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Special Section:
Carbon Cycling in Tidal Wetlands and Estuaries of the Contiguous United States

Key Points:
- Tidal wetland flux budgets of particulate organic matter and carbon are poorly constrained
- Particulate organic matter and carbon fluxes are strongly linked with the unvegetated-vegetated marsh ratio and elevation
- Application of flux estimates to a large wetland complex indicates that export due to lateral erosion is balanced by import through tidal channels

Supporting Information:
- Supporting Information S1

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Role of Tidal Wetland Stability in Lateral Fluxes of Particulate Organic Matter and Carbon

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Abstract Tidal wetland fluxes of particulate organic matter and carbon (POM, POC) are important terms in global budgets but remain poorly constrained. Given the link between sediment fluxes and wetland stability, POM and POC fluxes should also be related to stability. We measured POM and POC fluxes in eight microtidal salt marsh channels, with net POM fluxes ranging between −121 ± 33 (export) and 102 ± 28 (import) g OM·m^{-2}·year^{-1} and net POC fluxes ranging between −52 ± 14 and 43 ± 12 g C·m^{-2}·year^{-1}. A regression employing two measures of stability, the unvegetated-vegetated marsh ratio (UVVR) and elevation, explained >95% of the variation in net fluxes. The regression indicates that marshes with lower elevation and UVVR import POM and POC while higher elevation marshes with high UVVR export POM and POC. We applied these relationships to marsh units within Barnegat Bay, New Jersey, USA, finding a net POM import of 2,355 ± 1,570 Mg OM/year (15 ± 10 g OM·m^{-2}·year^{-1}) and a net POC import of 1,263 ± 632 Mg C/year (8 ± 4 g C·m^{-2}·year^{-1}). The magnitude of this import was similar to an estimate of POM and POC export due to edge erosion (−2,535 Mg OM/year and − 1,291 Mg C/year), suggesting that this system may be neutral from a POM and POC perspective. In terms of a net budget, a disintegrating wetland should release organic material, while a stable wetland should trap material. This study quantifies that concept and demonstrates a linkage between POM/POC flux and geomorphic stability.

Plain Language Summary The worldwide budgets of organic material, especially carbon, are important to understand future climate change, environmental health, and habitat change. Tidal wetlands and salt marshes are large “banks” of organic material and carbon that can store material over centuries or lose it quickly if they are eroded by waves or submerged by sea level rise. We measured the “deposits” and “withdrawals” from this organic material bank, at eight salt marshes across the United States. We found a wide range of deposits and withdrawals and determined that the budget is related to how stable the marsh is. Marshes with a lot of plants and more height were more likely to have deposits of organic materials, while marshes with less plants and less height had withdrawals. These results will help complete the accounting of organic material and carbon in worldwide budgets.

1. Introduction

The stability of tidal wetlands depends, in part, on in situ production of organic matter and allochthonous deposition of organic matter and mineral sediment (Craft et al., 1988, 1993; Hatton et al., 1985; Nyman et al., 1993). Mineral sediment provides the substrate and elevation to foster emergent plant colonization and growth, which sets the primary limit on the ability for wetlands to withstand high rates of sea level rise (Blum & Roberts, 2009; Day et al., 2011; Kirwan et al., 2010) and lateral retreat due to wave activity (Fagherazzi et al., 2013; Mariotti & Fagherazzi, 2013). Particulate organic matter (POM) accumulates in wetland soils and contributes to marsh elevation change but can be released through edge erosion or internal disintegration.

Prior work has indicated that fluxes of POM in tidal marshes are strongly influenced by geologic and environmental factors (Childers et al., 2002). Geologically young marshes tend to experience net trapping of organic matter, while older marshes approximate equilibrium conditions with respect to productivity, respiration, and constituent tidal fluxes (Childers, 1994). Across various systems worldwide, tidal range, subbasin area, and distance to the ocean explained 87% of the variability in total organic carbon (TOC; dissolved + particulate) flux and 92% of the variability in total suspended sediment (TSS) flux. Export of TOC and TSS tended to be greater in subbasins that were smaller, closer to the ocean, and characterized by lower tidal ranges (Childers et al., 2002). Subbasin size was the strongest explanatory variable for TOC flux, while tidal range was more important for TSS flux (Childers et al., 2002). Additionally, changes in POM supply can contribute to variability in POM import and export (McCallister et al., 2004).

Widespread submergence and erosion of tidal wetlands due to processes including sea level rise, reduced sediment supply, and ponding has the potential to release large quantities of POM from marshes to the water column. The fate of previously buried POM has been of great interest, historically, due to its potential to support estuarine food webs (Dame et al., 1986; Kwak & Zedler, 1997; Langdon & Newell, 1990; Riera & Richard, 1996), and more recently, for its potential microbial oxidation and subsequent release of carbon dioxide to the atmosphere (Osburn et al., 2015; Pendleton et al., 2012). Alternatively, a large portion of eroded POM may be reimported into the marsh and deposited on the marsh platform (Hopkinson et al., 2018). Yet, given the tidal dynamics present in these systems, terms in the carbon budget, including POC fluxes, are difficult to constrain without continuous monitoring of water and constituent fluxes (Wang et al., 2016). Lateral exchanges of water through channels make point measurements and infrequent temporal sampling insufficient for characterizing and quantifying fluxes. This tidal-timescale exchange carries dissolved and particulate carbon between the marsh and the adjacent estuary; subtidal-timescale exchanges of water due to meteorological events may also be important for generating net fluxes of associated constituents (Ganju et al., 2013).

Measuring material fluxes through tidal wetland channels is complicated by errors in determining water flux and constituent concentrations (Ganju et al., 2005), but recent advances have demonstrated that quantitative information regarding dissolved carbon fluxes can be gleaned through consistent methodologies. Downing et al. (2009) demonstrated the use of acoustic and optical methods for estimating dissolved organic carbon fluxes in a tidal wetland channel; Wang et al. (2016) used similar techniques to estimate dissolved inorganic carbon fluxes over seasonal timescales. Previous studies (Ganju et al., 2017, 2015, 2013) have also documented suspended-sediment budgets in tidal wetlands and identified mechanisms controlling net sediment fluxes and linkages with geomorphic stability, but few studies have focused on POM or POC budgets using similar methodologies. Several recent syntheses have compiled regional-scale POC flux estimates (Herrmann et al., 2015; Kroeger et al., 2012; Najjar et al., 2012), but the uncertainty of these estimates is large due to limited temporal coverage and/or a lack of continuous monitoring over relevant timescales.

