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Left running head: P. Morgan et al.

Right running head: Fringing salt marshes

The Functions and Values of Fringing Salt Marshes in Northern New England, USA

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ABSTRACT:

Although large salt marshes of the northeastern United States have been studied extensively, very little is known about the smaller, fringing marshes in this area, despite the fact that they are a common habitat type. We compared the functions and values of five fringing salt marshes (FM) to those of five meadow marshes (MM) along the southern Maine/New Hampshire coast. Specifically we compared their primary production, soil organic matter content, plant diversity, sediment trapping ability and wave dampening properties. Also explored were the relationships between these functions and several physical characteristics at each site, including soil salinity, percent surface slope, elevation and size.

Differences between fringing salt marshes and meadow marshes included their soil organic matter content (12% FM; 42% MM), plant species richness (8.8 FM; 15.6 MM) and density of plant species in $1m^2$ samples (2.8 FM; 4.5 MM). Although our results suggest that fringing marshes trap more sediment per unit area than meadow marshes, this difference was not significant, probably due to the great variability among sites. Traps located 1 m from the edge trapped an average of 21.6 ±18.6 g m^{-2} d^{-1} (FM) and 3.2 ±0.8 g m^{-2} d^{-1} (MM), and traps randomly distributed on the marsh surface trapped an average of 1.6 ±0.7 g m^{-2} d^{-1} (FM) and 0.6 ±0.2 g m^{-2} d^{-1} (MM).

Similarities between fringing salt marshes and meadow marshes included aboveground (285±52 g m^{-2} FM; 274±22 g m^{-2} MM) and belowground (1379±200 g m^{-2} FM; 1884±360 g m^{-2} MM) peak season biomass. Also, both marsh types reduced the height of waves coming onto the marsh surface by approximately 63% only 7 m into the marsh. The plant diversity of fringing marsh and meadow marsh sites as measured by the Evenness Index was also found to be similar (0.557 FM; 0.536 MM).

The results of this study indicate that despite their small size, fringing salt marshes are valuable components of estuaries, performing many ecological functions to the same degree as nearby meadow marshes. More effort should be made to include them in regional efforts to conserve and restore coastal habitats.

Key Words: Fringing salt marsh; meadow marsh; functions and values; Gulf of Maine

INTRODUCTION:

Our current understanding of salt marsh ecology comes from studies of large marsh systems, especially those along the Eastern coast of the United States. These salt marshes typically have a distinct zonation of plant communities, which reflect their surface elevation and the effects of tidal flooding (Miller and Egler 1950; Niering and Warren 1980). They are valued for a number of reasons, including their role as nursery grounds for finfish and shellfish, their ability to accrete sediments and counter the effects of sea level rise, their role in storm surge protection, and their recreational and aesthetic values (Teal 1986; Short et al. 2000). However not all salt marshes are large meadow marshes. Particularly in the northeastern United States, many of the salt marshes that line the edges of bays and rivers are quite narrow in width and small in size (Roman et al. 2000, Morgan 2002). In the state of Maine, Jacobson et al. (1987) found that nearly half of the coastal salt marsh area was comprised of marshes 0.2 ha (0.49 acres) or smaller. These smaller marshes are often referred to as fringing salt marshes. Despite the fact that they can be quite extensive, little is known about the ecology or the functions and values of fringing salt marshes. Studies in Massachusetts and Rhode Island have examined the role that fringing salt marshes may play as transformers of nitrogen that enters the estuary from adjacent uplands (Lyons et al. 1995; Tobias et al. 2001b; Davis et al. 2004), but other aspects of fringing marsh ecology have been studied little or not at all.

Fringing salt marshes are in need of study not just because of the paucity of information available about them, but also because they are particularly susceptible to environmental impacts. On their landward borders they are often abutted by residential and commercial development, and on their seaward borders they are exposed to the erosive force of waves. Because they are narrow, impacts to the borders of a fringing marsh have proportionately large effects on the entire marsh. Also because they are narrow, fringing marshes provide convenient access to open water for fishermen and boaters, who may impact them unintentionally.

The purpose of this study was to compare the functions and values of fringing salt marshes to those of larger, meadow salt marshes and in some cases, to shoreline areas where no marsh was present. We chose to use a functions and values approach to studying salt marshes for two reasons. First, indicators of salt marsh functions can be measured objectively with repeatable and quantitative methods. Second, functions can be linked to values, to which the general public can relate. The distinction between functions and values is an important one. Functions are ecosystem activities or processes that occur over time and do not depend on societal perceptions; that is, they continue to occur whether or not people care about them (Brinson and Rheinhardt 1996). Values are things that people care about because they are "worthy, desirable or useful to humans" (Mitsch and Gosselink 1993). Citizens can more easily understand the concept of wetland values than the concept of wetland functions, and values often weigh heavily in decisions concerning the future of coastal resources. Based on past experience and the scientific literature we developed a list of the functions and values of New England's salt marshes (Short et al. 2000). We then selected several of these for study in salt marshes in southern Maine and New Hampshire.

