Lateral Marsh Edge Erosion as a Source of Sediments for Vertical Marsh Accretion

Charles S. Hopkinson[1], James T. Morris[2], Sergio Fagherazzi[3], Wilfred M. Wollheim[4], and Peter A. Raymond[5]

[1]University of Georgia, Athens, GA., U.S.A.

[2]University of South Carolina, Columbia, SC., U.S.A.

[3]Boston University, Boston, MA., U.S.A.

[4]University of New Hampshire, Durham, NH., U.S.A.

[5]Yale University, New Haven, CT., U.S.A.

Corresponding author: Charles Hopkinson (chopkins@uga.edu)

Key Points:

- Sediment input from rivers (3,210 MT y^{-1}) and marsh edge erosion (10,032 MT y^{-1}) provides only 39% of the sediment required for marshes to maintain elevation relative to SLR.
- The marsh platform has been able to maintain its relative elevation at the expense of total marsh area.
- Sediment inputs from the ocean or from erosion of tidal flats are likely an important factor in the mineral sediment budget of the system and together must contribute 19,070 MT y^{-1} in order for the marsh to accrete at its current rate of 2.8 mm y^{-1}.

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Abstract

With sea-level rise accelerating and sediment inputs to the coast declining worldwide, there is concern that tidal wetlands will drown. To better understand this concern, sources of sediment contributing to marsh elevation gain were computed for Plum Island Sound estuary, Massachusetts, USA. We quantified input of sediment from rivers and erosion of marsh edges. Maintaining elevation relative to the recent sea-level rise rate of 2.8 mm yr^{-1} requires input of 32,299 MT yr^{-1} of sediment. The input from watersheds is only 3,210 MT yr^{-1}. Marsh edge erosion, based on a comparison of 2005 and 2011 LiDAR data, provides 10,032 MT yr^{-1}. This level of erosion is met by <0.1% of total marsh area eroded annually. Mass balance suggests that 19,070 MT yr^{-1} should be of tidal flat or oceanic origin. The estuarine distribution of ^{14}C and ^{13}C isotopes of suspended particulate organic carbon confirms the resuspension of ancient marsh peat from marsh edge erosion and the vertical distribution of ^{14}C-humin material in marsh sediment is indicative of the deposition of ancient organic carbon on the marsh platform. High resuspension rates in the estuarine water column are sufficient to meet marsh accretionary needs. Marsh edge erosion provides an important fraction of the material needed for marsh accretion. Because of limited sediment supply and sea-level rise, the marsh platform maintains elevation at the expense of total marsh area

Plain Language Summary

Tidal marshes in the Plum Island Sound estuary have been gaining elevation over the past 100 years at about the same rate as sea-level rise, but there is concern that they will drown and disappear if rates of SLR increase substantially due to CO_2 emissions and climate change. What are the sediment sources enabling elevation gain? Rivers were not the primary source, providing less than 10% of elevation gain needs. Marsh edge erosion is much more important – providing over 30% of needs. We estimate the remainder comes from the ocean or erosion of tidal flats. If the ocean is a major source, these marshes might be able to maintain elevation throughout the 21st century even if sea-level rise greatly accelerates. However, if erosion of tidal flats is the primary source of sediments, the future outlook is less favorable because the more tidal flat erosion increases, the more edge erosion will also increase. The net result will be a loss of marsh area in this system. Results of this study are likely to be occurring globally, as declining sediment inputs from rivers, and increasing rates of sea-level rise due to climate change are worldwide phenomenon. Loss of marshes will have a major impact on the resilience of coastal communities landward of the marshes and the productivity of most coastal fisheries.

1 Introduction

The tidal wetlands we know today are for the most part the product of geomorphic processes that played out over the past 2000 to 4000 years. Formation of tidal wetlands as we know them today was largely tied to the stabilization of shorelines and barrier islands with the onset of the late Holocene deceleration of sea-level rise (SLR – eustatic SLR, not including vertical land movements, such as subsidence, which can be regionally important in determining the relative sea-level rise, see Rovere et al., 2016) to rates as low as 0.5 mm y^{-1} (Redfield, 1967a; Donnelly, 2006; Engelhart & Horton, 2012; Hein et al., 2012). At extremely low rates of SLR, bay infilling with sediment enabled tidal wetlands to prograde into open water areas, to build vertically through accretion, and to transgress uplands (Redfield, 1967b; 1972; Fagherazzi et al., 2012). In the U.S., increased soil erosion from land clearing for agriculture following European colonization led to increased sediment flux from watersheds, contributing to further tidal wetland expansion (Trimble, 1977; Pavich et al., 1985; Pasternack et al., 2001; Mattheus et al., 2009; Kirwan et al., 2011). Tidal wetland expansion following deforestation has been documented worldwide for marshes and

mangroves (Swales & Bentley, 2008). There are limited accounts of present-day tidal wetland expansion however, and they seem to be limited to locations with continued high riverine sediment loads, such as the Mekong and Yangtze deltas, and where there has been a major human action taken, such as in the Mississippi River delta following Atchafalaya River capture of a major portion of the Mississippi River (Blum & Roberts, 2012).

There is increasing concern for the survival of tidal wetlands because of the acceleration of SLR and the decrease in sediment delivery to the coast (Weston, 2013). Rates of sea-level rise have increased over the past 150 years (Donnelly et al., 2004; Rahmstorf et al., 2012) to rates that are now about 3.2 mm y^{-1} globally. Sea level is projected to further increase by 2100 at rates not seen since the maximum meltwater pulse about 9,000 years ago as a result of climate change brought about by anthropogenic CO_2 emissions – up to 2 m by 2100 (Donnelly et al., 2004; Walsh et al., 2014; Sweet et al., 2017). Improved land management (e.g., contour plowing), agricultural abandonment and reforestation, and river damming have reduced sediment delivery world-wide substantially (Milliman & Syvitski, 1992; Syvitski et al., 2005). In North America it has been estimated that sediment delivery to the coast decreased about 50% in the 20th century (Meade & Trimble, 1974; Warrick et al., 2013; Weston, 2013). Reductions in sediment availability and delivery and rising sea level has been linked to tidal wetland loss globally (Reed, 1995), with examples in the Mississippi River delta (Blum & Roberts, 2009; Day et al., 2011), Choptank River and Blackwater Creek marshes in the Chesapeake Bay (Ganju et al., 2015), and Venice Lagoon (Day et al., 1998).

Tidal wetlands provide critical ecosystem services to mankind, including protection from coastal storms and carbon dioxide sequestration (Costanza et al., 1997; Barbier et al., 2011). We already see management activities taking shape to reduce erosion of marsh shorelines through the installation of armored shorelines and living shorelines (Gittman et al., 2015). Yet we do not know the impact and long-term effects of shoreline erosion reductions on estuarine sediment budgets and the sediment supply required for tidal wetlands to maintain elevation relative to SLR.

There are two aspects of tidal wetland survival that are impacted by reductions in sediment availability and sea-level rise (incorporating rise in sea surface height and changes in land elevation, such as subsidence) – vertical elevation gain and maintenance of areal extent. Relative SLR can be even greater when augmented by land subsidence, thereby making tidal wetland survival even more precarious. It is generally accepted that there is a positive relationship between maintaining elevation relative to increasing rates of SLR and the availability of suspended sediment (Kirwan et al., 2010; Day et al., 2011; Mudd, 2011; Fagherazzi et al., 2012). There are strong stabilizing feedbacks between the depth of tidal inundation, marsh biomass and sediment trapping efficiency (Morris et al., 2002; Morris, 2016) such that as long as inundation depth does not exceed a critical threshold, marshes will respond to increasing sea level by increasing their productivity and aboveground biomass, which leads to enhanced sediment trapping efficiency, increased sedimentation on the marsh surface, and increased gain in marsh elevation. Mariotti and Fagherazzi (2013) and Fagherazzi et al. (2013) have proposed that the stability of the marsh boundary (and hence marsh area) is also strongly linked to sediment availability and the rate of SLR. Marsh boundaries are inherently unstable and even in the absence of SLR, marsh boundaries will retreat when sediment erosion is higher than the input of sediment to the system. Only a complete sediment budget can evaluate both vertical gain and maintenance of areal extent that determine the fate of intertidal wetlands in an estuarine system (Marcus & Kearney, 1991; Fagherazzi et al., 2013), yet few sediment budgets focused on wetland stability exist (French et al., 2008; Ganju et al., 2017).

Here we develop a sediment budget of marsh elevation gain for the Plum Island Sound salt marshes in order to assess the long-term survival of the extensive tidal marshes currently present. In this system we have evidence that marshes are maintaining elevation relative to SLR, but we also find substantial rates of erosion along the marsh boundaries of Plum Island Sound, and therefore declining areal extent of marshes. Our research questions are as follows: How widespread is edge erosion and what is its significance relative to riverine sediment sources in contributing to marsh elevation gain? If these two sources do not provide sufficient sediment to sustain marsh elevation gain, what are the other likely sources?

2 Materials and Methods

2.1 Description of the area

The Plum Island Sound marsh-dominated estuary is located in northeastern Massachusetts, USA, adjacent to the Gulf of Maine and the Parker and Ipswich River watersheds (Figure 1). The combined watersheds are about 600 km^2 in size and experiencing significant suburbanization. Agriculture has been declining since its peak in the mid-1800's (Claessens et al., 2006). Precipitation is uniform throughout the year but runoff is highly seasonal ranging from about 110 to 8 mm mo^{-1} in March and September. The watershed is of very low relief and punctuated with wetlands (21%) and the river has hundreds of dams, natural (beaver ponds) and man-made (Claessens et al., 2006). These wetlands and dams influence streamflow dynamics and particulate matter entering the estuary.

The Plum Island Sound estuary is a typical but large marsh-dominated estuary in New England. The estuary is about 60 km^2 in size with tidal wetlands making up about 40 km^2 of the total area. The main axis of the estuary is about 24 km long, with the Parker River entering at the head and the Ipswich River debouching near the mouth. It is a macro-tidal system in the cold water Acadian biogeographic province. The estuary stabilized into its current barrier island/inlet configuration about 2,500 to 3,500 years ago, once the rate of SLR had decreased to about 1mm yr^{-1} (Hein et al., 2012). From about 1000 years ago until the 19th century, the SLR rate was about 0.5 mm y^{-1} (Donnelly, 2006; Hein et al., 2012). The average rate of SLR increased to about 2.8 mm y^{-1} in the 20th century. Mean tidal range is 2.5 m. Tidal fluxes dominate over river flow (Vallino & Hopkinson, 1998; Hein et al., 2012) and the estuary is ebb-tide dominated with an ebb tidal delta.