Similar to suspended-sediment fluxes, POM fluxes should be strongly dependent on wetland geomorphic trajectory. Given the inherent geomorphic instability of tidal wetlands (Fagherazzi et al., 2013), it is likely that lateral POM fluxes are linked with contraction of wetland area, either due to sea level rise, internal pond expansion, or lateral erosion. Constraining flux rates under changing wetland stability is necessary as lateral erosion directly releases organic material to the adjacent waters, while also decreasing the ability of the system to trap material from the water column due to a reduction in marsh plain area (Theuerkauf et al., 2015). Closure of wetland-estuary carbon budgets requires evaluating these two aspects of vertical and lateral change.

The likely dependence of POM fluxes on marsh stability implies that spatial patterns of marsh vulnerability should be considered in flux estimates. In a comparative study of deteriorating and relatively stable marshes in Chesapeake Bay, USA, a negative flood-ebb suspended-sediment differential (i.e. higher average suspended-sediment concentration on ebb tides as compared to flood tides), indicating net sediment export, was measured at the deteriorating site, while a positive flood-ebb sediment differential (i.e., higher average suspended-sediment concentration on flood tides as compared to ebb tides) was measured at the stable site (Ganju et al., 2015). Importantly, there was twice as much suspended POM at the deteriorating site, likely sourced from eroded marsh substrate. Further, Ganju et al. (2017) used continuous measurements of tidal flows and suspended-sediment concentration to estimate net sediment fluxes of eight wetland complexes on the Atlantic and Pacific coasts (Table 1) and linked the net sediment budget with the spatially explicit unvegetated-vegetated marsh ratio (UVVR) determined through aerial imagery.

Given the novelty of the data set presented by Ganju et al. (2017), we expanded those results of by analyzing the organic matter characteristics of the suspended sediment in the water column at those eight sites. Applying these results to the suspended-sediment flux time series allows us to estimate POM fluxes at those wetland complexes and test relationships between POM fluxes and two key measures of marsh stability: the UVVR and elevation. Finally, we apply the correlation to individual marsh units within a large wetland complex and compare this tidal channel POM transport with an estimate of POM liberation from edge erosion, to

Table 1
Site Information from Ganju et al. (2017); Site Name, Elevation, Unvegetated-Vegetated Marsh Ratio (UVVR), Total Area (Vegetated and Unvegetated), Tide Range, and Suspended-Sediment (SS) Flux

Site	Elevation (MSL, m)	UVVR	Total area (km^2)	Tide range (m)	SS flux ($g \cdot m^{-2} \cdot year^{-1}$)
Blackwater, Maryland (BW)	0.24	0.94	70	0.35	−460 ± 125
Fishing Bay, Maryland (FB)	0.38	0.09	1.7	0.75	560 ± 153
Seal Beach, California (SB)	0.71	0.17	1.4	2.5	120 ± 33
Point Mugu, California (PM)	0.72	0.12	0.14	1.6	250 ± 69
Reedy Creek, New Jersey (RC)	0.29	0.40	0.52	0.31	20 ± 5
Dinner Creek, New Jersey (DC)	0.43	0.16	4.2	0.73	150 ± 42
Ogunquit, Maine (OG)	1.34	0.14	1.4	2.1	−30 ± 7
Schooner Creek, New Jersey (SC)	0.53	0.17	0.21	1.0	210 ± 56

Note. UVVR is determined using aerial imagery from the National Agricultural Imagery Program as detailed by Ganju et al. (2017). Error estimate of 27% (Ganju et al., 2015) is applied here and in Table 2 flux estimates

estimate the net POM budget of the entire system. Given the strong relationship between measured percent organic matter and percent carbon in salt marsh organic material across systems (Holmquist et al., 2018), we extend our POM estimates to POC as well.

2. Methods

2.1. POM Fluxes

POM fluxes were estimated for tidal channels within eight marshes on the east and west coasts of the United States (Figure 1). Complete details of the field campaigns are described by Ganju et al. (2013), Montgomery et al. (2015), Rosencranz et al. (2016), Suk et al. (1999) and Suttles et al. (2016). All sites are tidal salt marsh complexes drained by a primary tidal channel, with maximum tidal ranges varying from 0.30 to 2.5 m (Table 1). The marsh complexes feature a mixture of marsh vegetation species, elevation, climate, and relative sea level rise, as described in Ganju et al. (2017). These sites were primarily chosen based on their geomorphic layout: a primary tidal channel well constrained by either upland or infrastructure. Additionally, six of the eight sites were chosen as a paired comparison between historically stable and unstable sites within a similar geographic setting (e.g., Fishing Bay versus Blackwater, Point Mugu versus Seal Beach, and Dinner Creek versus Reedy Creek). The northernmost site, Ogunquit, was chosen as representative of a higher latitude, sediment-poor, mesotidal system; Schooner Creek was identified from prior literature (Suk et al., 1999) and utilized methods similar to Ganju et al. (2017).

Estimation of time series of suspended-sediment fluxes within tidal channels at these eight sites is detailed by Ganju et al. (2017); we briefly summarize the method here. Within the primary tidal channel at each site, we deployed acoustic Doppler current profilers and water quality sondes to measure water velocity, acoustic backscatter, optical turbidity, and water level at <15-min intervals over periods ranging from 10 weeks to 10 months. Additionally, channel cross sections of velocity and turbidity, as well as water samples (point samples near the turbidity sensor, using a van Dorn-type sampler) for suspended-sediment concentration and organic content were collected on flood and ebb tides for a variety of tidal conditions. Using the above data sets, continuous time series of suspended-sediment fluxes were generated for each site. This time series was then assumed to be representative of the entire year, scaled up to a yearly estimate, and normalized by the drainage area of each channel (determined using DEMs and watershed analysis; Ganju et al., 2017). Errors associated with temporal extrapolation are discussed in section 4.1.

To estimate POM fluxes for this study, the suspended sediment within the water samples from each wetland complex was processed for organic content, that is, %POM, via loss on ignition (APHA, 1995; van Reeuwijk, 2002). Data are presented in Table S1 and are available from Ganju et al. (2012) and Suttles et al. (2016). At each site, the average value of %POM was multiplied by the suspended-sediment flux data to yield an estimate of POM flux into and out of the marsh channel (Table 2). Following the suspended-sediment flux methodology, POM fluxes were estimated per unit area of the channel's watershed and were extrapolated to an annual timescale.

