilarity indices (BCDI) for the three community types (wall, control, transition) were calculated and compared (Table 3). Lower marshes were similar to others in the same community group, and between the two lower marsh groups (0.4193). The transition zones were less similar to the lower control and wall marshes, while the highest mean BCDI resulted from comparing transition zone communities from different sites to each other. Community differences are illustrated in the cluster diagram, which shows the relative difference between communities as the sum of the branch lengths that connect the different marsh areas on the tree (Figure 5; Podani et al. 2000). The lower marsh areas grouped together in three main clusters and joined close to the base of the tree, indicating that they were similar to one another. The transition zone communities (except site TL) grouped into a separate cluster that had very long branches, an indication that these communities were quite different from the lower marsh communities and from each other.

Mapping marshes bound by seawalls

There was a total length of 165.8 km of marsh abutting the upland in Great and Little Bays and their tributaries (Table 4). There were 9511 m of barriers against the shoreline, with 5876 m of these barriers located between a salt marsh and the upland (Figure 6). Although the percentage of marsh shoreline in Great Bay bounded by hardened structures was only 3.5%, certain areas had high concentrations. Within Great Bay, the middle of the southern shore had 42.7% of the marsh shoreline bounded by seawalls. In Little Bay, the southern shore of Dover Point had 43.4% of the marsh shoreline bounded by seawalls (Figure 6), while the southern shore of Cedar Point had 25.3% of the marsh shoreline bounded by walls.

Table 2. Phytosociological table of species percent cover in each of the three main communities (lower marsh in the wall area, lower marsh in the control area, and transition zone in the control area) at all sites.

	Wall marsh					Control marsh					Transition				
	TL	PR	CP	BR	NC	TL	PR	CP	BR	NC	TL	PR	CP	BR	NC
Number of quadrats	9	9	9	9	9	9	9	9	9	9	8	6	8	10	12
Spartina alterniflora	70.0	23.8	32.1	31.0	23.1	86.4	42.2	58.3	26.9	25.5	31.3	0.7	1.8		
Spartina patens	10.3	34.9	10.0		34.7			1.1		0.9	30.2	10.6			
Atriplex patula	0.2	0.3			0.3						3.6		0.1		
Juncus gerardii		7.1					1.9					33.6			
Salicornia europaea		0.3			0.3			0.1		3.7					0.3
Solidago sempervirens		0.5									3.9	24.2			13.2
Unknown vine			0.3									0.4			
Limonium nashii					0.4			0.1		1.6					0.2
Suaeda linearis					0.6					5.7					3.6
Puccinellia maritima					0.2					4.6					0.3
Scirpus robustus							2.8					2.6			
Crassula aquatica											2.5				
Eleocharis parvula											3.8				
Unknown grass															0.5
Scirpus maritimus											5.6				
Polygonum punctatum											1.5				0.1
Mentha arvensis												2.5			0.1
Toxicodendron radicans												11.5			
Asparagus officinalis												0.4			
Solanum dulcamara													4.7		
Cakile edentula														4.3	
Sonchus asper														7.9	
Agropyron pungens															0.3
Convolvulus sepium															0.1
Iva frutescens															0.3
Geranium sp.															0.1
Parthenocissus quinquefolia															0.6

Table 3. Average of site Bray–Curtis Dissimilarity Indices within the three community types (lower control marsh, lower wall marsh, and transition zone in control area) and among the three community types.

	Lower control marsh	Lower wall marsh	Transition zone
Lower control marsh	0.3536		
Lower wall marsh	0.4193	0.3795	
Transition zone	0.8854	0.8283	0.9591

Discussion

Sediments and wrack

Indicators were examined at five sites to determine whether seawalls affect processes associated with marsh health and stability. There was no significant effect of the seawall treatment on sediment weight at any distance, but some interesting trends were found. At the 0.5 m distance, four of the five sites had higher sediment weights in front of the wall compared to the same elevation in the control area. High sediment deposition on sediment pads, such as was found at the 0.5 m distance, has been attributed to the redeposition of surface sediment resuspended by wave action (Morgan and Short 2002). Thus, greater deposition in the upper area of the walled marsh could be due to sediment movement, possibly indicating more sediment movement next to the wall because of wave reflection. Several studies of seawall effects on beaches have concluded that there may be more