Plum Island Sound estuary wetlands are distributed between mean sea level and 2 m (Millette et al., 2010; Morris et al., 2013b). There is a gradient in tidal wetlands along the estuary ranging from oligohaline marshes dominated by *Typha* spp. and *Spartina patens* in the upper 5 km of the Parker river, to brackish and saline marshes further downstream that are dominated by *S. patens* and *Spartina alterniflora*. The final 10 km of the estuary consists of a 1-km wide broad sound that narrows only near the mouth. The ratio of marsh area to estuarine water area varies along the length of the estuary from >10:1 to about 1:1 adjacent to Plum Island Sound. As is typical for the New England region, the tidal marshes can be characterized as having high and low marsh platforms dissected by numerous tidal channels and mosquito-control ditches. The high marsh platform (75% of the marsh area; elevation about 1.4 m above NAVD88 (~1.38 m above MSL) is dominated by *S. patens* in areas showing a gradient in elevation and short form *S. alterniflora* on nearly flat pannes that exhibit poor drainage (Millette et al., 2010). Ponds are numerous within many pannes (Wilson et al., 2014). The low marsh platform dominated by tall form *S. alterniflora* comprises only about 10% of the marsh. The transition elevation to the high marsh platform

is at about 1.0 m. MHW and MHHW elevations are at about 1.1 and 1.28 m (Millette et al., 2010).

2.2 General approach

We use a mass balance approach to determine the relative importance of various sediment sources that enable the marsh platform to maintain elevation relative to sea-level rise (Figure 2). The estuary is divided into 3 zones of roughly equivalent length along the Parker River and one for Plum Island Sound (Figure 1). Each zone has three components: 1) the water column, which connects all elements within the system including external inputs, 2) subtidal and intertidal sediments, which we simply label tidal flats, and 3) the marsh. There are 4 potential sources of sediment, two internal and 2 external. The internal sources include edge erosion of the marsh shoreline and erosion of creek and bay bottoms and intertidal flats. The external sources include rivers and the ocean. The only component for which we quantify sediment standing stock is the sediment suspended in the water column and we assume this stock is roughly at equilibrium over annual periods and longer.

The overall equation describing the sediment mass balance is:

Marsh Sediment Accretion = River + Edge Erosion + (Net Ocean Exchange + Net Tidal Flat Erosion),   (1)

where marsh accretion is seen as a sink of sediment, and rivers, edge erosion and the ocean or tidal flats are seen as potential sources. Marsh sediment accretion, river, and edge erosion are quantified in a manner described below. The net ocean exchange and tidal flat erosion is the unknown for which we solve. We assign the shortfall to either the ocean or tidal flats, as we are unable with this single equation to solve for more than 1 unknown at a time. All sediment stocks or fluxes are reported in units of metric tonnes of sediment per year (MT y^{-1}). Our budget is calculated for a mean annual interval. While we budget gains and losses of marsh sediment due to surface accretion and edge erosion, we do not track total marsh stocks. Nor do we track sediment stores associated with tidal creek bottoms and intertidal flats, even though these are the proximal source and sink of sediment resuspended by tidal currents. We apply this approach separately for both mineral and organic sediments, fully cognizant of, but ignoring, the potential importance of undecomposed roots and rhizome accumulation in contributing to marsh elevation gain, but not to surface accretion.

2.3 LiDAR data

The PIE-LTER study area was flown by the National Center for Airborne Laser Mapping (NCALM) with LiDAR on two occasions at times of minimal vegetation height (after winter icing, plant scouring and vegetation compression, and prior to spring growth), in spring of 2005 and 2011 and within 90 minutes of predicted low tide. Details on LiDAR orthorectification are described by Millette et al. (2010). The data from both flights were projected on the horizontal datum of UTM NAD83 (2007), UTM Zone 19, and a vertical datum of NAVD88 computed from the GEOID09. The final products were converted to 1.0 × 1.0 m raster DEMs in grid format.

2.4 Marsh sediment accretion

Volumes, areas, standing stocks and fluxes of materials used to calculate a sediment budget for the Plum Island Sound estuary wetlands were obtained from previous reports as well as new measures in this study. The marshes along the estuary are distributed between mean sea level and 2 m (Millette et al., 2010; Morris et al., 2013b). ArcMap 10.2.2 was used to calculate the surface area of marsh in each section using the surface volume tool querying

the 2005 DEM as to area between 0 and 2 m in elevation. We used previous studies of Plum Island Sound estuarine hydrodynamics and metabolism for estimates of water volumes along the length of the estuary (see Vallino & Hopkinson, 1998; and Vallino et al., 2005).

The mass of sediment required to maintain marsh elevation relative to sea-level rise was assessed in two ways. First we simply multiplied the annual increase in sea level × sediment bulk density × surface area of marsh in each box. Wilson et al. (2014) analyzed marker horizon and surface elevation table data maintained by the National Science Foundation-supported, Plum Island Ecosystems – Long-term ecological research project (PIE-LTER) for the past 15 years and concluded that the marshes throughout the system have been increasing in elevation at about the same rate as historic records of sea-level rise (NOAA – 2.8 mm per year since 1920). The increase in sea level at this site is primarily driven by the increase in sea surface height. Subsidence as determined by repeated measures of the heights of dozens of surface elevation tables (SETs) over the past decade is not discernible. Mineral and organic matter contributions to elevation gain were determined from specific measures of sediment bulk density, organic carbon density, mineral content and organic matter content (PIE-LTER database - see also Schmidt et al., 1998; Hopkinson et al., 2012; Morris et al., 2016).

We also calculated inorganic and organic sediment inputs from the simultaneous solution of two equations.   The organic input can be met from a combination of *in situ* accumulation of undecomposed marsh plant roots and rhizomes and POC from estuarine tidal waters. The first constraint is that the proportions of organic (x) and inorganic (y) inputs (MT/yr) must be consistent with the observed organic matter fraction of marsh sediments of 0.3, so that:

1) $x/(x+y) = 0.3$

The second constraint is that the total volume (V) required annually must be met by the sum of individual inorganic and organic inputs (Morris et al., 2016), given by:

2) $V = x/k_1 + y/k_2$

Where the constants k_1 and k_2 are the self-packing densities of organic and inorganic sediment, or 0.085 MT/m^3 and 1.99 MT/m^3 (Schmidt et al., 1998; Morris et al., 2016; PIE-LTER database), respectively. ArcMap 10.2.2 was used to calculate the surface area of marsh in each section using the surface volume tool querying the 2005 DEM as to area between 0 and 2 m in elevation. We used previous studies of Plum Island Sound estuarine hydrodynamics and metabolism for estimates of water volumes along the length of the estuary (see Vallino & Hopkinson, 1998; and Vallino et al., 2005).

2.5 Distribution and mass of total suspended solids along the estuary

The spatial distribution of total suspended solids and other substances has been monitored by the PIE-LTER during spring, when river flow is highest, and fall, when river flow is lowest, for the past 15 years. We used the median of all spring and fall data over this interval as the average mass of material suspended in the water column for the 4 estuarine sections. This is the material that is potentially deposited on the marsh during high tide inundation. We acknowledge the potential importance of resuspension during storms, which is not accounted for by our sampling approach, and discuss this further in the discussion. Water samples from eleven stations spanning the full salinity gradient and length of the estuary are sampled, returned to the laboratory, and filtered through pre-combusted (450 °C)

and pre-weighed GF/F filters (Whatman brand with nominal 0.7 µm pore size) until clogged. Filters were dried to constant weight at 60°C, then weighed to determine mass of total suspended solids or to determine C content by Perkin Elmer CHN elemental analyzer after acidification. A subset of filters was ashed at 450 °C then reweighed to determine percent loss on ignition and, by difference, percent organic matter and mineral content. Chlorophyll-*a* (chl-*a*) was determined from a second filter using acetone extraction, accounting for phaeophyton (Strickland & Parsons, 1972). From these measures, we estimated the mass of total suspended solids in each section of the river and the relative importance of algae, other particulate organic matter, and mineral matter. We converted POC to POM assuming 50% C. We converted chlorophyll-*a* to carbon and then to POM assuming a 60:1 chl-*a* to C ratio.

2.6 Estimation of total suspended solids resuspended during a single tidal cycle

We estimated the tidal current-induced resuspension of sediment particles relative to that at slack water from the calculated median absolute deviation (MAD) of our total suspended solids measures collected during spring and fall sampling cruises over a 15-year period. As sampling was not conducted at times of maximum and minimum total suspended solids concentrations during a tidal cycle, we had to estimate the max-min difference to derive resuspension, assuming that the minimum concentration is the background sediment concentration always present. Our field sampling was conducted irrespective of tidal stage or storm/wind conditions. It is our assumption that the variability we observed in spring and fall over long time intervals (15 yrs) mostly reflects differences in when we sampled relative to tidal stage, with high values coming from sampling during maximum tidal currents and low values from sampling near slack water. Thus the amount of total solids resuspended during each tidal cycle is two times the MAD (difference between (median+MAD) and (median-MAD) – e.g., median of 10 mg/l and MAD of 4 gives resuspension of 8 mg/l from (10+4) – (10-4). To estimate resuspension on an annual basis we accounted for the number of tidal cycles in a year (~730).

2.7 River loading of particulate matter

We used total suspended sediment (TSS) concentration data collected by the PIE-LTER and USGS discharge data for the Parker and Ipswich Rivers (USGS ID = 01101000 and 01102000 respectively) to calculate mean annual loading of suspended solids into the Plum Island Sound estuary. We scaled USGS discharge data to cover ungauged portions of the watersheds using scaling factors determined in Vallino and Hopkinson (1998). Flow-weighted mean TSS was estimated for each watershed using just under 9 years of monthly data collected between the end of 2006 and 2014 (n= 98 samples). Data were collected over three orders of magnitude variation in river discharge, and a range of baseflow and storm flows, including both rising and falling limbs of storm hydrographs. Monthly sampling was assumed to provide adequate estimates of longer term TSS concentrations in these rivers because discharge is not flashy due to the relatively high wetland abundance that store and release storm flows. DOC floc was similarly estimated from total DOC inputs from the watersheds, assuming 10% of DOC in freshwater flocculates as sediments. Inputs were distributed to the respective boxes (Figure 2) as appropriate.

2.8 Marsh edge erosion estimation

Erosion at the marsh-water edge was assessed by analyzing the 3-dimensional change described by the difference between the 2005 and 2011 DEMs of the marsh edge (Figure 3, Figure 4). Based on the hypsometric profile of the cumulative distribution of marsh area versus marsh elevation for the entire marsh (figure 5 in Millette et al., 2010), we chose the 1 m contour as the best demarcation point for the "edge" of the marsh – still on the marsh, yet

not down the marsh ramp, where elevation rapidly drops. When erosion of the marsh edge occurs, the marsh ramp continues to exist, but it moves inland across the marsh platform. It is the marsh platform that loses area and sediment volume. We quantify edge erosion by examining change in a 10 wide zone (buffer) behind the 1 m contour (up across the marsh platform) as defined in 2005. Erosion occurs when the edge advances across the platform buffer, ultimately causing a decrease in total marsh area and an increase in open water area.

