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**Key Points:**

- High sediment and elemental deposition occurred in floodplains at head-of-tide
- Low deposition occurred in riverine tidal freshwater forests downstream
- Tidal flow blocks watershed sediment from reaching tidal wetlands impacted by rising sea level

**Supporting Information:**

- Figure S1
- Tables S1 and S2

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# Head-of-tide bottleneck of particulate material transport from watersheds to estuaries

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**Abstract** We measured rates of sediment, C, N, and P accumulation at four floodplain sites spanning the nontidal through oligohaline Choptank and Pocomoke Rivers, Maryland, USA. Ceramic tiles were used to collect sediment for a year and sediment cores were collected to derive decadal sedimentation rates using $^{137}$Cs. The results showed highest rates of short- and long-term sediment, C, N, and P accumulation occurred in tidal freshwater forests at the head of tide on the Choptank and the oligohaline marsh of the Pocomoke River, and lowest rates occurred in the downstream tidal freshwater forests in both rivers. Presumably, watershed material was mostly trapped at the head of tide, and estuarine material was trapped in oligohaline marshes. This hydrologic transport bottleneck at the head of tide stores most available watershed sediment, C, N, and P creating a sediment shadow in lower tidal freshwater forests potentially limiting their resilience to sea level rise.

## 1. Introduction

Sediment moving from rivers to estuaries passes through a gradient of fluvial to estuarine dynamics within the tidal freshwater zone, a poorly understood linkage between continents and oceans. The counteracting forces of river floods and tides can be imagined as pistons pushing masses of channel water against one another, and the surrounding intertidal zone can be imagined as the exhaust valve through which suspended material in these water masses is vented. If river floods are not strong enough to push through the tide and past the tidal freshwater zone, floodborne suspended particles will be vented to the freshwater tidal floodplain. While large rivers push their sediment loads to the ocean and build freshwater river deltas, small rivers covering most of the world's coast have tidal freshwater zones far inland where flood tides push sediment upstream. Here tidal freshwater wetlands store C, N, and P for hundreds to thousands of years [*Pasternack*, 2009] before salt water intrudes and liberates elements to the atmosphere or estuary [*Marton et al.*, 2012; *Ardon et al.*, 2013; *Neubauer*, 2013; *Noe et al.*, 2013] and rising water levels erode the riparian shoreline [*Doyle et al.*, 2007]. Predicting this chain of events hinges on knowing how vertical accretion in tidal freshwater wetlands can influence soil elevation change to help counteract increasing inundation as sea level rises.

Tidal freshwater wetlands accrete quickly during periods of extreme sediment loads and river floods, burying saltwater wetlands and pushing the saltwater estuary downstream [*Gottschalk*, 1945; *Hilgartner and Brush*, 2006]. But watershed sediment supply may not be a good predictor of tidal freshwater wetland accretion [*Ensign et al.*, 2013b] because of deposition on the floodplain upstream [*Noe and Hupp*, 2009] and below-ground processes which affect accretion. Position within the tidal gradient is a better determinant of tidal freshwater wetland accretion [*Darke and Megonigal*, 2003] because of the dual sources of sediment delivered to the tidal freshwater zone: the river upstream and the downstream oligohaline maximum turbidity whose sediment concentration is independent of fluvial input [*Dalrymple and Choi*, 2007]. Sediment entering the tidal freshwater zone from upstream and downstream results in high wetland deposition at both ends of the tidal freshwater zone and a sediment accretion "shadow" in between [*Ensign et al.*, 2014]. The current study sought to corroborate the existence of this accretion shadow over a longer historical record and examine the ramifications for wetland accumulation of C, N, and P.

## 2. Methods

We studied the Choptank and Pocomoke Rivers in Maryland, USA, which drain Coastal Plain watersheds of 2059 km$^2$ and 2105 km$^2$ into the Chesapeake Bay. Study sites on each river included a nontidal riparian floodplain, a tidal freshwater forested wetland (TFFW) floodplain near the head of tide (hereafter referred to as "head of tide"), a TFFW 16–19 km downstream from head of tide, and an oligohaline marsh 28–42 km downstream from the head of tide. Average annual river sediment loads are 2096 and 3222 Mg $yr^{-1}$ on the nontidal Choptank and Pocomoke Rivers, respectively [*Gellis et al*., 2008]. The median suspended sediment concentrations in the tidal freshwater Choptank and Pocomoke Rivers were 3.1 and 1.8 mg $L^{-1}$, respectively, over a month of moderately low river discharge, while concentrations in the oligohaline estuary were 21 and 31 mg $L^{-1}$, respectively [*Ensign et al*., 2014]. Tidal range is approximately 0.6 m in the oligohaline zone of both rivers, but the Choptank exhibits standing wave characteristics while the Pocomoke exhibits progressive wave characteristics [*Ensign et al*., 2014].