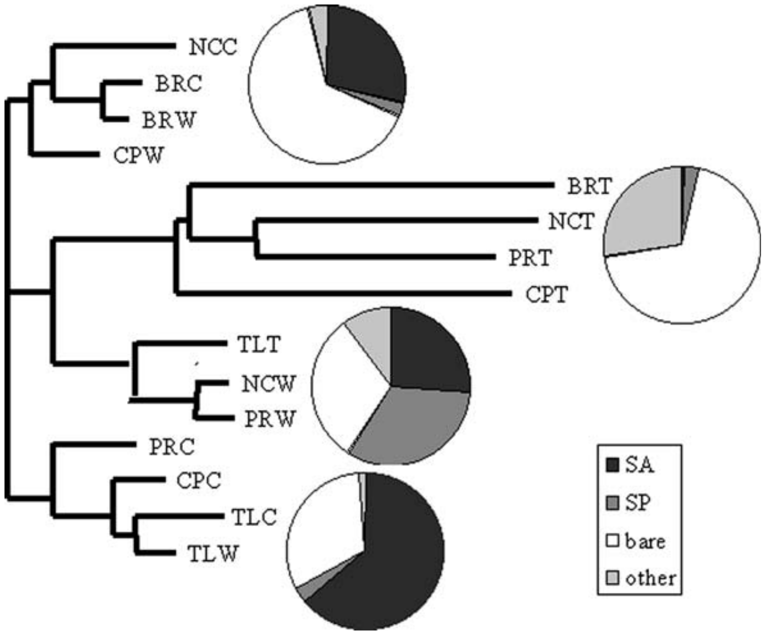

Figure 5. Additive cluster tree of diversity among the three main communities of all five sites, based on the Bray–Curtis Dissimilarity Index. Site codes are along the right side of the cluster tree. The first two letters of the code indicate the study site. The last letter of the code indicates the community type (T = transition zone, W = lower marsh in front of wall, C = lower marsh in control area). Pie charts show each cluster's average percent cover of *Spartina alterniflora* (SA), *S. patens* (SP), bare, and other species.

erosion in front of walls, but that this erosion is temporary and the sand is actually returned to the beach at a later time (Jacobson 1997; Pope 1997). Nevertheless, temporary movement of sediment will stress marsh vegetation (Keddy 1985; Kennedy and Bruno 2000).

Another researcher studying fringing marshes in this estuary placed sediment pads randomly in the marsh (Morgan 2000). She found site means much lower (0.44–4.31 g m^{-2} day^{-1}) than the weights in the gravel and sand beach area, but comparable to the sediment weights in the mid-marsh of the four highest exposed sites (0.56–3.34 g m^{-2} day^{-1}). The lower weights in the middle of the marsh probably represent true sediment deposition (rather than movement). Site TL was the least exposed site, and here sediment weights were greatest in the middle of the marsh, possibly because these stations received more sediment associated with river discharge. Sediment pads were only collected in the summer and fall, so wall effects on long-term sediment dynamics are unknown.

At every site except for BR, there was a bigger difference in grain size between the two distances in the wall area compared to the control area (Figure 3d). This agrees with a study of seawall effects on a sand flat that found grain size increased after the wall was built. The authors attributed the coarser grain size to stronger hydrodynamic disturbance in the presence of the seawall (Ahn and Choi 1998). Even without a significant wall effect in the present study, there may have been an increase in wave energy that removed fine grains close to the wall. Sediments containing mud are less susceptible to erosion (Houwing et al. 1999), and the removal of fine grained sediments and their associated nutrients can result in lower growth rates for shoreline vegetation (Keddy 1985), further increasing the potential for marsh erosion.

Soil bulk density and LOI were affected by site exposure and distance into the marsh. This occurred because the high energy sites had more gravel and sand (dense materials), and less dense organic material did not accumulate. Farther into the marsh plant matter and fine grained sediments accumulated, increasing sediment pore space and resulting in lowered bulk densities, as found by others (Anisfeld et al. 1999). The mean LOI for this study's sites were similar to the site mean range of

Table 4. Shoreline bordered by marsh and seawalls in the Great Bay Estuary and its rivers.