We used ArcMap 10.2.2. to develop a buffer shapefile and to calculate the volume of sediment lost during the 2005-2011 interval. The shapefile was based on the 2005 DEM and included only the 10 m wide buffer greater than or equal to the 1.0 m elevation contour. This contour follows the shorelines of all waterbodies, including the Sound, first through fourth order tidal creeks, and most mosquito ditches and marsh ponds. We also created shape files for each of the 4 zones along the estuary (Figure 1): 0-5, 5-10, 10-15, and 15-24 km. These shape files were used to quantify edge erosion, and the areas of marsh (0-2 m elevation) and water (< 0m elevation) for each zone. Having four zones enabled us to compare and contrast reaches with and without riverine inputs and to contrast the sound from the tidal river. As mentioned earlier there is also a great range in marsh area to water areas from the top zone to the bottom (Sound) zone.

The sequence of steps we employed in creating a buffer shape file is: 1) convert all elevations to integers starting with our 2005 DEM; 2) reclassify all elevations into the binary 0 or 1 depending on whether elevation was < 1m or ≥ 1m to define the marsh platform; 3) convert from raster to polygon in order to define 3 zones as shape files – marsh only, water only, water plus 10 m buffer adjacent to water and of elevation greater than 1m; 4) remove water from the buffer, leaving only the buffer as a shapefile; 5) extract the buffer from the 2005 and 2011 DEMs.

We calculated edge erosion using the ArcMap tool, *functional surface / surface area and volume*, querying the 2011 DEM (just the buffer) as to the area and volume below 1 m in elevation. Remember that the entire buffer was ≥ 1 m in elevation in 2005 and the area < 1 m was by definition 0. Any surface lower than 1 m in 2011 represented erosion that occurred between 2011 and 2005.

2.9 Carbon dating of estuarine suspended particulate organic matter

We ^{14}C-dated the suspended POC of estuarine water to determine the presence of eroded marsh peat in the water column. If eroded marsh peat is an important source of sediment for the marsh platform, it has to be resuspended into the water column prior to its being deposited on the marsh. Samples were collected along the length of the estuary 4 times over 3 yrs, during times of high and low river discharge. Estuary water was filtered through ashed (450 °C) 2.5-cm GF/F (nominal pore size, 0.7 μm) filters using a 100 ml glass syringe. Filters were frozen until preparation. In the laboratory, filters were acid-fumed to sparge off any inorganic C and then dried and sent to the National Association of Oceanic Mass Spectrometry (NOSAMS0 facility in Woods Hole for accelerator mass spectrometric analysis of Δ^{14}C and δ^{13}C. All reported Δ^{14}C values were corrected for fractionation using the δ^{13}C values of the samples, according to the conventions of Stuiver and Pollach (1977). The potential contribution of eroded ancient marsh peat to the distribution of suspended POC along the estuary was calculated with a simple end-member mixing model of Δ^{14}C using the average Δ^{14}C value measured at 67.5 cm depth in a core taken from the high marsh platform as described below (Raymond and Hopkinson (2003).

2.10 ^{14}C dating of marsh organic matter

We also ^{14}C-dated the depth distribution of organic carbon in Plum Island marsh sediment to check whether any of the ancient marsh organic carbon that erodes from marsh edges is returned to the marsh platform during tidal inundation. The presence of ancient organic carbon in near surface sediments could be indicative of this process. We analyzed just the humin fraction of sediment organic matter. This is the organic carbon fraction bound by clay minerals that often contaminates bulk sediment in archeological studies causing its age to deviate substantially from the charcoal, wood or plant macrofossils of interest (MeGeehin et al., 2001). We assume that the presence of ancient humin carbon near the marsh surface is an indication that it is derived from tidal waters with suspended ancient humin-POC. As the vast majority of organic matter near the marsh surface is expected to be live and recently dead roots and rhizomes of marsh plants, by sampling the age of humin material, we minimize the contribution of organic matter recently produced *in situ*. As the humin is likely clay bound, the presence of ancient humin is likely indicative of mineral matter also eroded from the marsh edge.

We analyzed a single core collected in 2006 from the high marsh adjacent to the Rowley River near where the PIE-LTER project monitors marsh productivity. The core was subsampled at depths of surface, 2.5, 22.5, 42. 5 and 67.5 cm. Subsamples were passed through a 63 μm screen after removal of any visible *Spartina* macro-organic matter and then treated with acid-alkali-acid washes following the procedure in McGeehin et al. (2001) to remove all but the humin fraction (the classical humic and fulvic acid fractions are alkali soluble and hence removed). The humin fraction for each layer was isolated, dried and analyzed for ^{14}C at the NSF-Arizona Mass Spectrometry Facility at the University of Arizona. Mass balance was not determined so we do not know the percentage humin relative to bulk organic content.

2.11 Mass balance estimation of sediment shortfall in meeting marsh accretionary needs

Sediment required to support measured rates of marsh elevation gain (marsh sediment accretion) was balanced against measured inputs from the watershed (River) and measured rates of marsh edge erosion (Equation 1) to determine the accretion shortfall. As Equation 1 indicates, two potential sediment sources could make up for the shortfall – 1) net ocean exchange and 2) net tidal flat and bay bottom erosion. We examined each one separately assuming all or nothing, even though it is likely a combination of the two occurs. Thus our estimates of these inputs are likely high. On the other hand, if not all river or edge erosion inputs are retained within the system and deposited on the marsh platform, our mass balance estimation of the shortfall will be underestimated.

Mass balance was also used in the net tidal flat erosion scenario to assess sediment settling following resuspension. The amount settling back to tidal flat and bay bottoms is the difference between the amount resuspended and the amount required to meet the marsh sediment accretion shortfall: resuspension minus net tidal flat erosion = sediment settling. The difference would result in water body deepening, if the shortfall was not made up by oceanic inputs.

4 Results

4.1 Marsh sediment accretion

Based on analysis of over 20 16×50 cm cores collected along the estuary with varying distances from tidal creeks, we found no significant spatial patterns for marsh sediment bulk density or the relative mineral vs organic matter composition of sediment throughout the estuary (Schmidt et al., 1998, PIE-LTER database). There was considerable variability however. Bulk density averaged 0.272 mg cm^{-3} (Standard Error (SE)=0.022) and mineral and organic fractions of sediment dry weight were 0.7 and 0.3 g g^{-1}, respectively. These values are similar to those reported in Morris et al., (2016) and follow closely the power function that described the relation between bulk density and organic content for over 5000 sediment samples from 33 tidal marshes and mangroves distributed around the U.S.A.

Plum Island marshes require a total particulate or solids input equivalent to 32,300 MT y^{-1} in order to maintain elevation relative to an average SLR rate of 2.8 mm y^{-1} (Table 1). The distribution along the length of the estuary is skewed highly towards the marshes adjacent to Plum Island Sound, because 75% of all marshes are found in this region. By contrast, only 1,110 and 1,292 MT y^{-1} are required to meet needs in the upper two zones of the estuary. Mineral inputs required to meet marsh elevation changes range from 778 to 16,928 MT y^{-1} along the length of the estuary. Organic matter inputs to meet marsh changes ranged from 332 and 7,253 MT y^{-1}.

4.2 River loading of particulate matter

The annual loading of TSS from the watersheds varied over an order of magnitude between 2007 and 2014, from < 300 to > 5000 MT y^{-1}. The 8-year average was 2656 MT y^{-1} (standard error (SE) = 561). This wide range over time is primarily due to the extreme range in discharge during the same time period (226 – 608 x 10^6 m^3 y^{-1}). The average discharge during the 8-year record was approximately 10% higher than the USGS 80-year average. Particulate organic matter loading (a subset of particulate matter) averaged 823 MT y^{-1} (SE=172) and varied as much over the 8-year record as total suspended solids. We also include an estimate of organic carbon that flocculates when in contact with the high salinity estuarine waters, assuming that 10% of total DOC loading flocculates (Sholkovitz 1976). Dissolved Fe, Mn, and Al also flocculate with the humics, but at insignificant mass relative to organic matter itself. We estimate that organic matter that flocculates from river water contributed an additional 554 MT y^{-1} (SE=48) to the particulate matter input to the estuary. DOC input was much less variable than particulate loading. Total particulate loading averaged 3210 MT y^{-1}, of which 43% was organic and 57% was mineral matter.

4.3 Marsh edge erosion

Erosion of the marsh edge was readily detected over the 2005-2011 LIDAR defined interval (Figure 4 and Table 2). Measures along the northwestern shoreline of Plum Island Sound (shown in Figure 4) agree favorably with direct measures along a 1-km stretch of shoreline between 2008 and 2013 (Leonardi and Fagherazzi 2014, 2015). The area of marsh land lost in each region of the estuary ranged from 3,146 to 142,832 m^2 over the 6-yr interval (Table 2). While significant in terms of mass, this level of erosion represents a small fraction of total marsh area in each region – losses ranged from 0.03% of the mid-Parker section to 0.12% of the lower-Parker region. Only 0.07% was lost annually from the marsh boundaries in the Plum Island Sound region of the estuary.

The mass of sediment lost (calculated from measured bulk density) was estimated to be 10,023 MT y^{-1}, with almost an order of magnitude more from the Lower Parker and Sound zones than the mid- and upper Parker zones. Considering that the average mineral content of Plum Island marsh sediments is 70% mineral matter by weight (Morris et al., 2016, Schmidt et al., 1998, PIE-LTER database), mineral matter inputs to estuarine waters from edge erosion ranged from 37 to 3,836 MT y^{-1} for the various zones and totaled 7,019 MT y^{-1}.

4.4 Sediment storage in the water column

The water column stock of suspended solids (particulate matter- TSS) shows the typical estuarine longitudinal distribution with a distinctive estuarine turbidity maximum (ETM) in the oligohaline region of the estuary (Figure 5). The distribution is shifted down-estuary in spring reflecting higher freshwater runoff with lower salinities and lower TSS concentrations in the upper estuary. Median total suspended solids concentrations range from less than 10 mg L^{-1} at the head and mouth of the estuary to 30-40 mg L^{-1} within the ETM during spring and fall. The median TSS concentration over space and time was 15.6 mg L^{-1} (SE=3.6). Variability at any one station is very high reflecting that this data represents 13 yrs of transect data taken during spring and fall: average CV for all stations was 97 and 93% for spring and fall, respectively.

The spatial distribution of POM and chlorophyll-*a* is similar to that of total particulate matter, but median concentrations are considerably lower. POM comprised between 11 and 59% of TSS at any one station, but averaged 17%. The overall median POM concentration was 2.7 mg L^{-1} (SE=0.5). It was only at the very head of the estuary, just below the Parker River dam, that POM made up over 50% of total suspended solids, consistent with expectations based on watershed measurements. Chlorophyll-*a* (converted to OM), a proxy for live phytoplankton, made up between 8 and 75% of POM, but averaged 37%. The overall median Chl-a concentration was 1.0 mg organic matter L^{-1} (SE=0.2). Phytoplankton comprised a larger fraction of the total particulate organic matter in fall (53%) than in spring (16%), reflecting the long residence time of water relative to phytoplankton growth rates in late summer / early fall. On average, mineral matter made up the largest fraction of suspended solids along the Plum Island Sound estuary – averaging 83%. The organic fraction made up only 17% of the total.