Our specific objectives were to: (1) measure several of the ecological functions of fringing salt marshes and meadow salt marshes, including (a) primary production, (b) soil organic matter accumulation, (c) filtration/trapping of sediments, (d) maintenance of plant biodiversity, and (e) dissipation of physical forces of waves; (2) compare these ecological functions in fringing salt marshes and meadow salt marshes; and (3) determine how marsh physical characteristics (size, elevation, surface slope and soil salinity) are related to these marsh functions.

MATERIALS AND METHODS:

Five fringing marshes and five meadow marshes were selected for study from the Saco River, Maine, south to the Great Bay Estuary in New Hampshire (Fig. 1; Table 1). The mean tidal range within the area is approximately 9 ft, with semi-diurnal tides. The fringing marshes chosen are all located along the edges of rivers, bays or coves, and the meadow marshes are found behind barrier beaches (Fig. 2). All of the meadow marshes are naturally divided into sections by large creeks or rivers, so we selected one of these sections for study in each meadow marsh.

Nine sample stations were established on each marsh site using a stratified random sampling design, according to the proportion of high marsh area to low marsh area. In fringing marshes, an x-y coordinate system was used to locate the random points. In meadow marshes, a latitude/longitude grid was placed over a base map of the marsh area and then nine random points were chosen from the grid. These points were then located in the field using global positioning system technology (GPS). Physical data (porewater salinity, surface elevation, surface slope) and biological data (primary productivity, soil organic matter accumulation and plant diversity) were then collected at these sample stations.

Physical Characteristics of Marsh Study Sites

Physical characteristics were measured at each of the nine stations per site. Previous studies have shown that the physical characteristics of salt marsh sites can influence their ecological functions (e.g. Jacobson and Jacobson 1989; Knutson et al. 1982; Osgood and Zieman 1993; Warren and Niering 1993; Kastler and Wiberg 1996). We therefore measured several physical characteristics that might influence the functions we were investigating and looked for correlations between them. We measured soil porewater salinity, surface elevation, percent surface slope, and the distance of each sample point from the seaward edge of the marsh. Soil porewater salinity was determined in July and August with a temperature-corrected optical refractometer after extracting water from 10-15 cm depth with a soil sipper. Elevations of all sample locations were determined using a Meridian L6-20 level and stadia pole. The relative elevations of all stations on a site were first measured by surveying from the station points to a relative benchmark nearby each site. These relative benchmarks were then tied into a high tide elevation on one date, which allowed for comparison of elevations between all sites. To determine the high tide line, three stakes painted with water-soluble paint were placed in each of the ten marsh sites before high tide (11.9' MHHW) on a windless day. Following high tide the water line on each stake was marked and then tied into the relative benchmark elevation at each site. The elevations of all the quadrats on all the sites were then calculated relative to 0' tide elevation. Surface slope was measured at each sample station in a direction perpendicular to the water's edge, across a horizontal distance of 1 m. The distance from each sample station to the water's edge was measured using a 50 m tape or a Lytespeed 400 rangefinder. The area of each site was determined with NIH Image 1.47, from U.S.G.S. topographic maps, aerial photographs (1" = 200') and field measurements.

Means and standard errors of the nine data points for each of the physical characteristics above were calculated for each marsh site. Means of the ten sites were compared using Analysis of Variance (ANOVA) and then pairwise comparisons were made with Student-Newman-Keuls or Scheffe's S tests, as appropriate. The overall means and standard errors for meadow and fringing marsh types were also determined and compared using ANOVA.

Ecological Functions of Marsh Study Sites

Five salt marsh functions at each of the ten salt marsh sites were evaluated using a variety of indicators, each developed based on knowledge of the literature and previous experience. The functions we assessed and the corresponding indicators we used to measure them are listed in Table 2.

Primary production of vascular plants at each site was evaluated by measuring the annual standing crop, including both live aboveground and live belowground plant biomass. Samples were collected from the nine random sample points (stratified by proportion of low and high marsh) at each marsh site at the end of the growing season (late August) by clipping all vegetation in a 0.25 m^2 quadrat. Live plants were washed, then separated from dead material of previous years and dried at 60°C for 48 hr and weighed. A sediment core (20 cm deep, 3.5 cm diameter) was taken from each quadrat, then washed on a 2 mm screen. Live roots and rhizomes were separated from dead material and then dried at 60°C for 48 hr and weighed to determine belowground biomass (Gross et al. 1991).

To determine soil percent organic matter content, a core (15 cm deep; 3.5 cm diameter) was taken from each of the nine sample stations, and percent organic matter in the sediment determined from weight loss upon ignition in a muffle furnace (400ºC) for 4 hr (Craft et al. 1991).