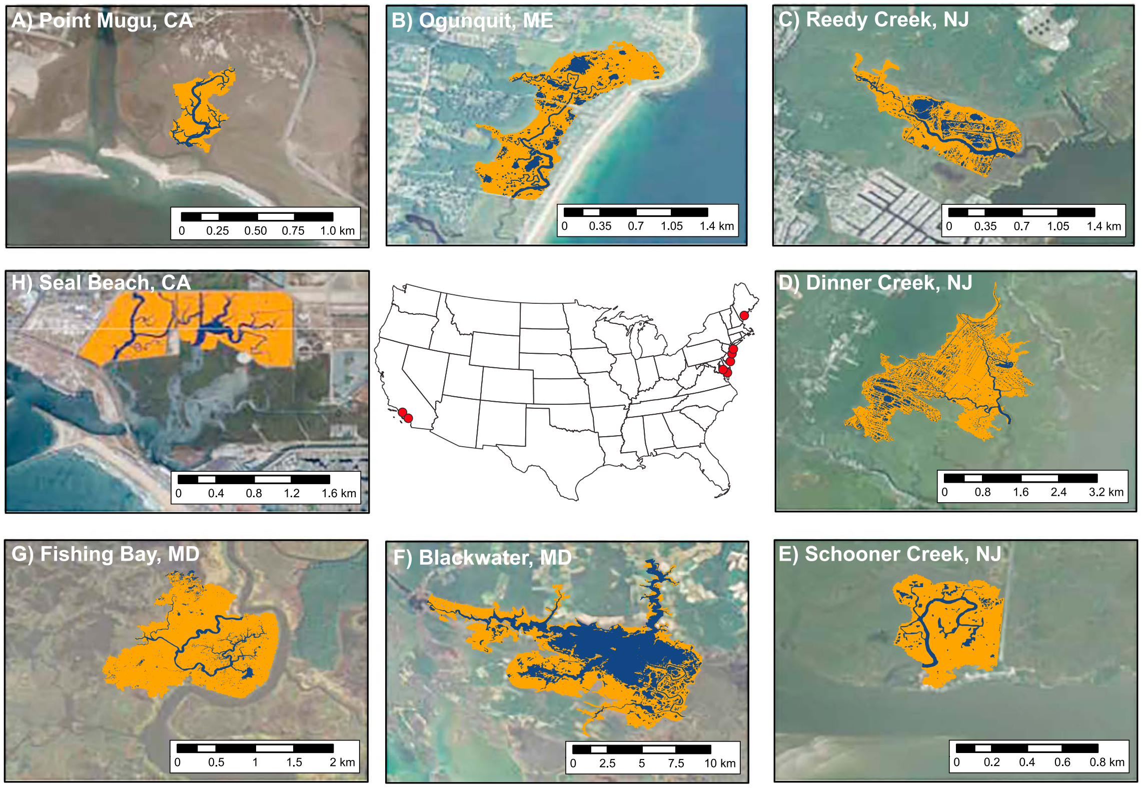

Figure 1. (a–h) Aerial imagery of national sites from Ganju et al. (2017). Shaded areas indicate drainage area for instrumented tidal channels; orange indicates vegetated marsh plain, blue indicates unvegetated tidal channels, intertidal flats, and open water within the drainage area.

In addition to POM, POC concentrations were measured for a subset of samples to estimate the POC fraction of suspended sediment and POM. Eight water column samples each from BW (Blackwater, Maryland) and FB (Fishing Bay, Maryland) were analyzed for carbon content at the Ecosystems Center Stable Isotope Laboratory. For sites where POC was not measured, we used POM/POC relationships to calculate an estimate of POC. Measurements of POM based on loss on ignition and measurements of POC from CHN analysis show generally good agreement (~POM = 0.45 ± 0.05 * POC; Whittaker & Likens, 1973) in areas

Table 2
Number of Water Samples for %POM (n), Average Percent Particulate Organic Matter (%POM) in Dry Weight Percent (DW%), Particulate Organic Matter (POM) Flux, Average Percent Carbon of Organic Matter (%C of POM), Particulate Organic Carbon (POC) Flux, Average Percent Carbon of Suspended Sediment (%POC), and Flood-Ebb Differential in the Acoustic-Optical Backscatter Ratio

Site	n	%POM (DW%)	POM flux ($g \cdot m^{-2} \cdot year^{-1}$)	%C of POM (DW%)	POC flux ($g \cdot m^{-2} \cdot year^{-1}$)	%POC of SS (DW%)	Flood-ebb backscatter ratio differential
BW	24	26% ± 2%	−121 ± 33	43% ± 3%	−52 ± 14	11%	0.28
FB	26	18% ± 4%	102 ± 28	42% ± 8%	43 ± 12	8%	−0.12
SB	28	33% ± 8%	40 ± 11	*45%*[b]	18 ± 5	15%[b]	−0.09
PM	30	6% ± 3%	16 ± 4	*45%*[b]	7 ± 2	3%[b]	−0.19
RC	31	46% ± 10%	9 ± 3	49% ± 5%	5 ± 1	23%	−0.05
DC	49	30% ± 10%	46 ± 13	49% ± 8%	23 ± 7	15%	−0.08
OG	13	36% ± 9%	−9 ± 3	*45%*[b]	−4 ± 1	16%[b]	−0.01
SC[a]	>500	23% ± 10%[c]	47 ± 14	*49%*[c]	23 ± 7	11%[c]	NA[b]