Shore type	Length (m)	% Of marsh shore
Marsh shore adjacent to upland	165,791	
Walls adjacent to upland	9511	
Walls between marsh and upland	5876	3.54
Rock wall	2296	1.39
Rip rap wall	1615	0.97
Questionable wall (low rock line)	1304	0.79
Wooden wall	384	0.23
Cement wall	250	0.15
Metal wall	26	0.02

The length of each type of shoreline is listed, and the percent of marsh shoreline bordered by each type of wall is given.

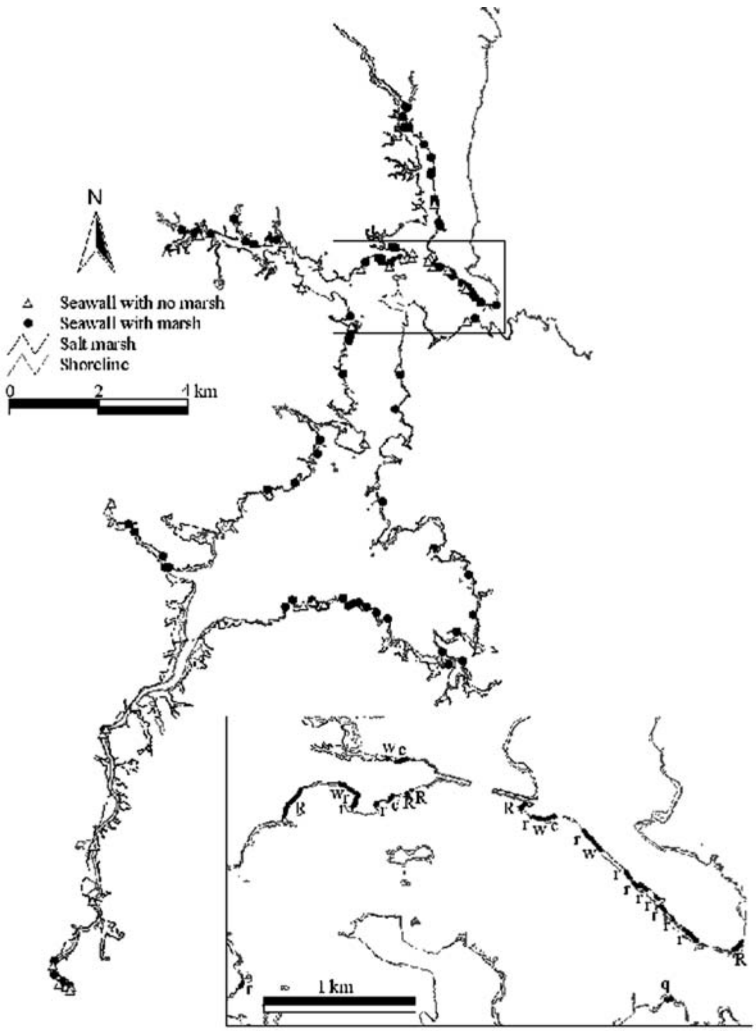

Figure 6. Seawall locations in Great and Little Bays and their tributaries. Circles indicate seawalls in front of marshes, triangles indicate seawalls without seaward marshes, and heavy bars delimit the study area. Inset shows the detail of the GIS product along a particularly dense area of seawalls landward of marshes (43% of marsh length). Seawall types are coded: c = cement wall, q = questionable wall, R = rock wall, r = rip rap wall, w = wood wall.

4.5–21.8% LOI found in the previous study of fringing marshes in this region (Morgan 2000). Because the presence of soil organic matter can buffer marsh systems against fluctuations in water and nutrient levels (Mitsch and Gosselink 2000), the areas of marsh with less organic material may be more susceptible to changes in the environment. Although there were no trends in bulk density or LOI associated with the wall in this study, an increase in energy near seawalls could result in less fine grained and organic material accumulation and reduce the stability of the system.

The difference in salinity between sites corresponded to their position in the estuary: NC, located close to the Gulf of Maine, had the highest salinity, while TL, located along the Oyster River, had the lowest salinity. The seawalls examined did not present a barrier to groundwater flow. Differences between wall and control salinities were apparently due to site specific conditions such as differences in slope (Harvey and Odum 1990) or watering regime (the two areas with significantly lower salinities had upslope lawns). Further studies on different types of walls may reveal more about how altering the slope or porosity of the upland transition affects groundwater flow into the marsh.