Sediment filtration and trapping was assessed by measuring the amount of sediment accumulated on sediment traps (discs) over a ten day period in mid-August**.** Sediment traps were designed after those of Reed (1989), and consisted of a pre-weighed mylar disc (8 cm diameter) attached to a piece of sheet metal with plastic coated clips and held onto the marsh surface by 6 in long metal sod staples. Five sediment traps were distributed randomly at five of the sample stations at each site, stratified by proportion of low to high marsh. Five additional traps were placed on the marsh surface 1 m from the water's edge. These traps were randomly distributed along the seaward edge of each marsh site. Three traps were also placed in areas where no marsh was present, adjacent to the five fringing marsh sites. Discs were collected after two weeks, dried at 60°C for 48 hr and weighed. In addition, the surface elevation and the distance between each trap and the seaward edge of the marsh were measured. The number of plant stems and the percent cover of plant species present in a 1 m^2 quadrat around each trap on the marsh surface were also recorded. The suspended sediment concentration in the water flooding the marsh surface at high tide was determined by collecting water as it flooded all sites on the same spring tide night. Samples were later filtered through pre-weighed 0.45 μm glass fiber filters, then dried at 60°C for 48 hr and weighed.

The species richness and relative abundance of higher plants were assessed once at each site, in late July. Percent cover of all species in 1 m^2 quadrats was estimated visually using the following cover classes: 0%, $0\% < x \leq 1\%$; $1\% < x \leq 5\%$; $5\% < x \leq 10\%$; $10\% < x \leq 20\%$; and continuing above 20% in 10% increments up to 100%. Total percent cover per quadrat did not exceed 100%. The number of quadrats sampled on fringing and meadow marshes was based on preliminary sampling and calculation of running averages for small and large marsh sites. The results of this initial analysis indicated that the minimum number of quadrats needed on fringing and meadow marsh sites was 10 and 30, respectively, in order to include the majority of plant species on the two different sized sites. These quadrats were then distributed in a stratified random manner, according to the proportion of high and low marsh at each site.

To assess how well fringing and meadow marshes dissipate wave energy, we looked at the difference between wave heights at the marsh/water edge and 5 m and 7 m into the marsh, along a transect perpendicular to the water's edge. We surveyed three of the fringing marsh sites, three of the meadow marsh sites, and three areas where no marsh was present. Three transects were laid out at each site, evenly spaced along the marsh/water edge. Stakes with meter sticks attached were placed at 0 m, 5 m and 7 m along each transect. Waves were generated by the wake of a 17' aluminum boat and then videotaped simultaneously at 0 m and 5 m, then at 0 m and 7 m. Waves from the boat were filmed three times (takes) at 0 m and 5 m and three times at 0 m and 7 m along each transect. Videotapes were later viewed frame-by-frame (30 frames s^{-1}) and wave peaks and troughs were recorded for each take at 0 m and at 5 m or 7 m. The maximum trough to peak height was determined for each take, as were the two wave heights following the maximum wave. The percent reduction in maximum wave heights from 0 m and 5 m, and from 0 m to 7 m was calculated for the three takes at each transect and then averaged. The mean height of three waves (maximum and two following) per take was also calculated and then the percent reduction in this 'three wave mean' height was determined from 0 m and 5 m, and from 0 m to 7 m. Finally, percent wave height reduction values (maximum and three wave) obtained for the three transects were averaged to determine means for each fringing marsh, meadow marsh and 'no marsh' site. In addition, the depth of the water at the time of filming was also recorded at the 0 m, 5 m and 7 m points along transects.

Before comparing fringing marsh and meadow marsh functions, the possible relationships between each of the functions and the physical characteristics measured at the sites were explored. Scatterplots were drawn comparing the quantitative assessment for each function with each of the physical characteristics investigated for that function. Correlation coefficients were then calculated for each function-physical characteristic pair. Results of these correlations aided in the choice of which variables to use as covariates in the means comparisons described below.

For each of the functions in Table 2 and their associated metrics, the means and standard errors of the five fringing marshes and the five meadow marshes were calculated. Means were also calculated for the areas where no marsh was present when assessing sediment filtration and trapping, and the dissipation of wave energy. Analysis of Variance (ANOVA) or Analysis of Covariance (ANCOVA) was then employed to compare the mean values from the fringing marsh sites with those of the meadow marsh sites for each function. If data were collected at 'no marsh' sites, these were included in the means comparisons as well.

Data collected to assess the function of maintenance of plant diversity were analyzed to compare the number of species per site, species density, and evenness (E) of vascular plant species in meadow and fringing marshes. The percent covers of *Spartina alterniflora* and of the dominant high marsh species *Juncus gerardii*, *Puccinellia maritima* and *Spartina patens* were also calculated for each marsh site. Average values for each of these plant community attributes were then calculated and compared using ANOVA. Calculations were based on ten random quadrats per marsh site when calculating plant species evenness (E), as this diversity parameter requires an equal sample size to compare two communities. For the other indicators of plant species diversity, fringing marsh means are based on ten quadrats and meadow marsh means on thirty quadrats, although the means of ten randomly selected meadow marsh quadrats are also presented.