Rates of C, N, P, and bulk sediment deposition were measured over a 1 year period (April and May 2011 through April and May 2012) using 15 ceramic tiles (square 16.3 cm glazed ceramic tile) distributed 10 m apart along three to five perpendicular transects positioned at 50 m intervals longitudinally along the channel. After 1 year of deployment, sediment was scraped and rinsed from the tiles into plastic storage bags, returned to the lab, and dried at 60°C until a constant weight was measured between 1 h increments. Accretion was measured as the total dry weight divided by the number of days deployed and surface area. Dried samples were combusted at 550°C for 4 h and weighed to determine the mass lost on ignition.

The short-term (annual) bulk deposition rate measurements using tiles may indicate higher rates than actually occur over decadal periods because of insufficient time for respiration of organic matter and erosion cycles. Short-term rates may also be biased by extreme events: Hurricane Irene passed over the study area in late August 2011 followed by Tropical Storm Lee in early September, allowing us to contrast deposition between the Choptank River, which experienced the largest flood of the U.S. Geological Survey's 67 years discharge record (251 $m^3 s^{-1}$ at site 01491000 draining 293 $km^2$), and the Pocomoke River where flooding was minor (event peak discharge of 12 $m^3 s^{-1}$ at site 01485000 draining 157 $km^2$).

Rates of accumulation over the past six decades were measured from $^{137}Cs$ peaks in sediment cores collected in 2012 near the middle of each ceramic tile array. Sediment cores were collected using a single piston core at each measurement site ($n = 8$) using a metal tripod to suspend a gasketed plug at ground level within an 8.5 cm diameter clear plastic core barrel. The core barrel was pushed 0.5 m into the soil while the gasketed plug remained in place at ground level to create suction and resist compression of soil as the barrel filled. The mean compaction of the cores was 12.1 cm with a standard deviation of 6.6 cm. Cores were sectioned every 1 cm, and material was dried at 60°C until a constant weight was measured between 1 h increments.

Dried and ground (<1 mm) material from both tiles and cores was analyzed for total C and total N (Flash 2000 CHNS analyzer; Thermo Electron, Milan, Italy), total P (microwave-assisted acid digestion (MARS5, CEM, Matthews, North Carolina, USA)), and ICP-OES analysis (Perkin-Elmer, Waltham, Massachusetts, USA). Determination of $^{137}Cs$ activity was determined at 661.6 KeV on a Canberra Broad Energy Germanium detector. Counting was performed until the integration error of the peak was <10%. Detector efficiency was established using standard reference material for sediment from the National Institute of Standards and Technology. One centimeter thick core samples were counted every 2 cm through the core except around the region of peak activity where samples were counted in every 1 cm. Peak $^{137}Cs$ activity was assumed to represent 1964, and the mass and elemental accumulation rates were numerically integrated at and above this stratum.

Analysis of variance (ANOVA) was performed to test whether inorganic sediment (mass following combustion), C, N, and P accumulation measured on tiles differed between wetland habitats and rivers. Accumulation rates were normalized using cubed root or natural log transformation. We used the inorganic portion of short-term sediment deposition to isolate allochthonous mineral sediment inputs from the combined allochthonous riverine organic matter and autochthonous floodplain organic matter contributions. Pairwise comparisons between sites were performed using Tukey tests; all statistical test were performed using R [*R Core Team*, 2014].

## 3. Results and Discussion

The Choptank River showed highest short-term deposition and long-term sediment accumulation at the head of tide but lowest rates immediately downstream in the TFFW site (Tables S1 and S2 in the supporting information and Figure 1). This peak in sedimentation at the head of tide was absent in the Pocomoke River,