Note. Error estimates compound sediment flux error (27%) along with standard deviation of water sample measurements as the square root of the sum of squared errors. UVVR is determined using aerial imagery from the National Agricultural Imagery Program as detailed by Ganju et al. (2017).
[a]Suk et al. (1999) [b]No data carbon data were available for these sites, so the fraction of POM that was carbon, by mass, averaged over all sites, was used; maximum value for standard deviation was used [c]No data carbon data were available for this site, so the fraction of POM that was carbon, by mass, from the nearby site DC, was used

without very high sediment clay content (Barillé-Boyer et al., 2003). To address potential local site variability in POM/POC relationships, we used measured values of POM/POC from nearby sites to calculate tidal channel POC from measured POM. At sites RC (Reedy Creek, New Jersey) and DC (Dinner Creek, New Jersey), carbon fraction of POM in the water column was estimated by measuring POC concentrations in surface marsh sediments ($n = 3$). One gram of soil from the top 2 cm of the marsh surface was homogenized, fumed with 6 M HCl for 12 hr to remove inorganic carbonates (Schumacher, 2002), and analyzed using a CE NA 2500 flash elemental analyzer. At site SC (Schooner Creek), we use the percent C of organic matter values from nearby sites RC and DC. At sites OG (Ogunquit), PM (Point Mugu), and SB (Seal Beach), we used the average percent C of organic matter from all sites, applied to the measured organic matter percentage at the specific site (error of this approximation is addressed below). For all sites, consistent with the method for estimating POM fluxes, average POC concentrations were multiplied by the suspended-sediment flux estimates to yield POC fluxes on an areal basis, extrapolated to an annual timescale (Table 2). Nonaveraged data are available from Table S1, Ganju et al. (2012), and Suttles et al. (2016).

2.2. Identification of Flood-Ebb Differences in Organic Content

Sampling constraints preclude regular sampling of organic content over multiple tidal cycles, thereby limiting our ability to identify flood-ebb differences in organic content, which may alter the organic matter flux estimates. For example, use of a constant organic matter fraction (%POM) in the flux calculation ignores the possibility that ebb tides may carry relatively organic-rich particles relative to flood tide. We used variations in suspended-sediment density, estimated by using the ratio of acoustic backscatter to optical turbidity as a proxy, to diagnose flood-ebb differences in POM content. This proxy is based on the knowledge that acoustic backscatter is sensitive to changes in sediment mass concentration, while optical turbidity is more sensitive to changes in sediment volume concentration (Fugate & Friedrichs, 2002). Specifically, we calculated an organic proxy ratio as the acoustic backscatter strength S_v in the bottom acoustic Doppler current profiler bin divided by the optical turbidity. This assumes that denser flocs are more minerogenic while less dense flocs are more biogenic, with organic substances embedded within flocculated structures. The continuous time series of the organic proxy ratio was then separated based on velocity direction, averaged over flood and ebb tides, and normalized to enable comparison between sites.

2.3. Calculating Tidal Channel and Lateral Erosion Fluxes of POM and POC

Using the multivariate statistical relationships between POM and POC flux, UVVR, and elevation identified above, we can estimate tidal channel POM and POC fluxes across entire marsh systems. As a case study, we apply the relationship to Forsythe National Wildlife Refuge (NWR), a large wetland complex along the coast of Barnegat Bay, New Jersey. As input into the regression, we used maps of UVVR and elevation based on aerial imagery of individual marsh units provided by Defne and Ganju (2016, 2018a). We applied the regression to each unit and multiplied the result by the area of each unit, to estimate total tidal channel fluxes of POM and POC between the estuary to the wetland complex.

We separately estimated the contribution of POM and POC from lateral marsh erosion by multiplying observed shoreline change rates and shoreline length (Defne & Ganju, 2018b) by the mean marsh edge elevation of each unit and by the %POM and %POC of the marsh (Table S2), yielding a volumetric flux per year. Mean marsh edge elevation was generally calculated as the mean elevation of a 10-m wide marsh shoreline strip given by Thatcher et al. (2016). In particular cases where the strip conformed to the marsh shoreline but did not overlap, the strip was expanded to intersect the marsh boundary. Additionally, channel features narrower than 60 m were replaced by straight shoreline, and shorelines near the Little Egg Inlet were manually processed to minimize the disagreement between marsh boundaries and shoreline delineation of Thatcher et al. (2016). The volumetric flux was then multiplied by organic matter and carbon density values determined from soil cores collected in three marshes of Barnegat Bay (Unger et al., 2016; Table S2) yielding a lateral erosion flux of POM and POC between the wetland complex and estuary.

3. Results

3.1. POM Fluxes

The percentage of suspended-sediment mass that was organic (%POM) ranged from a minimum of 6% at PM, to a maximum of 46% at RC (Table 2). Standard deviation in %POM ranged from 2% at BW to 10% at RC and

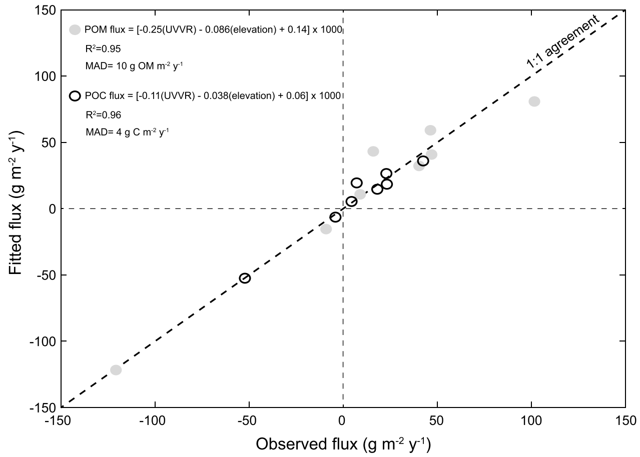

Figure 2. Comparison of observed and fitted tidal channel POM and POC flux via multiple linear regression with unvegetated-vegetated marsh ratio (UVVR) and marsh elevation as independent variables. UVVR is nondimensional; elevation is referenced to mean sea level in meters. Relationship is multiplied by 1,000 to yield fluxes in grams per meter per year from kilograms per meter per year. MAD indicates mean absolute deviation. POM = particulate organic matter; POC = particulate organic carbon.

DC (Table 2). There was negligible correlation between %POM and independent variables such as UVVR, elevation, or tide range ($r^2 < 0.04$). POM fluxes ranged from an export of -121 ± 33 g·m^{-2}·year^{-1} at BW to an import of $+102 \pm 28$ g·m^{-2}·year^{-1} at FB. Averaged across all sites, POM flux was +16 g·m^{-2}·year^{-1}; though the large standard deviation (65 g·m^{-2}·year^{-1}) indicates that the large spatial and temporal variation limit the utility of extrapolation over space and time. The percentage of suspended sediment that is organic carbon (%POC) ranged from 8% at FB to 23% at RC. Standard deviation in %POC ranged from 3% at BW to 8% at FB and DC. POC fluxes ranged from a net export of -52 ± 14 g·m^{-2}·year^{-1} at BW to a net import of $+43 \pm 12$ g·m^{-2}·year^{-1} at FB. Averaged across all sites, POC flux was +8 g/m^{-2}·year^{-1} (standard deviation of 28 g·m^{-2}·year^{-1}). Error estimation is detailed in section 4.