RESULTS:

Physical Characteristics of Marsh Study Sites

Soil porewater salinity, surface elevation, marsh area and distance to the water's edge of sample points were all significantly less in fringing salt marshes than in meadow marshes (calculated as means of five sites; $p < 0.05$) (Fig. 3a-d). However surface slope was significantly greater in fringing marshes than in meadow marshes ($p < 0.01$)(Fig. 3e). To see how each marsh contributed to these differences, Figure 3 also shows means and standard errors of the nine samples at each marsh site.

Comparison of Fringing Marsh Functions to Meadow Marsh Functions

Primary production

We found no difference in the production of aboveground or belowground biomass between fringing and meadow marshes (Fig. 4). The slope of the marsh surface may affect productivity in fringing marshes, as it was highly correlated with both aboveground ($r = 0.941$, $p < 0.05$) and belowground ($r = 0.951$, $p < 0.05$) biomass.

Soil organic matter accumulation

The organic matter content of meadow marsh soils was significantly greater than that of the fringing marsh soils (ANOVA; $p < 0.001$) (Fig. 5a). The five fringing marsh sites had lower surface elevations than the five meadow marshes, and two were significantly lower in elevation (Fig. 3g). Soil percent organic matter content was discovered to correlate with marsh surface elevation ($r = 0.801$, $p < 0.05$) (Fig. 5b), and in an ANCOVA of marsh type and elevation, organic matter in meadow marsh soils was greater than that in fringing marsh soils, even after the variability due to elevation was accounted for ($p < 0.001$).

Sediment filtration and trapping

Although there was on average more sediment deposited on the traps randomly distributed on the surface of the fringing marshes than on the surface of the meadow marsh sites, this difference was not significant (Fig. 6a). Areas where no marsh was present had an even greater amount of sediment deposited per unit area. However the variance around the mean was extremely high for 'no marsh' areas, with the standard deviation (6.84) greater than the mean (4.24 g m^{-2} d^{-1}). A comparison of the means for meadow, fringing and 'no marsh' areas showed no significant difference in the amount of sediment deposited on these three site types, even after removing the variance associated with elevation, which was a significant ($p < 0.001$) covariate in the model (ANCOVA; $p = 0.374$, log transformed data). If elevation was not included in the model, then $p = 0.134$ (log transformed data). Sediment deposition was less at sites with a higher mean elevation, at both fringing and meadow marsh sites.

Traps placed just one meter in from the edge of the marsh sites collected more sediment than those that were distributed randomly, as expected. Once again there was no significant difference in the mean amount of sediment deposited on fringing, meadow and 'no marsh' sites, as determined by ANCOVA with elevation used as a covariate ($p = 0.120$, log transformed data)(Fig. 6b). If the variability due to elevation was not removed, $p = 0.721$ (log transformed data). It should be noted that one trap at site DIM had an unusually large amount of sediment deposited on it (1847.89 g m^{-2} d^{-1}, compared to the next highest value of 0.92 g m^{-2} d^{-1}). This was attributed to the presence of a nearby culvert, which greatly increased the velocity of the water moving through the area, most likely causing large amounts of sediment to be resuspended and deposited. This data point was therefore considered as an outlier and was discarded.

We had expected that suspended sediment concentration of the tidal water moving onto the marsh surface would influence the amount of sediment deposited on the sediment traps, but this is not what we observed in meadow marshes (Fig. 7). Although significant in fringing marshes, the relationship in Figure 7 is driven by observations at a single site ($r = 0.999$, $p < 0.001$). We did find that vegetative cover may influence the amount of sediment deposited on the marsh surface, however. The greater the percent cover of plants around sediment traps, the less the amount of sediment deposited ($r = -0.732$, $p < 0.05$).

Maintenance of plant communities

Several measures of plant diversity showed no significant difference between fringing marsh and meadow marsh plant communities. The Shannon- Weiner Index (H'), Evenness (E), and species richness were all similar in the two marsh types (Table 3). However, if the full sample of thirty quadrats on meadow marshes was used, then species richness of meadow marshes was greater than that of fringing marshes (ANOVA, $p < 0.01$). Although the percent cover of *Spartina alterniflora* in fringing marshes was almost double what it was in meadow marshes, this difference was also not significant, in large part due to the short form of this species occurring in high marsh areas of meadow marshes. Species density, however, was less in fringing marshes than in meadow marshes (ANOVA, $p < 0.01$). The total percent cover of the dominant high marsh plants, including *Spartina patens*, *Juncus gerardii*, *Distichlis spicata* and *Puccinellia maritima* was also less in fringing marshes (ANOVA, $p < 0.05$).

Dissipation of physical forces of waves

An example of the wave profiles generated from videotaping passing waves at 0 m (the marsh edge) and at 5 m can be seen in Figure 8. Along all transects at all sites, the heights of the largest waves at 0 m ranged from 3.5 cm to 27.3 cm, averaging 12 cm tall. The ‘three wave mean’ height (mean height of the maximum and next two waves) at 0 m ranged from 2.7 cm to 21.2 cm, with an average of 7.8 cm.