Wrack was assessed only once, near the end of the summer. Although wrack decays over the summer (Valiela and Rietsma 1995), the assessments for this study could still show the relative differences in wrack cover and thickness between sites and treatments. Even though there was no pattern of wrack accumulation related to seawalls, the significant interaction between site and treatment suggests that site orientation, location, and currents may affect wrack accumulation. While numerous studies have shown a relationship between wrack and vegetation (Bertness and Ellison 1987; Valiela and Rietsma 1995; Tolley and Christian 1999), wrack cover and thickness were negatively correlated with vegetation cover only at the 1.5 m distance in this study. The 1.5 m stations were located between the poorly vegetated beach zone and the dense *S. alterniflora* stand at most sites. Wrack washed up to this location at high tide could have been trapped at the upper edge of the marsh by the dense seaward stand of *Spartina*. The lack of correlation at other distances could be because plants started to grow through the decaying wrack (Valiela and Rietsma 1995), or due to patchy distribution of wrack in time and space.

Vegetation

For the three measures of robustness (canopy height, *S. alterniflora* stem height, and total biomass) the only significant differences were between sites and between distances in the marsh. The mid-marsh plants had the highest canopy because they were not in the higher energy beach environment where plants can be stressed by sediment movement (Keddy 1985). Further, they may have benefited nutritionally from regular flooding (streamside effect; Mitsch and Gosselink 2000). There was a strong negative correlation between salinity and the average tallest *S. alterniflora* stems at each site, and salinity also appeared to have a negative effect on biomass. This agrees with the findings from studies by Smart and Barko (1980), Portnoy and Valiela (1997), and Mendelssohn and Morris (2000) that growth rates of *S. alterniflora* are lower when the plants are grown in high salinity sediments because of increased energy expenditures for osmoregulation and decreased nutrient uptake efficiency.

Significant correlations at the 0.5 m station between vegetative cover and the weight of sediment deposited on the sediment pads, as well as exposure, indicate that overall vegetative cover at this distance was largely controlled by the movement of sediment. The seawalls in this study were built within a high energy environment to provide erosion protection, so the upper stations often fell within a mixed marsh and beach environment, perhaps too exposed to allow substantial marsh development. Sediment movement can damage vegetation by burying or abrading the plants, by causing erosion of the soil surrounding the plant roots (Kennedy and Bruno 2000), or by ripping up the plants entirely (Keddy 1985). In the present study, the decrease in vegetative cover at the distance closest to the upland with an increase in exposure supported the idea that substrate instability was affecting the plants in this area. Even so, the trend of higher sediment weights at the wall at the 0.5 m distance did not translate to significant effects on the vegetation.

There are two main ways to describe ecological diversity: alpha diversity is the diversity within a community, while beta diversity is the diversity between communities or areas (Kent and Coker 1992). In this study, alpha diversity was measured by species richness and the Shannon Diversity

Index. This study showed no wall effect on alpha diversity of the lower marsh. However, the transition community, which was not present in marshes with walls, had greater average plant diversity than the lower wall marsh and the lower control marsh. The "niche diversification hypothesis" (Connell 1978) can help to explain the high vegetative alpha diversity in the transition zone community. If species are specialized to live in certain niches, more species can co-exist if there are a variety of niches available (Connell 1978). The transition area has the possibility for a large variety of habitat characteristics due to different flooding levels, shading from the upland overstory, and fresh groundwater flow from seepage faces.

The Bray–Curtis Dissimilarity Index comparisons, the cluster tree, and the phytosociological table illustrate aspects of beta diversity. The BCDI comparisons and the table indicated that among the different sites, the lower marshes were all fairly similar and had many species in common. This is to be expected because zonation of New England salt marshes follows species' salt and flooding tolerance (Bertness 1991b; Levine et al. 1998). *Spartina alterniflora*, a common low marsh plant, was present in every lower wall and lower control marsh, with a minimum site mean of 23.1% cover. *Salicornia europaea* Linnaeus was also commonly found in several lower marsh communities. The upper areas of the lower wall and lower control marshes often had *Spartina patens* (Aiton) Muhlenberg, which is commonly found in the high marsh zone (Bertness 1991b). In the cluster tree, the lower control and wall marshes were all joined to the main axis by short branches, indicating these communities were similar (Figure 6). The lower marsh areas were divided into three clusters, primarily because of different percentages in *S. alterniflora*, *S. patens*, and bare area, as indicated by the cluster averages shown in the pie graphs.