The mass distribution of suspended solids along the estuary reflects both concentration and volume of water in each region of the estuary. The mass averaged about 16 MT in Zone 1 of the upper Parker River portion of the estuary and 182 MT in Zone 4, the Sound portion of the estuary (Table 3). The average total mass of solids for the entire estuary was 284 MT. Thus about 1/3 of the total mass of suspended solids is in the Parker River portion of the estuary and 2/3 is in waters of Plum Island Sound.

4.5 Isotopic evidence of creekbank erosion and tidal deposition of ancient eroded material onto the marsh surface

4.5.1 Estuarine distribution of Δ^{14}C-depleted particulate organic carbon

The concentrations of POC in the estuary were consistently elevated relative to the river or marine end-members, which is indicative of an internal source of POC. Of particular interest for this study was the appearance of organic carbon that likely came from erosion of old marsh peat. Of our four isotope sampling transects, two showed the internal input of old, Δ^{14}C-depleted material – April 2000 and September 2000, and one showed an input of δ^{13}C-enriched OC. In September 2000 (Figure 6 and Table 4), Δ^{14}C-POC values ranged from -27 to -182‰ (Raymond & Hopkinson, 2003), with a corresponding ^{14}C age of 220 to 1614 years BP (Table 4).

The most likely source of this Δ^{14}C-depleted, δ^{13}C-enriched organic carbon was marsh peat eroded from marsh edges. It did not come from contemporaneous watershed or ocean inputs as the POC of both these sources was more Δ^{14}C-enriched than in the estuary in September, 47‰ for the watershed (Raymond & Hopkinson, 2003) and -48‰ for the ocean (Table 4). Watershed POC was δ^{13}C-depleted at -32.9‰ (Raymond & Hopkinson, 2003). The δ^{13}C-enriched signal in the estuary is consistent with an input of *Spartina* organic matter. Δ^{14}C-depleted, *Spartina*-derived organic carbon is indicative of eroded, old peat from marsh shorelines. The potential contribution of eroded marsh peat to the distribution of suspended POC along the estuary in September averaged 25% but ranged from 9 to 63% along its length, based on the end-member mixing model and an average Δ^{14}C value for marsh peat at depth of -220‰.

4.5.2 Distribution of Δ^{14}C-depleted organic carbon in marsh sediments

The <63 μm presumably clay-bound fraction of organic matter in a Plum Island Sound marsh core was Δ^{14}C depleted with values averaging -220‰ and ranging from -194 to -307‰, except for the marsh surface, which had a value close to modern levels (Levin and Kromer 1997 - Table 5 and Figure 7). The corresponding ^{14}C age of the subsurface sediments was 1806 to 2976 years BP.

Organic carbon, 1800-3000 years old in near surface marsh sediments is not what would be expected in marshes that have been building vertically for almost 4000 years (Hein et al., 2012) but is consistent with the input of eroded peats resuspended in the water column and deposited during marsh flooding. As we saw in September 2000, old marsh peat on occasion makes up 25% of the suspended estuarine POC.

4.6 Resuspension Fluxes

Our estimate of the amount of sediment resuspended and settled into and out of the water column in association with variations in tidal current velocity and waves was extremely large: >187,000 MT y^{-1} for mineral matter and >30,000 MT y^{-1} for organic matter (Table 6). For mineral matter, it ranges from over 10,000 MT yr^{-1} in the upper estuary to over 130,000 MT yr^{-1} in the Sound. For organic matter it ranges from over 1,200 MT yr^{-1} to over 22,000 MT yr^{-1} for the upper estuary and Sound, respectively. We note that this value represents only fair weather values (because we sampled by small motorboat), and therefore may underestimate true annual resuspension. This spatial pattern mostly reflects differences in water volume for various sections along the estuary (factor of 40) as differences in suspended solids concentration and varied by less than a factor of 10 (Table 3 and Figure 5). There were no spatial gradients in TSS variability along the estuary (median absolute deviation averaged 42% relative to the median overall). The high resuspension flux relative to the average mass of suspended solids in the estuary (Table 3) suggests a very rapid turnover rate (>700 yr^{-1}).

4.7 Mass Balance

The mass balance identifies a large shortfall between marsh accretion needs and measured sediment inputs from rivers and the erosion of marsh shoreline edges (Table 6). Rivers supply only 3,210 MT y^{-1} and edge erosion supplies 10,032 MT y^{-1}, or 10% and 31% of marsh accretion needs, respectively. The mass balance shortfall amounts to 19,070 MT y^{-1}, and is slightly higher for mineral matter (61%) than organic matter (55%). Indeed, riverine and edge erosion sources are insufficient to meet accretionary demands in any section of the estuary. The shortfall is greatest in Zone 2 of the estuary, a zone of no direct riverine input of sediments and least in Zone 3, a region with large edge erosion. Two possible sources of sediment to balance marsh accretionary needs are discussed in the conclusions: 1) the ocean and 2) estuarine tidal flats and bay bottoms.

5 Discussion

We used the mass balance approach to examine both mineral and organic particulate matter sources and sinks within the Plum Island Sound estuary. Both forms are important components that contribute to the bulk volume of marsh sediments (Gosselink et al., 1984; Morris et al. 2013a; Morris et al., 2016) and elevation gain of marshes over time. While mineral matter contributes to elevation gain only through surface deposition, organic matter can be accumulated by surface deposition or by *in situ* net production of refractory root and rhizome tissues (Cahoon et al., 2003; McKee et al., 2007). It is challenging to tease apart the relative importance of these two pathways. We draw on additional studies conducted in the Plum Island Sound ecosystem to put the results of this study in perspective. Measures of metabolism using the eddy covariance approach in the marshes adjacent to Plum Island Sound show net ecosystem exchange (NEE) to average 168 gC m^{-2}y^{-1} (Forbrich et al., 2018), indicating the potential for accumulation of refractory root and rhizome material produced *in situ*. If all the NEE is associated with belowground production, then *in situ* production can provide 147% of the organic matter required to support historic rates of marsh elevation gain of 2.8 mm y^{-1} (Forbrich et al., 2018). Thus there is no need for additional organic matter inputs to maintain marsh elevation gain at the rate of 2.8 mm y^{-1}. Interestingly, marker horizons show accretion of mineral and organic matter on the marsh surface (Cavatorta et al., 2003) matches total marsh elevation gain as observed with sediment elevation tables (SETs) (Wilson et al., 2014; PIE-LTER database). Thus in addition to net belowground production of organic matter, there is an additional input of organic matter to the marsh deposited during tidal inundation. We do not have quantitative measures of the mass of organic matter accumulating over marker horizons, just depth. We can estimate organic matter deposition however, on the basis of the amount of mineral matter associated with marsh accretion (Table 6) and the relative organic matter content of total suspended solids in tidal water (mineral matter * [1-(mineral/TSS)] converted to organic matter or 1570 MT y^{-1}. If none of the deposited organic matter is decomposed (unlikely), this is only 16% of the amount organic matter required to support marsh elevation gain (Table 6). Surface organic matter deposition could become more important in the future if the balance between primary production and respiration shifts towards less NEE with a changing climate (Megonigal et al., 2016). Therefore, the Plum Island Sound marshes are both a sink for mineral and organic matter brought in from a variety of potential sources (e.g., river, edge erosion) and a source of organic matter for the estuary and perhaps the coastal ocean. Estuarine metabolic studies show the estuary to be heterotrophic and dependent on allochthonous organic matter inputs from the marshes (Vallino et al., 2005).

As there are large differences in the relative importance of sediment sources along the length of the estuary, we discuss them separately.

5.1 Rivers

Particulate matter inputs from rivers draining into the estuary were of low overall importance in meeting accretionary needs of estuarine marshes (Figure 8 and Table 6). On average, river inputs are equivalent to 8% of marsh mineral needs and 14% of organic matter needs. The large organic contribution reflects the high organic content of riverine suspended particulate matter (31%) and the fact that we included dissolved organic matter that flocculates once it meets the higher ionic strength of seawater as a river input of particulate matter. River inputs were very important in meeting accretionary needs in Zone 1, the upper estuary, with inputs equivalent to 30% of mineral (Figure 8) and 53% of organic matter needs. In contrast, river inputs are able to meet only between 0 and 14% of particulate needs lower in the estuary. The importance in the upper estuary reflects the small wetland area

there relative to the mass of inputs – only 3% of estuarine marshes are in the upper stretches of the estuary.

While riverine inputs of sediment are a large component of estuarine sediment budgets in some systems (e.g., 40% in the Brisbane Estuary, 50% in the Hudson River estuary, and 28% in the Chesapeake Bay estuary), the relatively low importance in the Plum Island Sound estuary should not be unexpected (Eyre et al., 1998; Hobbs et al., 1992; Geyer et al., 2001). The overall sediment yield from the Ipswich and Parker River watersheds is extremely low (3.1 MT km^{-2}) in comparison to the range reported in the literature: 5 – 1460 MT km^{-2} (Lane et al., 1997) and the global mean of 120 MT km^{-2} (Syvitski et al., 2005). The low relief of the Ipswich and Parker River watersheds, coupled with relatively high fresh water wetland and forest land cover and high density of dams retards sediment erosion and promotes sediment trapping within the watershed itself.

The importance of riverine particulate matter inputs may decline in the future given current trends in declining river sediment inputs regionally and globally (Meade & Trimble, 1974; Milliman & Syvitski, 1992; Syvitski et al., 2005; Weston, 2013). Agriculture has declined considerably in the Parker and Ipswich River basins over the last century, replaced by forest (Claessens et al., 2006). In recent decades, urban areas have expanded. Forest lands have much lower erosion rates than agriculture or urban areas. However, urbanization is concentrated in the upper portions of the largest watershed draining to the estuary (Mineau et al., 2015). It is unlikely much of the urban sediment sources are currently reaching the estuary because of the distant location of sources combined with the shallow slopes, extensive riparian wetlands, several reservoirs, and expanding beaver ponds in the region (Wollheim et al., 2014; 2015). Ongoing and potential human dam removals will lead to increasing sediment exports (Magirl et al., 2015; Warrick et al., 2015; Foley et al., 2017). Current dam removals are in mid-reaches of the watershed so that even if sediments are liberated following dam removal most will probably be trapped behind dams lower along the river. However, the head of tide dam in Ipswich is also currently being discussed for potential removal, which would have a much greater impact on sediment loading if it was removed.