It should be noted that the waves used to calculate percent height reductions along each transect were not shallow water waves. We determined this by measuring wavelengths of suspect waves on the video screen and comparing them to water depths at those points. The water depth was always significantly greater than 1/20 of the wavelength (Denny 1988).

In both fringing and meadow marshes, the heights of the largest waves traveling 7 m across the marsh surface were reduced by more than 60% (Fig. 9a). Where no marsh was present, wave heights were reduced by only 33%. This difference between marsh and 'no marsh' areas was statistically significant (ANOVA, $p < 0.05$, square root transformed data; Student-Neuman-Keuls test, $p < 0.05$). The percent reduction in wave height across 7 m was less when we considered the ‘three wave mean’ height (55% in fringing and 52% in meadow marshes, compared to 28% in ‘no marsh’ areas), and again the difference between marsh and ‘no marsh’ areas was statistically significant (ANOVA $p < 0.05$, square root transformed data; Student-Neuman-Keuls test, $p < 0.05$) (Fig. 9b).

DISCUSSION:

Although there have been some studies of fringing marsh ecology (e.g. Kastler and Wiberg 1996; Tobias et al. 2001a; Davis et al. 2004; Bozeck and Burdick 2005), few studies have considered fringing salt marshes as unique habitats, distinct from larger, meadow salt marshes. To clarify the role of fringing salt marshes in estuaries along the southern Maine/New Hampshire coast, we studied how they function compared to large meadow marshes in the same area. We discovered that fringing salt marshes are diverse in terms of their physical characteristics and that this diversity is sometimes reflected in their ecological functions. We also found that despite this diversity, fringing marshes as a group often function at levels similar to meadow marshes.

Physical Characteristics of Fringing and Meadow Marsh Study Sites

In general, fringing marshes are narrower, steeper, and have lower mean surface elevations than meadow marshes. They are also more variable than meadow marshes in terms of their elevations and surface slopes (Fig. 3). This variability is an important property of fringing salt marshes, in part because elevation and slope may influence marsh function, as will be discussed. In addition, their variability makes it difficult to describe a “typical” fringing salt marsh. For example, some fringing salt marshes contain predominantly low marsh plant communities, but others have extensive high marsh areas. Although the fringing marsh study sites had statistically lower mean soil porewater salinity than the meadow marsh sites, this difference was primarily due to the very low soil salinity at one fringing marsh site (Fig. 3a,f). We found no strong correlations between salinity and any of the functions we studied.

Comparison of Fringing Marsh Functions to Meadow Marsh Functions

Primary production

Our results demonstrate that the primary productivity of fringing marshes is as great as that of meadow marshes, indicating that they are important contributors to estuarine food webs. Mean aboveground production in fringing marshes was similar to that in meadow marsh sites, and although the mean belowground production in meadow marsh sites was greater than that in fringing marsh sites, this difference was not significant (Fig. 4). It should be noted that although harvesting the peak season standing crop as a measure of aboveground production is a commonly used method, it underestimates true aboveground net production by 10-15% (Nixon and Oviatt 1973). Comparing the aboveground biomass values we obtained to those of other studies is difficult because of the variety of sample methods that have been employed to measure aboveground production (Marinucci 1982). Nevertheless, our values are within the range of those found in studies of other Maine and New Hampshire salt marshes (Lindthurst and Reimold 1978; Gross et al. 1991).

Studies of salt marsh belowground biomass production are few in number compared to studies of aboveground biomass production, due to the difficulty of sampling and processing belowground tissues (Gross et al. 1991). However investigating the belowground component of production is important, as it can be 4-7 times greater than that of aboveground production (Marinucci 1982). The belowground to aboveground biomass ratio was 4.8 in the fringing marshes we sampled and 6.9 in the meadow marshes. Also, our values for belowground production agree with what others have found in New England marshes (Lindthurst and Reimold 1978; Gross et al. 1991).

The positive relationship we observed between above and belowground production and surface slope (r = 0.941 and p = 0.951, respectively) could be attributed to the "streamside effect." In general, marsh surfaces are more steeply sloped where they are adjacent to tidal waters, either along the edge of a creek or along the seaward edge of the marsh, and aboveground primary production is greater here (Gallagher and Kibby 1981; Burdick et al. 1989). Soils in areas exposed to tidal waters more often are typically more well-drained, and sediment oxidation rates are higher, so gas exchange between roots and the surrounding soils can take place more rapidly than in waterlogged areas (Burdick et al. 1989). Although differences in belowground biomass production in *Spartina* marshes have not been well studied, Gallagher and Kibby (1981) found that streamside plants had greater recoverable underground reserves than back marsh plants in a *Carex lyngbyei* tidal marsh. Ellison et al. (1986) also found that belowground production in a Massachusetts salt marsh was greater at the marsh edge than on other parts of the marsh.

Soil organic matter accumulation

Our results show that the percent organic matter content of meadow marsh soils is more than three times that of fringing marsh soils (Fig. 5a). The meadow marshes we sampled had greater surface elevations than the fringing marshes (Fig. 3b), and there was a positive correlation between elevation and soil organic matter content (Fig. 5b). Schmitt et al. (1998) also found an increase in the amount of organic matter deposited in the sediment and on the marsh surface with increasing elevation in a Massachusetts salt marsh.