3.2. Correlating POM Fluxes With Geomorphic Variables

The correlation between UVVR and POM flux ($r^2 = 0.78$) was lower than the correlation between UVVR and net sediment budget ($r^2 = 0.89$; Ganju et al., 2017), with three notable outliers representing marshes with the highest elevation relative to mean sea level and the largest tide ranges (sites PM, SB, and OG). We therefore performed a multiple linear regression model fit (with a leave-one-out cross validation, performed in Matlab) with POM flux as the dependent variable, and UVVR, elevation, and tidal range as the independent variables. We found that a combination of UVVR and elevation accounts for 96% of the variability in POM flux (Figure 2), with a mean absolute deviation between observed and fitted values of 10 g OM·m^{-2}·year^{-1}. Inclusion of tidal range had a negligible effect on the regression, while removing elevation decreased the quality of the prediction. The relationship between UVVR, elevation, and POC fluxes was similar (expected given the narrow range of %OC relative to OM), with a mean absolute deviation of 4 g C·m^{-2}·year^{-1}. These deviations are applied as error estimates in the estuary-wide calculations presented in section 3.4.

3.3. Temporal Variations in Organic Matter Content

We used the acoustic backscatter-turbidity ratio as a proxy for the relative difference in organic matter fraction between flood and ebb tide. Sites with a positive differential (indicating less dense, more organic particles on ebb tide) may be diagnosed as biased toward POM export, while sites with a negative differential may indicate increased POM import. The ratio of acoustic to optical backscatter demonstrated noticeable flood-ebb differences, potentially related to differences in particle density and organic content. The largest positive difference (indicating organic-rich particles on ebb) was at site BW, which is also the largest exporter of sediment and organic material (Figure 3 and Table 2). Sites with greater observed POM import tended to have more negative ratios, indicating organic-enriched particles being transport on flood tide. Overall, there was a notable correlation ($r^2 = 0.75$) between the backscatter ratio differential and POM flux, increasing confidence in the estimated POM flux directions. The potential error of temporal variations in organic content is discussed in section 4.1.

3.4. Quantifying Marsh-Estuary POM and POC Exchange Across a Wetland Complex

We applied the relationship (and mean absolute deviation error) between POM (and POC) flux, UVVR, and elevation (Figure 2) to each of the ~1,300 marsh units within Forsythe NWR (Figure 4), multiplied the result by the area of each unit, to yield a total tidal channel POM flux of 2,355 ± 1,570 Mg OM/year (POC flux of 1,263 ± 632 Mg C/year) from the estuary to the wetland complex. The individual marsh unit calculations (Figure 5) demonstrate the variability of POM flux in UVVR and elevation space, with high elevation, low UVVR marshes tending to import material, and low elevation, high UVVR marshes tending to export material. The majority of units within this wetland complex imported material.

The estimate of POM and POC fluxes is the same order of magnitude as POM and POC inputs from the wetland complex to the estuary due to lateral marsh erosion (Figure 6). The volumetric flux per year,

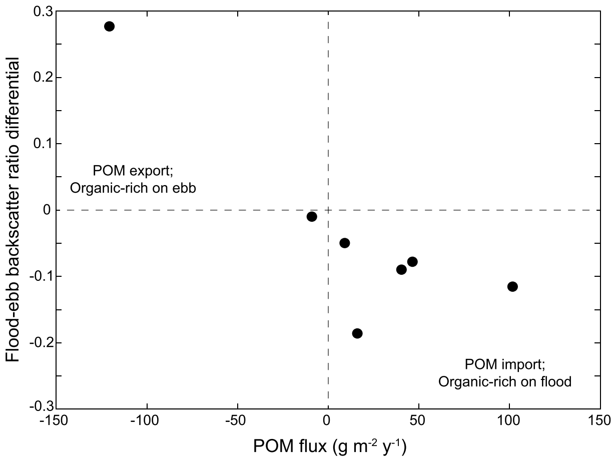

Figure 3. Comparison of observed tidal channel POM flux and flood-ebb differential in acoustic-optical backscatter ratio. All but one site with POM import demonstrate a negative differential, indicating organic-rich particles are relatively more prevalent on flood tide, lending confidence to the POM flux direction. The site with the largest POM export shows the largest positive differential, indicating organic-rich particles are more prevalent on ebb tide. POM = particulate organic matter.

calculated as the product of shoreline length, retreat, and elevation, was multiplied by organic matter and carbon density values in Barnegat Bay reported by Unger et al. (2016). Soil bulk density to 64- to 84-cm depth averaged 0.219 ± 0.009 g/cm^3, organic matter content averaged 27.1 ± 1.0%, and organic matter densities averaged 0.053 ± 0.002 g OM/cm (Unger et al., 2016; Table S2), yielding a total POM load from the marsh complex to the estuary of 1,263 Mg OM/year. Carbon content averaged 13.9 ± 0.5%, and carbon densities averaged 0.0270 ± 0.0009 g C/cm^3 (Unger et al., 2016; Table S2), yielding a total POC load from the marsh complex to the estuary of 1,291 Mg C/year. Note that this carbon density value matches the CONUS-wide carbon density estimate of Holmquist et al. (2018).