Climate change may also contribute to altered sediment delivery in the future. Spring runoff is less pronounced than previously due to less snowpack (Claessens et al., 2006) and this may decrease the sediment load to the estuary. Cook et al. (2015) suggest that a wetter future climate in the New England region will contribute to a greater incidence of landslides, which will have a greater influence on erosion than land-use change. The low relief of the Parker and Ipswich River watershed however will likely not translate into landslides as observed in more mountainous regions of New England. However, future climates are also likely to result in greater extreme events, which could lead to storm events with sufficient power to transport more sediments to the estuary (Dhillon & Inamdar, 2013).

Our estimate of sediment inputs to the estuary are based on almost a decade of sampling (end of 2006 through 2014) at river stages running from record highs to record lows since 1929 and on rising and falling limbs of storm hydrographs. It is possible that we have underestimated sediment inputs, but even if we are off by a factor of 2, the relative importance of river inputs of particulate matter would only increase from 8% to 16%. It appears that given the increase in rates of sea-level rise in the past century, watershed inputs of sediments have not played an important role in marsh expansion and elevation gain since the mid-1800's when land clearing and agriculture were at their greatest extent (Kirwan et al., 2011; Priestas et al., 2012). Agricultural abandonment, reforestation and damming likely contributed to declines in sediment yield from the watershed since then, as has been observed

elsewhere (Meade & Trimble, 1974; Milliman & Syvitski, 1992; Syvitski et al., 2005; Warrick et al., 2013; Weston, 2013).

5.2 Edge Erosion

Our measures of marsh shoreline erosion support our personal observations of marsh loss over the past 25 years, empirical data on shoreline erosion in Plum Island Sound (Leonardi & Fagherazzi, 2014; 2015), and simulation models that predict bay expansion due to low estuarine suspended solids concentrations and SLR (Mariotti & Fagherazzi, 2010; 2013). Our results show that shoreline erosion is prevalent throughout the Plum Island Sound estuary however and not just where it has been measured by field survey in the Sound (Leonardi & Fagherazzi, 2014; 2015). On an absolute basis, annual erosion rates from zone to zone ranged from 834 to 23,800 m^2, being least in the upper 5 km of the estuary and greatest in the marshes adjacent to Plum Island Sound. The percentage of marsh area lost was low for all regions and ranged from 0.03% to 0.12% per year. While the area eroded was related to the area of marsh in each region (R^2 – 0.68), edge erosion was disproportionately higher in Zone 3 of the estuary with erosion rates twice the average for the entire estuary. At these rates of edge erosion and current rates of SLR and wave climates, 50% of existing marshes in the Plum Island estuary will have eroded within 1000 yr. Ganju et al. (2017) observed for microtidal systems on the east and west coasts of the U.S., that the ratio of unvegetated to vegetated marsh area (UVVR) for an estuarine system was a good indicator of marsh health, i.e., a marsh complex that imported sufficient sediment to counter sea-level rise and internal erosion. They found that as the UVVR increased (less marsh relative to water), the greater the net sediment budget deficit (sediment was being lost) and the shorter the lifespan of the marsh complex. Based on the average UVVR for Plum Island Sound marshes, which is 0.41:1, the lifespan should be on the order of 200 yrs based on the relation Ganju et al. found. This is much shorter than the rate we calculated based on measured edge erosion rates and presumably is related to the large sediment capital associated with the mesotidal Plum Island marshes that are perched above MHHW for the most part (Millette et al., 2010). Compared to a microtidal marsh much more sediment volume must be eroded before the sediment stored in the marsh plain above mean sea level is expended through a net sediment deficit. This supports the idea of Kirwan et al. (2010) that vulnerability of marshes to submergence decreases with increasing tidal range.

Hughes et al. (2009) and Wilson et al. (2014) previously documented headwater erosion and widening for 1st order tidal creeks in Plum Island sound estuary. Our results agree with observations of marsh shoreline erosion from other tidal wetland systems as well, e.g., marsh losses in Louisiana - >25% marsh area lost since late 1800s (Blum & Roberts, 2012), southern New England – losing marsh at rate of 0.42% y[-1] for past 30-40 years (Watson et al., 2017), Choptank River in Maryland –losing marsh at rate of 0.11% y[-1] 1939-1980 (Yarbro et al., 1983) and Rehoboth Bay in Delaware - edge erosion at 14-43 cm y[-1] over 3 year period in 1980s (Schwimmer, 2001).

The liberated sediment has the potential to meet a substantial portion of marsh accretionary needs. As eroded marsh has the same mineral and organic content as the marsh platform, a cubic meter of eroded marsh can provide the necessary sediment for a large area of marsh: 1 m^3 volume lost per year (from ≤ 1 m erosion) is equivalent to 357 m^2 marsh surface at 2.8 mm y[-1] accretion. Edge erosion has the potential to meet on average 31% of the marsh organic and mineral needs of estuarine marshes currently in existence. The importance is especially high in zone-3, the Lower Parker River portion of the estuary, where we estimate that over ¾ of accretionary needs can be met by this pathway (Figure 8).

Our estimate of the relative importance of eroded marsh sediment in meeting accretionary needs of the marsh is potential only. Some material in undoubtedly exchanged with oceanic water during tidal mixing and lost from the system. Lemay (2005) suggested that mosquito ditches were an important sediment sink in heavily ditched portions of the Plum Island Sound marsh. Thus an unknown fraction of eroded marsh sediment actually is deposited on the marsh platform. Of course the same is true for sediments derived from any internal or external source.

Modeling studies suggest that shoreline erosion will increase in the Plum Island Sound estuary in the future (Fagherazzi et al., 2013; Mariotti & Fagherazzi 2013, Leonardi et al., 2016). With low suspended sediment concentrations, increasing rates of SLR, and increasing rates of storminess for this region (Hayden and Hayden, 2003), tidal flats in front of eroding shorelines deepen as waves erode the marsh shoreline. As tidal flats deepen, wave height increases, which leads to a positive feedback that results in continued marsh deterioration (Mariotti and Fagherazzi 2013).

5.2.1 Limitations to importance of edge erosion in meeting marsh accretion needs

As with any internal or external source of sediment, all sources mix into a common pool of sediment that resides in both the water column and bay bottoms and tidal flats until it is either deposited onto the marsh surface, accumulates in bay bottoms or is exported to the sea. Concentrations of suspended matter in the water column rise and fall in relation to tidal current strength and wave energy (Ganju et al., 2017). When we estimate the relative contribution of different sediment sources to marsh accretion, we assume they are proportional to relative inputs. In this study we have additional information about 2 sediment sources however, eroded peat from edge erosion and rivers. $\Delta^{14}C$ (highly depleted) and $\delta^{13}C$ (heavy) data confirms that sediment from eroded marsh shorelines contributes to particulate matter suspended in the water column along the Plum Island Sound estuary. In our September field sampling, we found that on average 25% of estuarine suspended particulate organic matter was comprised of ancient marsh peat, ranging up to 63% (Table 5). That we only observed this strong signal in September implies that resuspension of eroded peat is not continuous or that at other times of the year greater contributions from the watershed or estuarine phytoplankton overwhelm the marsh peat signal. On that day, there was 17 MT of ancient particulate organic matter suspended in the water column or enough to support marsh accretion for 0.6 days (17MT / 26.54 MT d^{-1} average daily organic matter accretionary need – Table 6). The extremely short residence time of particulate mineral and organic matter held in suspension in the water column shows how dynamic these pools are and that the resupply rate is extremely high.

In addition to the presence of ancient peat resuspended in the water column, the near surface depth distribution of $\Delta^{14}C$-depleted organic carbon in marsh sediments (Table 4 and Figure 4) was consistent with the deposition of old marsh peat via tidal flooding. We can not rule out the potential importance of watershed-derived organic carbon as the source of ancient organic carbon however, because at other times of the year the $\Delta^{14}C$ of riverine particulate organic carbon was also nearly as depleted, averaging -89‰ and ranging from 47 to -190‰ (Raymond & Hopkinson, 2003). This is not far from our marsh peat value of -220‰. The large $\delta^{13}C$ difference between watershed and Spartina-derived POC would help clarify sources. Unfortunately, we lack a measure of the $\delta^{13}C$ content of the $\Delta^{14}C$-depleted humin fraction of marsh sediment OC.

5.3 Sources calculated by mass balance: tidal flats or the ocean

A mass balance shortfall in river and marsh edge erosion inputs in matching marsh sediment accretion unequivocally shows the need for an additional sediment source. Rivers and edge erosion together supply 39% and 45% of mineral and organic matter needs (Table 6, Figure 9). The two most likely additional sources are inputs from the 1) ocean or inputs from 2) erosion of bay bottoms and tidal flats.

While we calculated budgets for both mineral and organic matter, our analysis approach is most appropriate for mineral matter, because we found earlier that there is sufficient marsh NEE attributable to the accumulation of undecomposed root and rhizome material to supply in excess of 100% of organic matter accretion needs (Forbrich et al., 2018). Further work will be required to more fully understand the production, respiration, transport, export and burial of organic carbon produced in Plum Island Sound estuary marshes and to balance the overall estuarine organic and inorganic carbon budgets. The remaining discussion pertains specifically to mineral matter budgets.

The magnitude and relative importance of oceanic or tidal flat mineral sediment inputs vary over the length of the estuary. On the order of $500 - 800$ MT y^{-1} are required to balance the sediment shortfall in each of the three zones along the tidal river, while an order of magnitude more is required to meet mineral needs of the marshes adjacent to Plum Island Sound (11,724 MT y^{-1} – Table 6, Figure 8). In contrast, the relative importance of additional mineral inputs is least in Zone 3 (18%) and highest in Zone 2 (90%).

We lack measures of net oceanic inputs or net erosion of bay bottoms and tidal flats for the Plum Island Sound system. A conceptual model lumped for the entire system simplifies discussion of the potential importance of the tidal flat and oceanic inputs (Figure 9). The settling flux is the balance between what is resuspended with each tide (187,263 MT y^{-1}) and the mass balance shortfall (13,764 MT y^{-1}). If the ocean provides all the additional sediment required to balance the sediment budget, then settling flux would be the same as the resuspension flux. The settling flux decreases in magnitude in direct proportion to a decrease in oceanic inputs, such that in the absence of oceanic inputs, all sediment would have to be derived from bay bottoms and tidal flats and the settling flux would be 173,499 MT y^{-1} (187,263 – 13,764).

5.3.1 Potential ocean sediment inputs

A potentially large importance of oceanic sources in meeting marsh accretionary needs (Table 6 and Figure 9) was unexpected, especially considering the typically low concentration of total suspended solids (SSC) at the ocean end-member (Figure 5). However, based on the total mass of suspended solids entering the estuary with each tide (tidal volume × maximum suspended solids concentration at the estuary-ocean inlet), the sediment volume needed for marsh survival would be only 7% of the total. Ganju (et al., 2017) suggest that the flood-ebb SSC differential is a measure of net sediment flux in the system, although a difference of 7% in SSC would be challenging to detect, considering the high variability in SSC in the estuary and expected spatial patterns across the inlet cross-section.