If salt marshes are to keep pace with rising sea level, they must be able to accrete at a rate equal to or greater than that of sea level rise (Donnelly and Bertness 2001, Patrick and DeLaune 1990). Vertical accretion relies on two sources of sediment; one from waters that flood the marsh surface, and the other from above and belowground plant biomass which does not completely decompose, contributing organic material to marsh soils (Redfield 1972; Nixon 1982). The build up of organic matter in marsh soils appears to be most important in the high marsh zone. In a study of five Rhode Island salt marshes, Bricker-Urso et al. (1989) found that the contribution of organic matter to accretion on the high marsh was more than twice that of inorganic sediments, but in the low marsh the contribution of inorganic and organic sediments was equal. In addition, Ellison et al. (1986) found that the decomposition rate of live roots and rhizomes was slower in the high marsh zone than at the marsh edge. Lower decomposition rates in interior, poorly drained high marsh soils may result in organic matter accumulation. The distance that sample points are from the marsh edge has also been observed to correlate with soil percent organic matter content. The percent organic matter in sediments of two Virginia salt marshes was lowest at the water's edge and increased along a 30 m transect into their interiors (Kastler and Wiberg 1996). In this study, we also found that the soil organic matter content correlated with the distance the sample points were from the edge of the marsh ($r = 0.704$, $p < 0.05$). Our results indicate that meadow marshes along the southern Maine/NH coast rely more on soil organic matter accumulation for accretion than fringing marshes do. We conclude that the salt marsh function of soil organic matter accumulation is performed to a greater extent in meadow marshes than in fringing marshes. If this is the case, then to keep pace with sea level rise, fringing marshes must rely to a greater extent on the trapping of inorganic sediments as their predominant mechanism of accretion.

Sediment filtration and trapping

Reed (1989) first developed the technique of trapping sediment on filter paper discs attached to the marsh surface. Due to the activity of green crabs in our area, we modified her design and used discs made of Mylar, which crabs do not find so appetizing. In one study of sediment deposition on Louisiana tidal marshes, Reed (1989) found rates of 2.9 g m^{-2} d^{-1} (excluding winter storm events, when sedimentation rates were much higher). We obtained similar values for sediment deposition, with marsh site means ranging from 0.44-4.31 g m^{-2} d^{-1} for traps randomly distributed on fringing marshes and 0.20-1.51 g m^{-2} d^{-1} for traps randomly distributed on meadow marshes.

We observed that sediment deposition rates decreased with increasing elevation ($r = -0.732$, $p < 0.05$), probably because tidal waters cover marsh areas at higher elevations less frequently and for a shorter period of time. Negative correlations between elevation and sediment deposition have also been observed in Massachusetts (Schmitt et al. 1998) and North Carolina (Leonard 1997) salt marshes.

Intertidal areas where no marsh vegetation was present (designated as ‘no marsh’ areas) showed a greater rate of sediment deposition (0.62-16.44 g m^{-2} d^{-1}) when compared to fringing marshes or meadow marshes, but these differences were not significant (Fig. 6a). Local resuspension of surface sediment on ‘no marsh’ sites may have contributed to greater deposition rates. We had expected to see reduced rates of sediment deposition on ‘no marsh’ areas, as the presence and density of marsh vegetation has been observed to correlate positively with sediment trapping (Gleason et al. 1979; Stumpf 1983).

We also expected greater sediment deposition per unit area on fringing salt marshes than on meadow marshes because, considering the length of marsh bordering tidal waters, fringing marshes have a greater edge: area ratio than meadow marshes, so a finite sediment supply would appear as more sediment deposited per unit area on fringing marshes. We did observe higher rates of deposition on fringing marshes than on meadow marshes, but this difference was not significant (Fig. 6a), likely due to the high variability in deposition rates between sites within each site type. To eliminate any effect of the greater edge: area ratio of fringing marshes, we placed traps at fringing and meadow marsh sites just 1 m from the water's edge. Again, the rates of sediment deposition were greater on fringing marshes, but this difference was not significant (Fig. 6b).

Our results suggest that fringing marshes trap greater amounts of sediment per unit area than meadow marshes, although the variability between sites was too high and our sample size was too small to confirm this. With slower rates of organic matter accumulation than occur in meadow marshes (Figure 5a), the trapping of inorganic sediments is an important mechanism of accretion for fringing marshes. Whether fringing marshes in this area are performing the function of sediment filtration and trapping at levels sufficient to ensure that their rates of accretion will keep pace with sea level rise is an important question that deserves further investigation. The use of feldspar clay marker horizons to measure marsh accretion over several years could help in answering this question (Cahoon and Turner 1989).