High BCDI averages resulted when transition communities were compared to lower marshes and to transition communities from other sites. Along with the phytosociological table, this indicated that not only were the transition communities different from the lower marshes, but also different from each other. In the cluster tree, most of the transition zone communities grouped together in Cluster 2, apart from the lower marsh clusters. The relatively long branches of Cluster 2 also show that transition zone communities differed substantially from site to site. A study of beta diversity in tropical forests (Duivenvoorden et al. 2002) revealed that variation in species between communities (beta diversity) is partly due to distance and environmental differences. The sites used in our study ranged from the upper tidal reaches of the estuary to the mouth of the Piscataqua River, limiting the potential for seed movement between sites (Rand 2000). The study sites also represented a wide range of environmental conditions (wave exposure, salinity, etc.) that could have led to differences in species survival. In the transition zone, interspecific competition is high (relative to the lower marsh areas) because many species can potentially live in this less stressful area (Bertness 1991b). Environmental variation between sites may favor certain species at sites (Barbour et al. 1987; Levine et al. 1998), helping to explain the large differences we found between the various transition communities.

Numerous studies have shown the importance of biodiversity in ecosystem function and stability. Greater stability, exhibited by increased resistance and resiliency, is attributed to the increased likelihood that some species can survive through a disturbance when more are present (Tilman and Downing 1994). Higher productivity occurs because a diverse plant community is able to use limiting resources more fully (Tilman et al. 1996). A decrease in biodiversity can result in the loss of genetic information and other valuable resources (Naeem et al. 1994), as well as effects on other trophic levels by reducing canopy complexity and animal habitat (Zedler et al. 2001). The transition community eliminated by seawalls is a significant contributor to the diversity of fringing salt marsh in the Great Bay Estuary. As more seawalls are built in different areas throughout this estuary, marsh diversity will be reduced on a regional scale, with potential impacts on marsh productivity, stability, and habitat functions.

Extent of seawalls and regional impacts

The actual linear extent of seawalls landward of salt marshes was relatively low compared with the length of fringing marshes, due in part to low residential density, low energy regime, protected conservation areas, and natural rock outcrops, which negate the need for walls along much of the coastline. Since marshes naturally provide protection for upland areas (Boorman and Hazelden 1995), landowners may also have decided that the need was not great enough or the cost too high to justify building a seawall landward of a salt marsh. Walls were concentrated in locations with high population densities, such as the southern shore of Great Bay, Dover Point, and Cedar Point. Areas with high seawall density may result from a perceived need by landowners. If one landowner builds a wall, neighbors may be more likely to want their property protected by a wall.

In addition to reducing in plant diversity (seawalls eliminate a high diversity transition zone between marsh and upland), seawalls may have other effects on the long-term sustainability of salt marsh systems. When a vertical seawall is built on the marsh border, transgression of the marsh over the upland is prevented as sea level rises, and marsh will be lost (Boorman 1992; Brinson et al. 1995). Some researchers advocate 'managed retreat', where seawalls are moved inland or removed completely, allowing the marsh to migrate landward with rising sea levels (Boorman 1999).

Because seawalls reduced salt marsh plant diversity, and because there were areas within the bay that had a high coverage of shore armoring, managers need to look carefully at options when reviewing future applications for seawall construction permits. First, they need to ask whether a seawall is in fact necessary. In many places, an expanse of vegetated salt marsh can provide adequate protection from wave erosion (King and Lester 1995). If construction is deemed necessary, they may consider whether the wall could be built on the upland following the idea of managed retreat. This could avoid filling or cutting off the transition zone, but still provide protection during storms or very high tides. Perhaps management plans should discourage further building of seawalls and develop strategies to remove walls where possible. Seawall removal would return the natural state of material and energy transfer across upland and marsh habitats, and allow for landward marsh migration with continued sea level rise.

Conclusions

Seawalls were not shown to have a statistically significant effect on several important marsh processes; instead the processes were largely affected by site exposure, the location of the sampling station in the marsh, and other site characteristics. However, there were trends which indicated greater sediment movement and winnowing of fine grains near the wall, possibly as a result of wave reflection. These trends did not lead to significant changes in vegetation. However, the presence of seawalls at the upland border of marshes eliminated a high diversity vegetative zone, and the high concentration of seawalls in some areas of the bay raises concerns about seawall effects on plant diversity, marsh stability and habitat quality.

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