While unexpected, our finding of critical ocean sediment inputs in support of marsh accretion is in agreement with other studies looking at overall estuarine sediment budgets (most of which lacked a focus on wetland survival) (Eyre et al., 1998). Over 61% of external sediment inputs to the Brisbane estuary are oceanic (Eyre et al., 1998). A sediment budget for Chesapeake Bay showed that at least 40% of sediment originates from the ocean (Hobbs et al., 1992) as riverine inputs and shoreline erosion measured over the past 100 yrs could not match measured rates of bay deposition. In the Humber estuary, while fluvial inputs were

substantially larger than erosion inputs, mass balance indicated the need for substantial inputs from the ocean (Townsend and Whitehead, 2003). Geyer et al. (2001) observed a strong seasonality in ocean inputs of sediment to the Hudson River estuary, being most important during low river flow, neap tide conditions. Meade (1969) concluded that under normal flow conditions most estuaries tend to import sediment from the sea. The calculated overall importance of ocean sediments is higher in the Plum Island Sound estuary than any of these previous studies.

The most likely source of oceanic sediments is the Merrimack River. Merrimack water enters the Gulf of Maine at the northern end of Plum Island and is carried south toward Plum Island Sound with the coastal current. Indeed, a complex recirculation loop between Plum Island Sound, the Merrimack River and the coastal ocean was recently identified through hydrodynamic modeling (Zhao et al., 2010). Historically, most sediment forming Plum Island and involved in initial bay infilling was derived from reworking of glaciogenic shelf deposits, but since that time the island has been in a stable post-paraglacial state (Hein et al., 2012), dependent on riverine sources. But can we assume that as long as the barrier island remains stable, the oceanic sources of estuarine infilling will be stable as well?

5.3.2 Potential tidal flat sediment input

Sediment resuspended into the water column during every flood and ebb tide is by far the largest sediment flux we examined in the Plum Island Sound estuary and mass balance shows it can easily meet marsh accretionary needs (Figure 9). On average the resuspension flux is 1 to 2 orders of magnitude larger than mineral inputs from rivers and edge erosion. The resuspension flux is 14x larger than that needed for mass balance. The settling flux, which represents the difference between resuspension and the amount required for marsh accretion mass balance lacking net oceanic inputs, is only 7% smaller than resuspension. Thus only a small fraction of what's resuspended needs to be deposited onto the marsh surface in order for the marsh to maintain elevation relative to SLR.

If there is a net loss of sediments from bay bottoms and tidal flats, bottom elevations will decrease and water depths increase. Based on the mass of resuspended sediments deposited on the marsh platform, we estimate a net loss in elevation of 3-7 mm yr^{-1} (depending on Sound and tidal creek bulk density which ranges from 1-2 g/cc). In conjunction with SLR, this would amount to an average deepening of up to 1 cm yr^{-1}, a rate substantially in excess of SLR.

A deepening of tidal flats is in accordance with models of bay enlargement and marsh edge erosion under conditions of rising sea level and decreased sediment availability (Fagherazzi et al., 2013; Mariotti & Fagherazzi, 2013;). As sea level rises and tidal flats erode in conjunction with sediment lost to marsh accretion, tidal flat depths increase, which enhances waves and bottom erosion. Thus the loss of resuspended sediments to marsh platform accretion results in a positive feedback to continued increases in tidal flat depth and bottom erosion.

5.5 Big picture

The sediment mass balance approach is a powerful tool for identifying the relative importance of internal and external sources of sediment contributing to elevation gain of Plum Island Sound tidal marshes relative to SLR. There are few reliable sediment budgets of estuaries (French et al., 2008) and most sediment studies lack one or more major sources or sinks required to balance the budget. Where they have been constructed however, it appears that both oceanic and internal erosion inputs are important components of the overall balance

(Meade, 1969; Yarbro et al., 1983; Marcus & Kearney, 1991; Hobbs et al., 1992; Eyre et al., 1998; Townsend & Whitehead, 2003).

Reliance on an internal source of sediments attributed to marsh shoreline erosion points to a long-term problem in tidal wetland survival. While marshes on the marsh platform appear to be maintaining elevation relative to SLR, to some extent it is at the expense of the areal extent of the overall marsh (Mariotti & Carr, 2014). Considering that the rate of SLR is predicted to greatly accelerate (Walsh et al., 2014), with water levels under some CO_2 emission scenarios to exceed 2 m by 2100 (Sweet et al., 2017), we can expect the areal extent of the Plum Island Sound marshes to decrease more rapidly in the future (Fagherazzi et al., 2013). A change in the relative area of wetlands to open water and the importance of sediments derived from eroding marshes in contributing to marsh elevation gain has been predicted and observed in other systems as well, including Blackwater River marshes (Ganju et al., 2015) and several microtidal systems along the Gulf of Mexico and Atlantic shorelines of the USA (Ganju et al., 2017).

By focusing attention on the survival of tidal wetlands, we may be underestimating the deterioration of the larger system including bay bottoms and tidal flats. It may be that the tidal flats are losing sediments and we do not know it, because it is difficult to quantify very small changes in bottom depth underwater or net exchange with the ocean. We do not perceive deterioration because the resuspension is so large and it appears as if there is a limitless sediment stock in the water column for the marshes. In the long run, it may be that tidal flats erode and no longer moderate wave energy at the marsh edge. With increased wave energy, marsh edge erosion will increase and the loss of marsh areal extent will accelerate, especially with increasing rates of SLR. The marsh platform is protected by the high resuspension rates. As tidal flats are eroded, the marshes are saved, but only temporarily. We conclude that we should focus more attention on quantifying net oceanic sediment exchange and long-term tidal flat and bay bottom dynamics in order to better understand the equilibrium of the system.

There has been a renewed interest in the global carbon balance of marsh-estuarine systems the past decade, primarily as a result of blue carbon burial of organic carbon in tidal wetlands (Hopkinson et al., 2012). Several of the organic matter fluxes measured and calculated in this study need to be considered in reexaminations of the global coastal ocean carbon balance. Deposition of organic matter onto the marsh surface in conjunction with mineral deposition as well as edge erosion need to be incorporated. These two fluxes are roughly 10-20% of recent measures of marsh net ecosystem exchange (Forbrich et al., 2018) and will likely increase substantially in the future as the rate of sea-level rise accelerates and river sediment export decreases. Current model estimates of marsh gross primary production, ecosystem respiration, net ecosystem production and burial (e.g., Bauer et al., 2013) underestimate the exchange with adjacent systems when not factoring in marsh surface organic matter deposition and marsh edge erosion.

5.6 Management

Recently there has been considerable scientific and management interest in armoring wetland edges with either living shorelines or hard surfaces, such as rip raps and seawalls. The interest stems from our realization of the immense value of the ecosystem services provided by these tidal wetlands (Costanza et al., 1997; Worm et al., 2006; Koch et al, 2009; Barbier et al., 2011) and our desire not to lose these services. Armoring is especially prevalent along wetland shorelines adjacent to urban/suburban lands (Alexander, 2016). Our study casts doubt on the wisdom of armoring, however. We show that the sediment eroded from marsh shorelines is essential to maintaining elevation of the marsh platform relative to

SLR. Reductions in sediment availability brought about by marsh armoring may lead to their inability to maintain elevation and to eventually drown. It remains to be seen how marsh loss by shoreline erosion compares to marsh loss due to drowning of interior marshes because of inadequate sediment availability. Marsh drowning losses will be especially true in systems currently dependent on erosion inputs of sediments, microtidal systems and systems with inherently low concentrations of suspended particulate matter (Kirwan et al., 2016; Ganju et al., 2015; 2017).

6 Conclusions

Inputs of sediments from rivers provide less than 10% of marsh accretionary needs in Plum Island Sound estuary.

Erosion of the marsh shoreline is occurring throughout the Plum Island Sound estuary. It represents a significant sediment source to the estuary that contributes to elevation gain of the remaining marsh platform.

The combined sediment input from rivers and marsh shoreline erosion provides only 39% of the mineral sediment required for marshes to maintain elevation relative to SLR. Yet marshes in this estuary have accreted at rates comparable to sea-level rise in past decades. This suggests that sediment input from the ocean or from erosion of tidal flats is an important factor in the marsh accretionary sediment budget of the system.

Deposition of eroded marsh peat and mineral matter from creekbanks makes up a significant portion of the marsh sediment budget. Consequently, the marsh platform has been able to maintain its relative elevation at the expense of total marsh area.

Marshes provide critical ecosystem services to communities living in the coastal zone through moderation of storm surge and wave energy and to people in general through their significant rates of carbon dioxide removal from the atmosphere (Hopkinson et al., 2013). Increased rates of SLR and increased coastal storminess as a result of continued increases in atmospheric CO_2 levels will compromise the ability of marshes to continue to provide ecosystem services, especially as sediment shortfalls become more prevalent worldwide.

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Tables

Table 1. Mass of mineral and organic matter needed for marshes to maintain elevation relative to a SLR rate of 2.8 mm y^{-1} for the 4 zones along the Plum Island Sound estuary. Based on a sediment bulk density of 0.28 g cm^{-3} and organic content of 30%.

Estuarine Zone	Area (km^2)	Total Mass (MT y^{-1})	Mineral (MT y^{-1})	Organic (MT y^{-1})	% Mineral
Upper Parker	1.46	1,112	778	333	70%
Mid Parker	1.70	1,292	905	388	70%
Lower Parker	7.51	5,716	4,002	1,714	70%
Sound	31.76	24,179	16,928	7,251	70%
Total	42.43	32,299	22,613	9,686	

Table 2. Estimated edge erosion throughout the Plum Island Sound estuary in terms of area eroded and the mass of sediments associated with that erosion during the period 2005-2011.

Zone	Area Eroded	Percent Area Eroded	Mass Eroded	Mineral Mass	Organic Mass
	$m^2 6y^{-1}$	% y^{-1}	MT y^{-1}	MT y^{-1}	MT y^{-1}
Upper-Parker	5,004	0.06%	50	35	15
Mid-Parker	3,146	0.03%	125	88	37
Lower-Parker	52,290	0.12%	4,367	3,058	1,309
Sound	142,832	0.07%	5,476	3,835	1,642
Total Estuary	203,423	0.08%	10,032	7,025	3,007

Table 3. Mass of mineral and organic fractions of suspended solids (excluding phytoplankton) along the length of the Plum Island Sound estuary based on 13 years of spring and fall sampling.

Estuarine Zone	Total Solids (MT)	Mineral Fraction (MT)	Organic Fraction (MT)
Upper Parker	16.3	14.5	1.8
Mid Parker	27.7	24.6	3.1
Lower Parker	57.9	50.9	7.1
Sound	181.6	154.5	27.1
Total	283.6	244.5	39.1

Table 4. $\Delta^{14}C$, ^{14}C age and concentration of POC in the water column along the entire length of the Plum Island Sound estuary in September 2000. Potential contribution of eroded ancient marsh peat to total POC calculated assuming no contribution from the watershed and an average $\Delta^{14}C$ of marsh peat of -220‰ (Table 4).