Maintenance of plant diversity

Fringing salt marshes in New England are often thought to have very low plant diversity, and to be comprised primarily of *Spartina alterniflora* (Cook et al. 1993; Bryan et al. 1997). In contrast to this, we found that fringing salt marshes often have very developed high marsh communities. All of the fringing marshes we studied contained *Spartina patens*, a typical high marsh plant, and at two sites, *S. patens* was more abundant than *S. alterniflora*. So although the proportion of high marsh to low marsh in the fringing marshes we studied was less (0.7:1) than in meadow marshes (3.4:1), high marsh species are an important component of fringing marsh plant communities.

Our results did confirm that meadow marshes are more species rich than fringing salt marshes in this part of New England (Table 3). This is likely due to the "area effect" (the number of species sampled increases with increasing sample size (Magurran 1988)); species richness was correlated with marsh area ($r = 0.818$, $p < 0.05$). Species density (number of species present per m^2) was also greater in meadow marshes than in fringing marshes, and correlated with marsh area ($r = 0.676$, $p < 0.05$).

The low marsh zone in New England salt marshes is typically dominated by *Spartina alterniflora*, and the sites we studied fit this pattern. However the high marsh zone of the majority of the meadow marshes in our study did not fit the pattern commonly observed in other New England marshes, where there are distinct bands of *S. patens* and *Juncus gerardii* (Miller and Egler 1950; Niering and Warren 1980). Instead, the high marsh often contained large areas of forbs (broad leaved plants), in a mosaic of patches of *S. patens, J. gerardii* and other dominant high marsh grasses. Ewenchuck and Bertness (2004) also noted the occurrence of forb pannes in a Wells, ME marsh (one of our study sites), and attributed the occurrence of these forb patches to the waterlogged, anoxic soils found in northern New England salt marshes. Because northern New England salt marshes have not been as extensively ditched as marshes farther south, they tend to be wetter (Ewenchuck and Bertness, 2004). Jacobson and Jacobson (1989) found mosaic patterns of vegetation in a number of the Maine salt marshes they sampled, which they hypothesized was due to microrelief in high marsh areas.

Although meadow marshes have greater species richness and density, their plant communities are comparable to those of fringing marshes in terms of two other measures of plant diversity, the Shannon-Weiner index (H') and Evenness index (E) (Table 3). The Evenness index we employed is the ratio of observed diversity to maximum diversity, $E=H'/H_{max}=H'/\ln S$ (Magurran 1988). Values for E describe how close the set of species abundances for a marsh site is to having maximum diversity, where the relative abundances for all species are equal. Our results show that the relative abundances of species were similar in the fringing and meadow marsh sites we sampled. It should be noted that these results are based on ten quadrats sampled in both fringing and meadow marshes, as equal sample sizes must be used when calculating H' and E.

Dissipation of physical forces of waves

Previous studies have shown that salt marshes reduce the height and energy of incoming waves, helping to protect the adjacent upland from erosion (Knutson et al. 1982; Moeller et al. 1996). In addition, salt marshes reduce wave velocity, resulting in increased sediment deposition on the marsh surface and decreased sediment erosion (Leonard and Luther 1995). We were interested in knowing if marsh type (fringing or meadow) or other characteristics (vegetation, slope) affected a marsh's ability to reduce the height (energy) of incoming waves.

Our results demonstrate that marsh type does not affect a site's ability to reduce the height of incoming waves, with fringing and meadow marshes both causing waves to lose energy as they traveled 7 m across the marsh surface (Fig. 9). The maximum wave height was reduced 62% in fringing marshes and 64% in meadow marshes after traveling 7 m across the marsh surface. These values are similar to those obtained by Knutson et al. (1982), who found wave heights reduced by 57% five meters into a *S. alterniflora* marsh, and 65% at ten meters. Leonard and Luther (1995) found a 65% reduction in the turbulent energy of water coming onto the marsh after it had traveled just 3 m in from the marsh edge.

Areas where no marsh was present were much less effective at reducing the height of maximum waves (33% over 7 m), as expected. In Moeller et al.'s (1996) study of a *S. alterniflora* marsh in England, they found that low marsh areas absorbed 2-3 times as much wave energy as adjacent sand flats.

Our results demonstrate that for waves up to 27 cm in height (typical of boat or wind generated waves), even narrow fringing marshes are capable of reducing wave energy by almost two thirds, helping to protect adjacent shorelines from the erosive forces of waves.

Summary and Conclusions

Fringing Salt Marshes Defined

Found along the edges of bays and rivers, the fringing salt marshes of New England have been described as relatively long and narrow in shape and dominated by *Spartina alterniflora*

(Bryan et al. 1997; Roman et al. 2000). We can now more clearly define fringing marshes as having steeper slopes, lower elevations and soils with less organic matter than those of larger marshes. In addition, their plant communities usually include both low marsh and high marsh zones, although in more equal proportions than is seen in larger marshes, where the high marsh dominates. It is also important to note that fringing salt marshes are quite diverse in terms of their physical characteristics (width, length, slope, elevation, soils).