4. Discussion

4.1. Uncertainty in Elements of Flux Estimation

Prior attempts to measure POC fluxes have reported export from tidal wetlands to estuaries of 49 g C·m^{-2}·year^{-1} (Herrmann et al., 2015); 0.6 Tg C/year over 1.2 × 10^{10} m^2 (Kroeger et al., 2012; Najjar et al., 2012), equating to 50 g C·m^{-2}·year^{-1}; and exports ranging between 11 and 55 g C·m^{-2}·year^{-1} and imports ranging between 3 and 140 g C·m^{-2}·year^{-1}, depending on location (Childers et al., 2002). None of these estimates

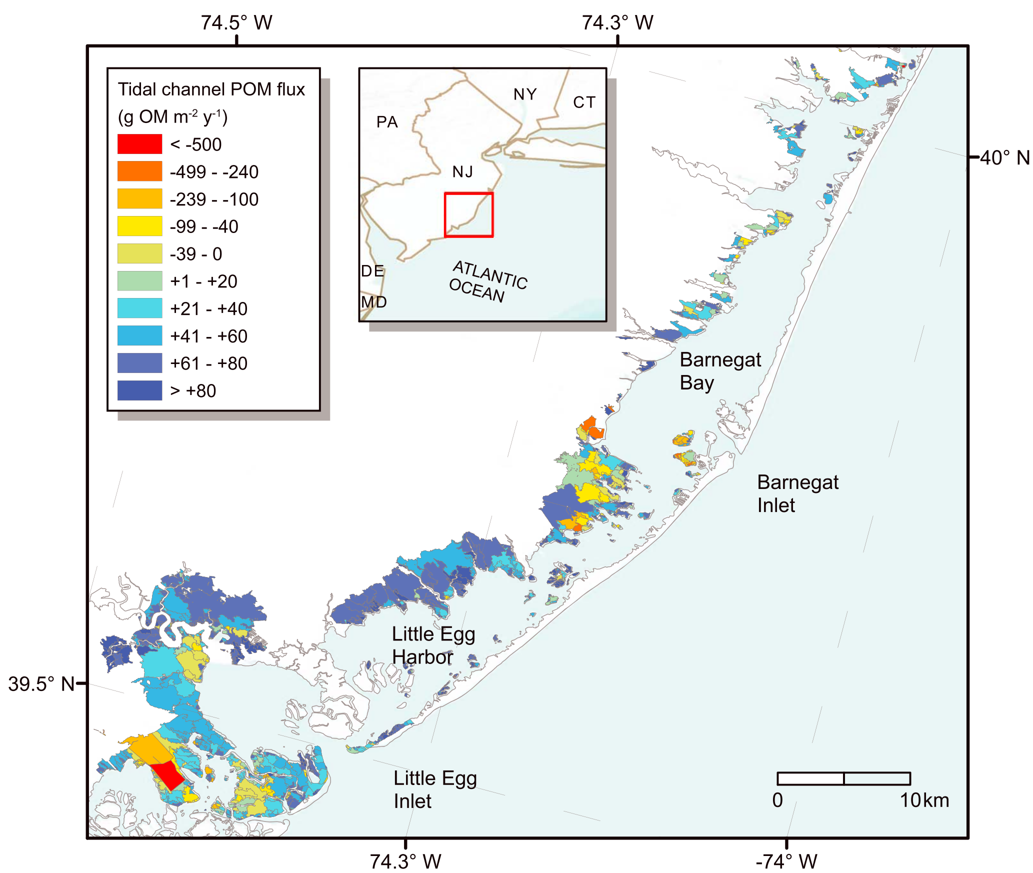

Figure 4. Tidal channel POM flux estimates based on multiple linear regression, applied to marsh units in Forsythe National Wildlife Refuge (Barnegat Bay). POM = particulate organic matter.

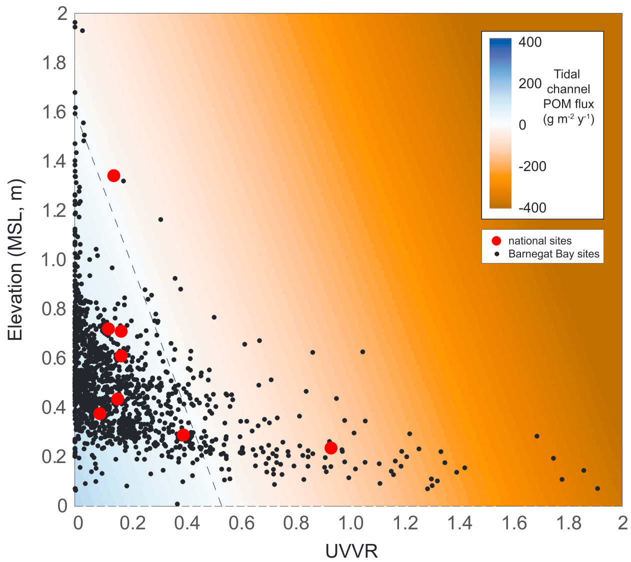

Figure 5. Surface map of variation in tidal channel POM flux (g C/m^2/year) as a function of UVVR and elevation. Solid red dots indicate national sites used to derive regression, black dots indicate marsh units within Forsythe National Wildlife Refuge (Barnegat Bay, New Jersey). Sites to the right of the dashed line are POM exporters, sites to the left are POM importers. The pattern of POC flux is similar given the relatively narrow range of the %C of OM ratio (Table 1). UVVR = unvegetated-vegetated marsh ratio; POM = particulate organic matter.

involved continuous monitoring over seasonal timescales nor are the methods between studies directly comparable due to differences in temporal coverage and measurement methods. Nonetheless, the methods used here present several sources of uncertainty, including variability in organic content and carbon content, errors in sediment flux, and uncertainty arising from extrapolation of short-term measurements to annual rates. For the errors presented in Table 2, we apply the square root of the sum of squared errors, with the assumption that errors are random and uncorrelated, following Ganju et al. (2005). Final error bounds include errors in %POM, %POC, and sediment flux estimation. Other unquantifiable errors are discussed as well.

4.1.1. Variability in Organic Content and Carbon Content

The variability in %POM between water samples gives some indication of potential error in these flux estimates; however, this assumes that the variability is not linked with flux direction, for example, due to a larger source of POM in the estuary or the marsh. A small bias in %POM on flood or ebb tide could reverse the net POM flux direction. For example, at FB, applying a constant flood-ebb bias of 4% in %POM (equivalent to standard deviation of the water sample measurements) to the suspended-sediment flux time series yields a possible range of organic matter fluxes between -250 and $+ 457$ g·m^{-2}·year^{-1}, thereby confounding any attempt at diagnosing net direction of POM flux. The flood-ebb backscatter differential lends a modicum of confidence in flux direction however, and in lieu of continuous measurements of organic content, the uncertainty is not quantifiable.