Conductivity (mS cm^{-1})	$\Delta^{14}C$ (‰)	^{14}C Age (BP)	[POC] µmol L^{-1}	% of POC Marsh Derived
0.29	47	0	47	0
0.92	-35	328	207	12%
2.67	-131	1119	196	45%
5.5	-27	203	131	9%
15.3	-53	583	105	18%
25.7	-68	1212	92	23%
45.3	-182	1594	53	63%
50.4	-49	328	31	
Average				25%

Table 5. Isotopic evidence for the deposition of ancient organic matter onto the marsh via tidal flooding.

Sample Depth (cm)	¹⁴C age (BP) & Δ¹⁴C		Calibrated 2σ formation time range
Surface (0)	Modern	70	1950s
2.5	1832	-197	82-313 AD
22.5	1806	-194	90-334 AD
42.5	2976	-307	1371 – 1055 BC
67.5	1925	-206	37 BC – 210 AD

Table 6. Balance of sediment fluxes in the Plum Island Sound estuary. Other than percentages, units are MT Y⁻¹

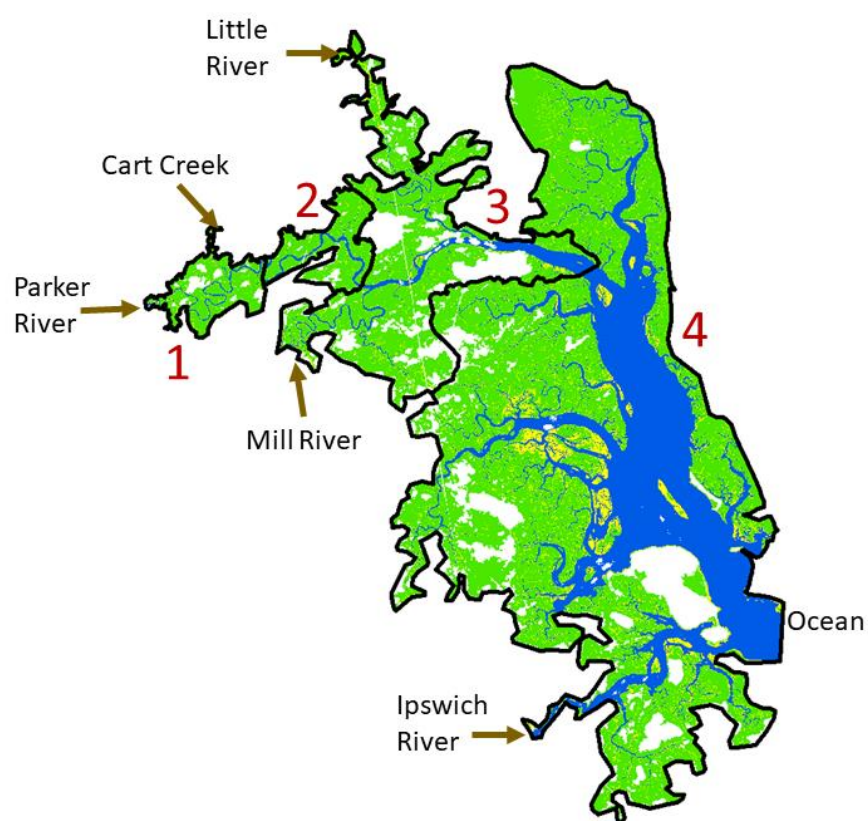| Sediment Source or Sink	Zone 1		Zone 2		Zone 3		Sound		Total Estuary	
	Mineral	Organic Matter	Mineral	Organic Matter	Mineral	Organic Matter	Mineral	Organic Matter	Mineral	Organic Matter
Marsh Accretion	778	333	905	388	4,002	1,714	16,928	7,251	22,613	9,686
River	237	178	0	0	227	171	1,369	1,028	1,833	1,377
Edge Erosion	35	15	88	37	3,058	1,309	3,835	1,642	7,025	3,007
Shortfall	506	140	817	351	717	234	11,724	4,581	13,764	5,306
Percent Missing	65%	42%	90%	90%	18%	14%	69%	63%	61%	55%
Ocean Scenario										
Ocean or Lower Estuary	506	139	817	350	718	234	11,724	4,580	13,765	5,303
Cumulative from Lower Estuary or Ocean	506	139	1,323	490	2,041	723	13,765	5,303		
Tidal Flat Scenario										
Resuspension	10,321	1,276	16,758	2,116	29,801	4,137	130,382	22,864	187,263	30,393
Settling	9,815	1,136	15,941	1,765	29,084	3,903	118,658	18,283	173,499	25,087
Percent Retained on Marsh	5%	11%	5%	17%	2%	6%	9%	20%	7%	17%

Figure 1. Plum Island Sound estuary highlighting the 4 zones along the 24 km axis where a sediment balance was constructed. The most significant river inputs to the system are identified. Colors correspond to elevation and land cover: white – uplands or barrier island > 2 m NAVD88, green – intertidal marshes dominated by *Spartina patens* between 0.8 and 2 m NAVD88, yellow – intertidal wetlands dominated by *Spartina alterniflora* between 0 and 0.8 m NAVD88, blue – open water and intertidal flats < 0 NAVD88. The ocean adjacent to the estuary is the Gulf of Maine. The coordinates at the mouth of the estuary are: 42°41.489' N 70° 45.555'W. North is straight up the image.