Functions and Values of Fringing Salt Marshes

Fringing salt marshes have important functions and values that had not been investigated prior to this study. They are as productive on a per unit area basis as meadow marshes, making valuable contributions to detrital and grazing food webs. Their ability to filter and trap sediments from the water column improves water quality and adds to marsh accretion, helping fringing marshes keep pace with sea level rise. By dampening the energy of incoming waves, fringing marshes help protect the adjacent shoreline from erosion. This is especially important because in New England, these narrow marshes are often the only buffer between the erosive forces of waves and valuable upland coastal property. Fringing marshes are important in maintaining plant biodiversity in the estuary, as they contain distinct low and high marsh zones dominated by the same plant species found in meadow marshes. And finally, the importance of connectivity between habitat patches is well known in conservation biology (Hunter and Gibbs 2007). Fringing salt marshes serve the function of connecting larger salt marshes in New England's estuaries. Lining the edges of rivers and bays, and distributed between the larger meadow marshes, they serve an important role in the dispersal ad colonization of salt marsh plant and animal species.

In many New England estuaries, fringing salt marshes are the dominant marsh type. And yet regional efforts aimed at marsh conservation and restoration still focus on larger, meadow marshes (Konisky et al. 2006, Taylor 2008). With an improved understanding of the ecological functions of fringing marshes and of their value to coastal communities, we can do a better job of protecting these important resources.

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Figure 1. Locations of fringing salt marsh and meadow salt marsh study sites. Complete site names and locations (latitude/longitude) are listed in Table 1. Sites ending in "F" are fringing marshes; sites ending in "M" are meadow marshes.

Figure 2. Relative sizes of five meadow and five fringing salt marsh sites (all shown at the same scale). Study sites are dark grey; surrounding salt marshes are medium gray.

Figure 3. Means of physical characteristics for each marsh type and for sample points at each site. Bars in each graph followed by the same letter are not significantly different from each other according to the pairwise comparison listed. Error bars are ±1 SE.

a. Mean porewater salinities of five fringing marsh and five meadow marsh sites. Means are significantly different from each other (ANOVA, $p < 0.05$).
b. Mean elevations of five fringing marsh and five meadow marsh sites. Means are significantly different from each other (ANOVA, $p < 0.01$). Elevation units are meters above 0' tide.
c. Mean areas of five fringing marsh and five meadow marsh sites. Means are significantly different from each other (ANOVA, $p < 0.001$, square root transformed data).
d. Mean distance from water's edge to nine sample quadrats at five fringing marsh and five meadow marsh sites. Means are significantly different from each other (ANOVA, $p < 0.01$, log transformed data).
e. Mean surface slope of five fringing marsh and five meadow marsh sites. Means are significantly different from each other (ANOVA, $p < 0.01$, log transformed data).

f. Porewater salinities at each site. Means are significantly different from each other (ANOVA, $p < 0.001$). Pairwise comparisons made with Student-Newman-Keuls (SNK).
g. Elevations at each site. Means are significantly different from each other (ANOVA, $p < 0.001$). Pairwise comparisons made with Scheffe's S. Elevation units are meters above 0' tide.
h. Areas of fringing and meadow marsh sites.
i. Mean distance from water's edge to nine sample quadrats at each site. Means are significantly different from each other (ANOVA, $p < 0.001$, log transformed data). Pairwise comparisons made with SNK.
j. Percent surface slope at each site. Means are significantly different from each other (ANOVA, $p < 0.001$, log transformed data). Pairwise comparisons made with SNK.

Figure 4. (a) Aboveground and (b) belowground plant biomass of fringing and meadow salt marsh sites. Error bars are ±1 SE from the mean. Neither aboveground ($p = 0.924$) nor belowground ($p = 0.195$, 1/x transformed) biomass was significantly different between fringing and meadow marshes.

Figure 5. (a) Percent organic matter content of fringing and meadow salt marsh soils. Error bars are ±1 SE from the mean. Means are significantly different ($p < 0.05$, elevation covariate $p = 0.001$). (b) Relationship between marsh surface elevation and soil percent organic matter content for five fringing and five meadow salt marsh sites. Elevation units are meters above 0' tide.

Figure 6. Amount of sediment deposited on meadow marshes, fringing marshes, and areas where no marsh was present. Error bars are ±1 SE from the mean. (a) Randomly distributed traps ($p = 0.374$, log transformed data) and (b) Traps placed 1m from the water's edge ($p = 0.120$, log transformed data).

Figure 7. Relationship between the suspended sediment concentration of tidal waters coming onto marsh sites and sediment deposition on (a) randomly distributed traps and (b) traps placed 1 m from the water's edge.

Figure 8. Wave profiles at MRM, a meadow marsh. Values for wave peaks and troughs were taken from videos simultaneously recording the passing waves at (a) 0 m and (b) 5 m along the transect.

Figure 9. Percent reduction in (a) maximum wave height and (b) 'three wave mean' height in fringing, meadow and no marsh areas. Error bars are ±1 SE from the mean. At 7 m, the difference between marsh and 'no marsh' areas was statistically significant (ANOVA $p < 0.05$, square root transformed data; Student-Neuman-Keuls test, $p < 0.05$).