The above analysis suggests that import and export of POM may be underestimated when flood-ebb differentials in %POM are unaccounted for, although the net flux direction may be unaffected. POM in tidal creeks and estuaries can be sourced from multiple end members, including delivery from the watershed, local marsh plant and algal production, water column production, and tidally delivered coastal and marine inputs (Hopkinson et al., 1998; McCallister et al., 2004; Thornton & McManus, 1994), which may cause this flood-ebb differential to occur. On tidal time scales, ebb tides are predicted to have an increased proportion of marsh-derived POM, especially in marsh systems experiencing erosion and/or vegetation loss (Chalmers et al., 1985; Childers et al., 2002). Conversely, flood tides may have a greater proportion of marine-derived POM. In addition, dominant sources of POM change tidally and seasonally (Countway et al., 2007), although this study was not able to quantify those differences. Overall, although POM flux magnitudes are prone to error given undersampling of organic content directly due to cost and technological limitations, our results suggest that future work to observe flood-ebb variations in %POM, as well as time series of isotopic analyses and particle size distribution may further increase confidence in net organic matter fluxes.

Though carbon generally composes approximately 50% of organic material, our lack of direct measurements of %POC at some sites introduces some uncertainty. Craft et al. (1991) reported a range of 40–45% organic carbon in salt marsh soils, while water column estimates of 50% organic carbon were presented by Hopkinson et al. (1998). These are within the ranges presented here, but for uncertainty at sites with no direct POC measurements, we compounded the maximum observed standard deviation of ±8% along with sediment flux errors and standard deviation of organic content to the calculated POC flux estimates (Table 2).

4.1.2. Errors in Sediment Flux Estimation

There are two elements to the uncertainty in sediment flux: the direction and magnitude. In terms of magnitude, Ganju et al. (2005) presented a detailed error estimation for sediment fluxes in a tidal wetland system similar to those studied here. Those errors arose within multiple measurements: velocity and water flux, channel area, and suspended-sediment concentration (composed of laboratory analysis, sensor calibration, and spatial variability). The single largest source of error was the determination of suspended-sediment concentration. The total error of all sources combined was estimated at 27%. In terms of direction, however, a

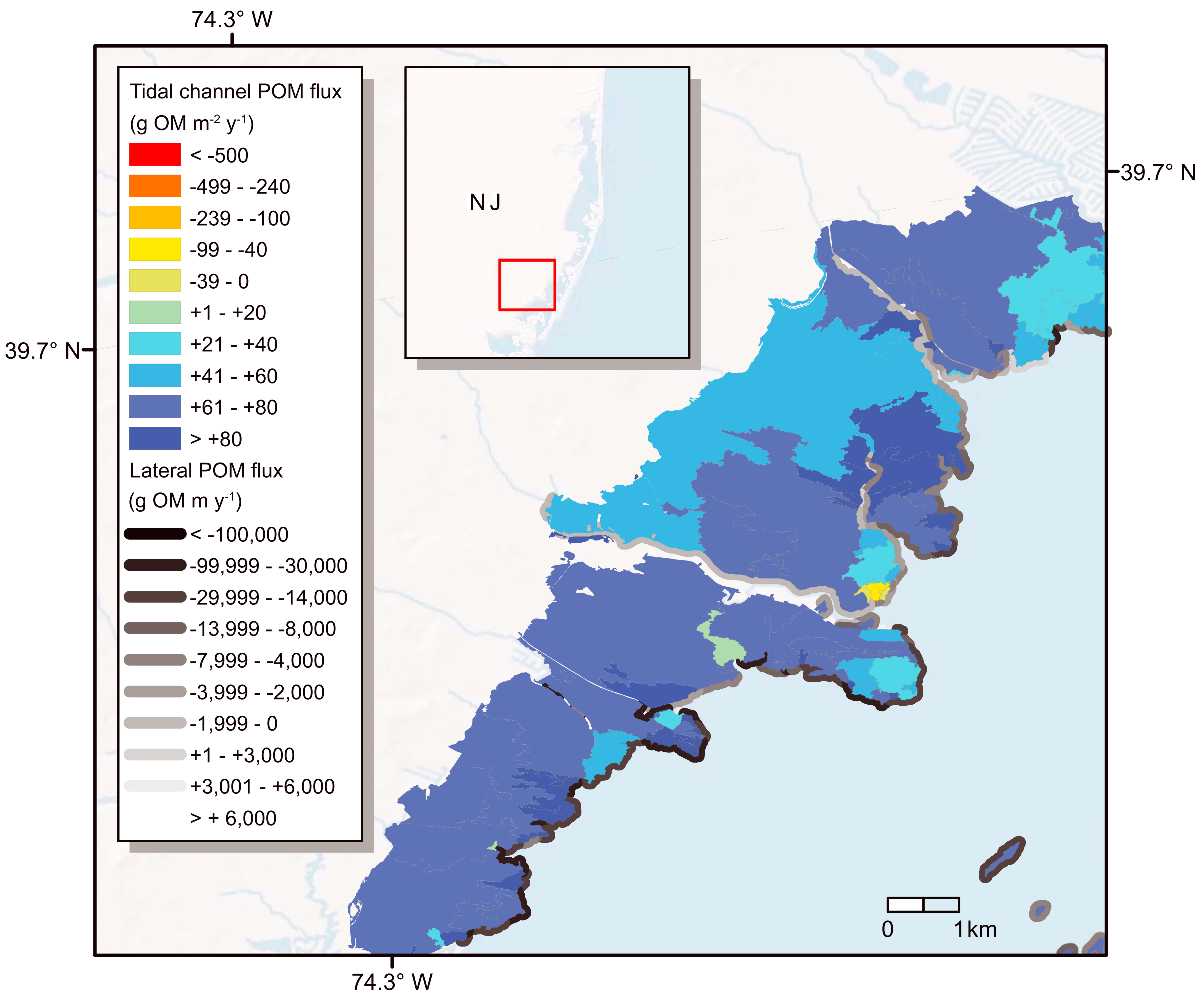

Figure 6. Detail of tidal channel POM flux map with lateral POM flux rates due to edge erosion. Units of tidal channel POM flux are per unit area of marsh, while lateral rates are per unit length of marsh edge. POM = particulate organic matter.

simpler metric of flood-ebb SSC differential as shown by Ganju et al. (2017) is a robust indicator of direction, echoing the sediment balance inference presented by French et al. (2008). Based on those results, the suspended-sediment differential matches flux direction in all but three systems, which are also the systems with the lowest net flux magnitude (sites SB, RC, and OG). This suggests that the larger the flux signal, the greater certainty in direction; flux magnitude is still sensitive to the aforementioned errors. The 27% error estimate is applied uniformly across all sites.