Figure 2. Box model used to examine sediment budget of the Plum Island Sound, marsh-dominated estuary. The estuary is divided into 4 sections, each with open water (estuarine tidal creeks and bays), intertidal flats and creek bottoms and adjacent intertidal marsh. Sediment enters the system via rivers (River-1 refers to the Parker River and other ungauged stream inputs to the upper 5 km of the estuary. R-2 refers to the Mill and Little Rivers that are also ungauged and that enter in the lower estuary. R-3 refers to the Ipswich River and other ungauged stream inputs including the Rowley River). Edge erosion (E) refers to the sediment entering each section of the river via erosion of marsh creekbanks. Surface accretion (A) is the mass of sediment coming from flood tide waters that sustains marsh elevation gain. Resuspension (R) and settling (S) refer to solids that exchange between the water column and creek bottoms in association with variations in tidal current velocities. Ocean refers to the sediment that enters or exits from the ocean. All terms including the standing stock of total suspended solids (TSS) in the water column of each estuarine section were measured explicitly in this study except for exchanges with tidal flats and the ocean, which were calculated by mass balance.
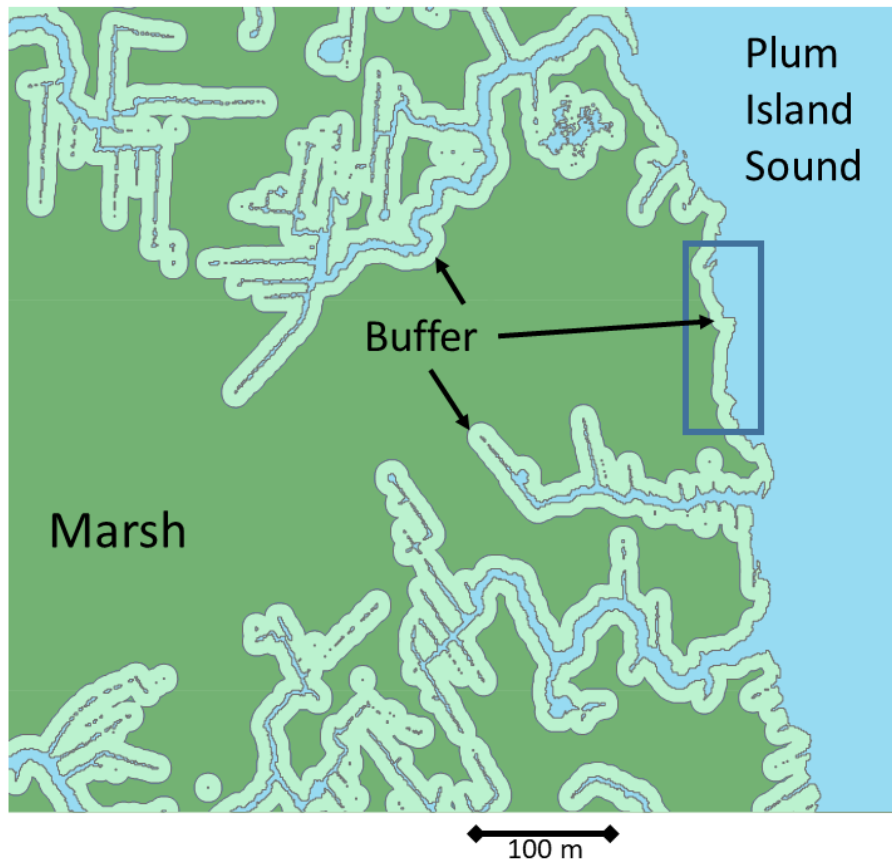
Figure 3. an example from along the northwestern edge of Plum Island Sound showing the delineation of the 10-m buffer. Note that the buffer is readily apparent along mosquito ditches, 1st, 2nd, 3rd, and 4rth order tidal creeks, Plum Island Sound, and marsh ponds. The blue rectangular box delineates the zone where we show selective results of marsh edge erosion during the 2005-2011 interval.
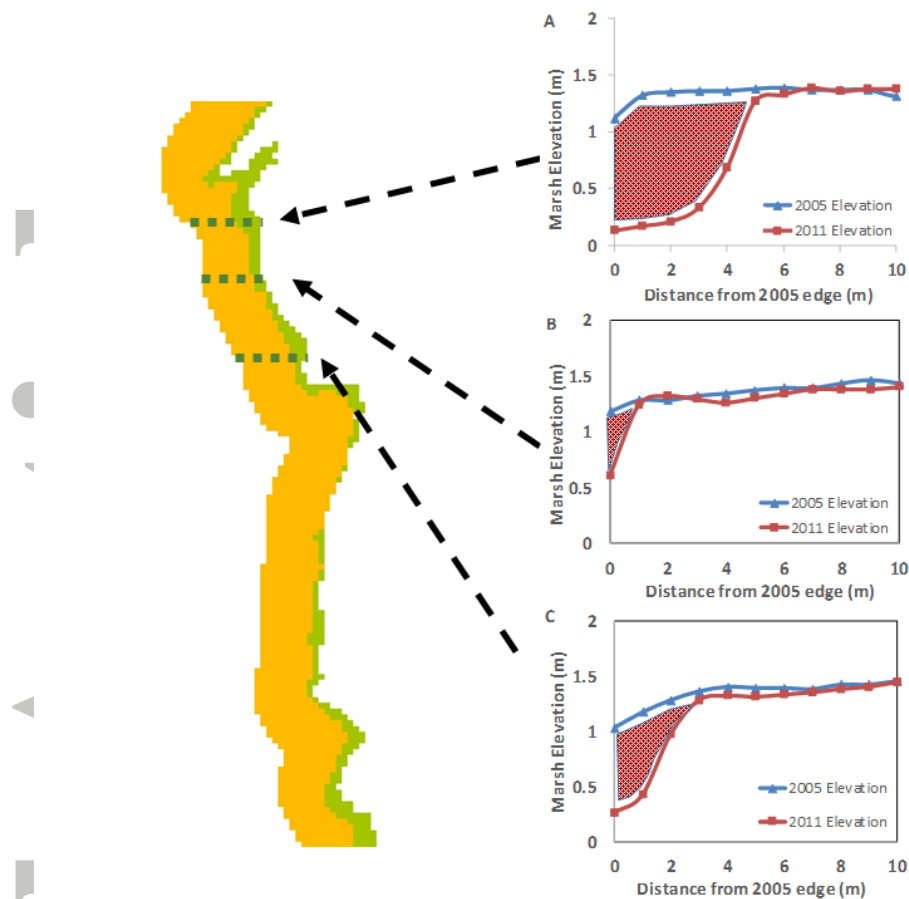
Figure 4. Example of edge erosion for 3 transects (dark green dotted lines on map) adjacent to the NW shoreline of Plum Island Sound (see Figs 2&3). The map to the left shows the 10 m buffer delineated from the 2005 DEM. The green band along the right side of the buffer represents area that had eroded by 2011. Cross-sections of marsh elevation along each of the transects are shown in graphs A-C.
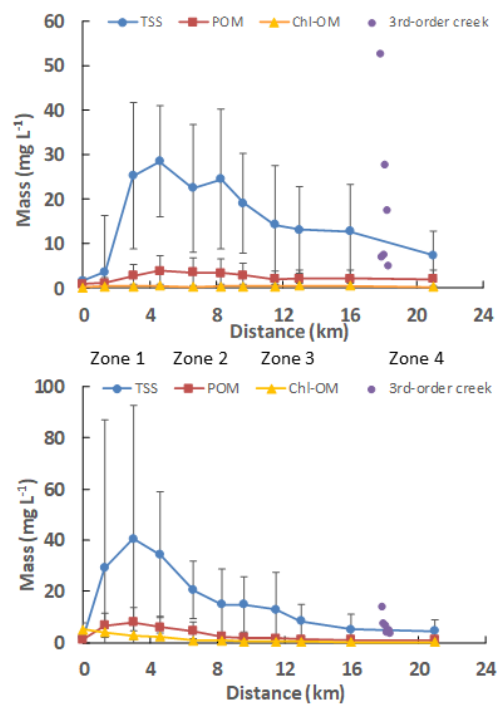
Figure 5. 13-yr median (CV- error bars) distribution of total suspended solids, particulate organic matter, and chlorophyll-a converted to organic matter along the main axis of the Plum Island Sound estuary in spring (top – during high river flow) and fall (bottom – during low river flow). Also shown is the distribution of suspended solids along the length of a 3rd order tidal creek off Plum Island Sound during 2016.
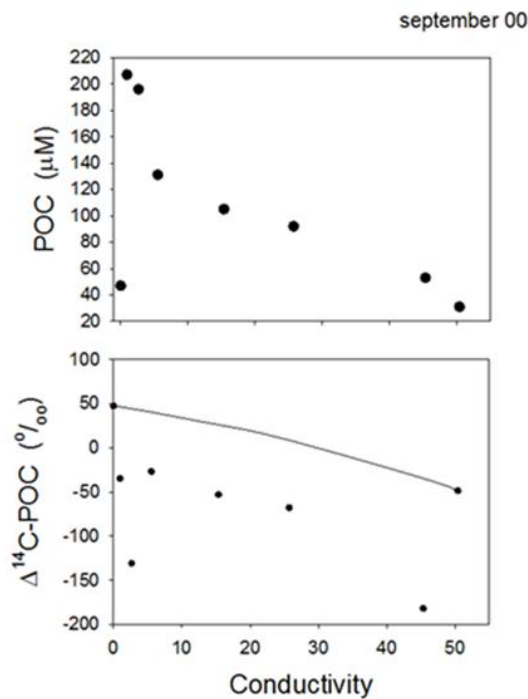
Figure 6. Particulate organic carbon (POC) concentration (top) and Δ^{14}C-POC versus conductivity (dots) and the conservative mixing curve (curved line in bottom figure) along the entire length of the Plum Island Sound estuary in September 2000. Plotting against a conservative tracer is essential for using a 2 end-member mixing model to calculate the mass of ancient marsh carbon required to match the ^{14}C values as observed.
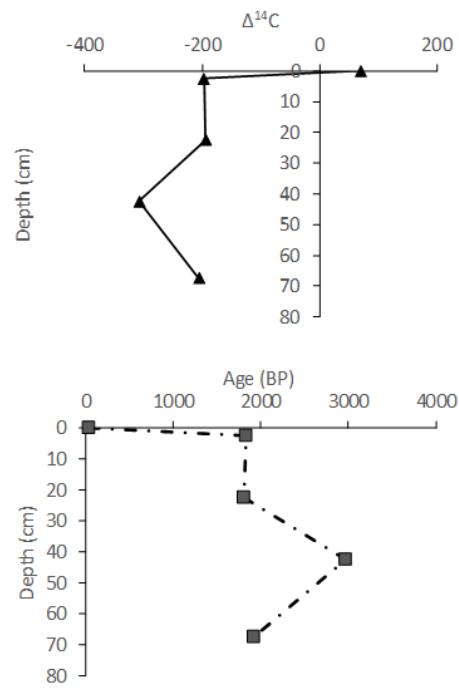
Figure 7. $\Delta^{14}C$ and ^{14}C age of clay-bound fine particulate organic carbon distribution in a core of *S. patens* marsh sediment from the Plum Island Sound estuary.
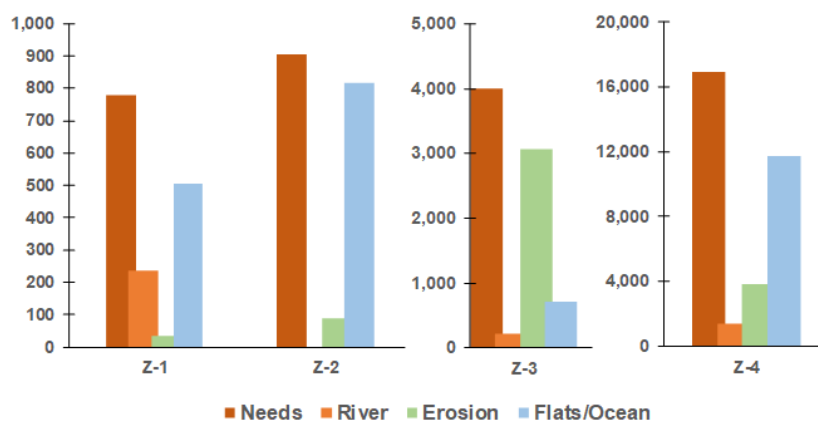
Figure 8. Summary of river, shoreline erosion, and ocean or tidal flats and creek bottom mineral sediment inputs to marshes in four zones along the Plum Island Sound estuary that enable marshes to maintain elevation relative to current rates of sea-level rise (2.8 mm y^{-1}). Units – MT d^{-1}.
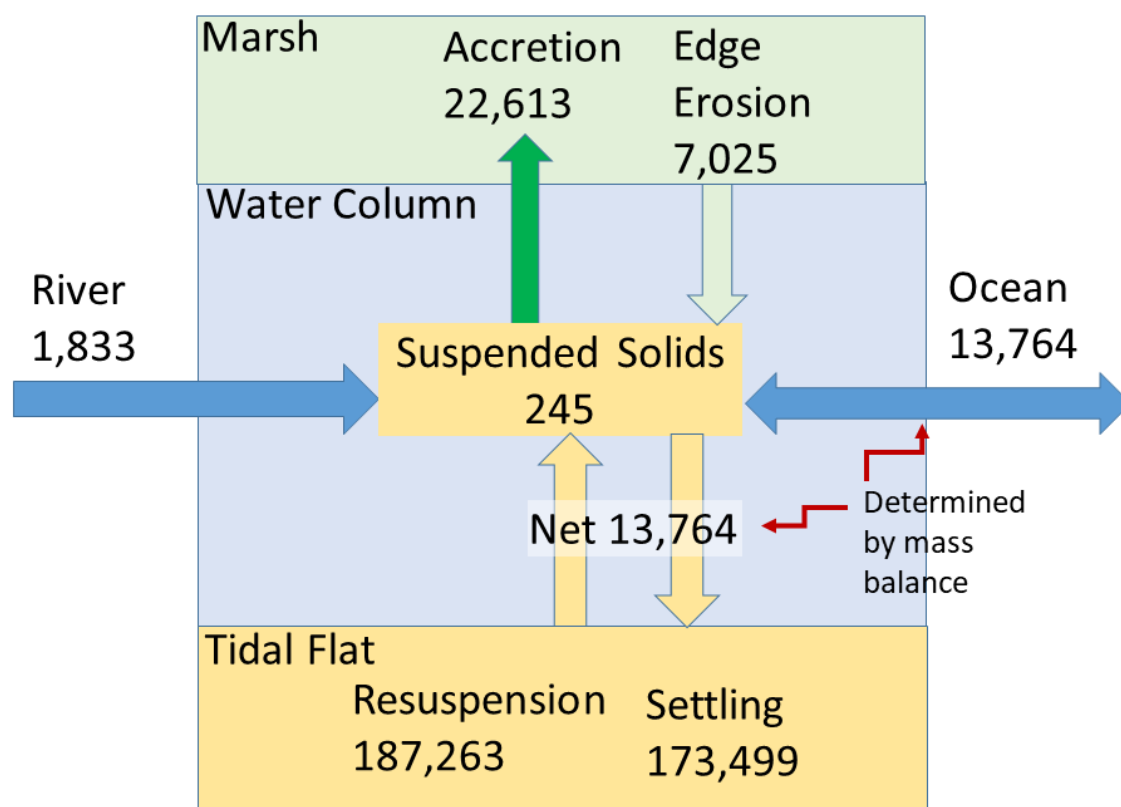
Figure 9. Sediment mass balance for the Plum Island Sound estuary highlighting the measured and potential sources of mineral matter sustaining accretion and elevation gain of the marsh platform. The ocean input of sediment was calculated by mass balance between accretion, river and edge erosion fluxes, assuming no net loss of resuspended solids. The difference between resuspension and settling is exactly the same as the ocean input and was also calculated by mass balance, but in this case assuming no ocean inputs. Units: MT (median annual mass of total suspended solids mass throughout the entire estuary - 245) or MT y^{-1}.