4.1.3. Errors in Temporal Extrapolation

The measurements presented here span periods ranging from ~10 weeks to 10 months, and net flux estimates are extrapolated to annual estimates for intercomparison and use in annual budgets. Seasonal variability in both external forcing as well as internal biogeochemical processes may introduce significant errors, which are largely unquantifiable at a given site. However, we can use the longest set of time series data (Dinner Creek, New Jersey), to subsample at the same temporal coverage of the shortest set of time series data (Blackwater, Maryland) and estimate seasonal variability. We sectioned the sediment flux time series into 10-week intervals and computed net fluxes. At this site, the net flux of each interval was consistently in the landward direction, in accordance with the complete flux time series, but standard deviation of the sediment fluxes from those intervals was 12 g/s as compared to the mean value of 20 g/s over the entire time period, resulting in a potential 62% error. However, it is inadvisable to substitute this error across all sites given different tidal and atmospheric forcing regimes. It is also possible that inter-annual variability may be just as large, therefore longer time series through permanent, continuous monitoring installations are necessary to constrain this error.

4.2. Implications of POM Import and Lateral Flux Estimates and Relative Importance of POM Flux and Marsh Stability for Carbon Budgets

The similarity in magnitude of POM and POC import through tidal channels and export via lateral edge erosion suggests that some portion of eroded marsh edge material may be advected back into the wetland system through tidal channels (i.e., cannibalization). This follows the conceptual model of marsh vertical growth through sediment trapping, in concert with lateral retreat due to wave erosion (Mariotti & Carr, 2014). This finding indicates that models such as Theuerkauf et al. (2015) that neglect import of material via tidal channels may overestimate the export of POM and sediment. However, as Theuerkauf et al. (2015) note, without landward migration of the marsh-land boundary, the aerial extent of the marsh will generally shrink as the marsh edge is eroded, limiting the extent to which sediment can be redeposited on the marsh and POM can be sequestered. Accounting for tidal imports of POM through marsh channels would effectively increase the Theuerkauf et al.'s (2015) carbon storage term, as well as the amount of time required for eroding marshes to turn from sinks to sources of carbon and organic matter. Note that if marshes can retreat landward, then POM imports via tidal channels may continue to approximately equal export from edge erosion.

The similarity in POM imports and exports also suggests that net lateral POM fluxes may be small in Barnegat Bay. Without a precise provenance of the organic matter pools however, it is speculative to attempt a strict accounting of these flux terms. For example, differences in source between exported and imported material, as well as transformations in organic matter characteristics between erosion and redeposition on the marsh, could affect the fate of POM. Imports of relatively labile estuarine-derived material, as well as oxidation of exported marsh organic matter could make imported POM less refractory than the material that was eroded from the edge of the marsh (Boschker et al., 1999; Ståhlberg et al., 2006). This implies that some fraction of the material that is redeposited on top of the marsh could be remineralized before it is permanently resequestered in anaerobic marsh sediments.

4.3. Linkages Between POM Fluxes and Marsh Stability

Conceptually, the regression between POM flux, UVVR, and elevation indicates that low elevation but intact marshes (low UVVR) tend to import POM, while high elevation but disintegrating marshes (high UVVR) tend to export POM (Figure 5). Mechanistically, lower marshes with intact vegetation should have greater trapping efficiency due to increased particle capture and inundation time. This result is consistent with expectations of positive correlations between POM and sediment fluxes and that the direction of both particulate fluxes would correlate with marsh stability, that is, the UVVR (Ganju et al., 2013, 2017). Overall, marshes with negative sediment and POM budgets are exporting material and disintegrating laterally, while marshes with positive sediment budgets are importing material and maintaining their planform.

The site-specific POM flux values, along with the Barnegat Bay example, show that tidal channel POM flux is a small but important term in the overall marsh-estuary organic matter balance. The average across the eight sites is similar to the Barnegat Bay-wide flux estimate (+15 g OM m^2/year). In Barnegat Bay marshes, for example, this net POM import represents approximately 5% of the annual organic matter accumulation rate (Unger et al., 2016). In contrast to Barnegat Bay marshes, which show a net import of POM and POC from the estuary to the marsh, Najjar et al. (2012) estimated a net POC export from tidal wetlands of the Atlantic coast of -50 g·m^2·$year^{-1}$, equivalent to ~100 g POM·m^2·$year^{-1}$ assuming a %POC of OM of 50%. This value was similar to the POM and POC export from the most unstable site in this study, Blackwater NWR. Blackwater NWR has experienced decades of open-water expansion, marsh collapse, and sediment export (Ganju et al., 2013; Stevenson et al., 1985) due to multiple factors including sediment starvation and sea level rise. Although POM export rates are smaller at the other sites in this study, the likelihood of ongoing sediment starvation and sea level rise (Weston, 2014) implies that the estimate of Najjar et al. (2012) may hold true over longer timescales as marsh plains disintegrate and liberate organic and carbon-rich sediment. This implies that wetland trajectory will continue to be important for coastal organic matter budgets on longer timescales.

5. Conclusions

We measured POM fluxes from eight tidal wetland complexes, and found a range of flux magnitudes and direction. Tidal channel POM fluxes ranged from -121 ± 33 to $+102 \pm 28$ g OM·m^{-2}·year^{-1}, and estimated POC fluxes ranged from -52 ± 14 g to $+ 43 \pm 12$ g C·m^{-2}·year^{-1}, which were well predicted by a combination of the UVVR (a measure of geomorphic stability) and elevation relative to mean sea level. The results indicate that marsh stability, as diagnosed by the UVVR and marsh elevation, is an important factor in net flux magnitude and direction. We also considered flood-ebb variations in organic content by using the ratio of acoustic to optical backscatter as a proxy for organic content; this approach established greater confidence in net flux direction and provides guidance for future improvements in methodology. A case study of the large wetland complex in Barnegat Bay, New Jersey, indicated that tidal channel POM fluxes were similar to an estimate of POM export from the marsh to estuary due to edge erosion, suggesting that the complex is currently neutral from a POM (and POC) perspective. Overall, our methods and results provide a general framework for estimating site-specific and regional scale constituent budgets, and linking those budgets with geomorphic trajectory.

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