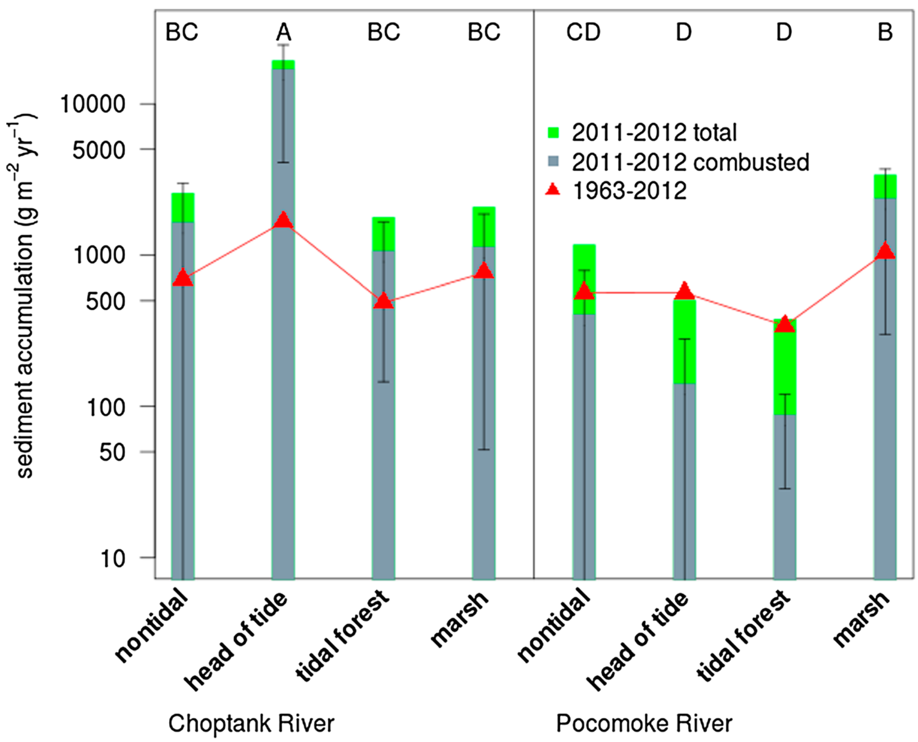


**Figure 1.** Sediment accumulation measured from tiles (2011–2012) and $^{137}Cs$ (1963–2012); error bars denote 1 standard deviation of the mean of the combusted sediment samples. Letters denote groupings from Tukey HSD test on combusted sediment accumulation rates on tiles.

where historical records indicate much lower fluvial suspended sediment concentrations than the Choptank River [*Ensign et al.*, 2014], and Hurricane Irene had minimal impact. The lowest rates of sediment deposition and accumulation on both rivers occurred in the TFFW, yet long-term accumulation was higher further downstream in the oligohaline marshes and short-term deposition was significantly higher in the Pocomoke's marsh. These patterns in sediment deposition support our previous interpretation of the dual mechanisms controlling sediment deposition: tidally oscillating flow velocity forces deposition of fluvial sediment loads within a short distance of the head of tide [*Ensign et al.*, 2014]. Downstream of the TFFW, oligohaline marshes receive abundant sediment supplied by the estuarine turbidity maximum, whose sediment concentrations are independent of those in the river upstream, demonstrated most notably in the Pocomoke River where fluvial sediment concentration was low and deposition in oligohaline wetlands was high. This trapping at both ends of the tidal freshwater zone casts a sediment shadow on the tidal forests in between, with minimal sediment trapping, leaving them immediately more vulnerable to inundation as sea level rises [*Ensign et al.*, 2013b, 2014; *Craft*, 2012].

The disparity between low sediment trapping in the tidal freshwater forests and high trapping in oligohaline marshes downstream cannot be explained by differences in inundation dynamics. The tidal freshwater forests on both rivers were inundated an equivalent or greater amount of time as the marshes, with equivalent numbers of inundation events, and equivalent or greater depth of inundation [*Ensign et al.*, 2014]. Furthermore, the fluvial flood wave generated by Hurricane Irene was completely attenuated by the time it reached the oligohaline marsh on the Choptank River [*Ensign et al.*, 2014]. Sediment entering oligohaline marshes must be delivered from the direction of the saltwater estuary because inundation occurs during flood tide, not ebb tide, and because suspended sediment concentration increases with proximity to the oligohaline estuary [*Darke and Megonigal*, 2003; *Newell et al.*, 2004; *Delgado et al.*, 2013; *Butzeck et al.*, 2014; *Ensign et al.*, 2014]. Moreover, tidal currents are more likely to push sediment upstream than downstream within the tidal freshwater zone [*Guézennec et al.*, 1999; *Yankovsky et al.*, 2012; *Ralston et al.*, 2013] due to greater velocity and shear stress during flood versus ebb tide [*Yankovsky et al.*, 2012; *Ensign et al.*, 2013a]. These data lead us to conclude that over decadal time scales, brackish marshes accumulate sediment delivered by estuarine tides that are independent of river flow and recently discharged watershed sediment.

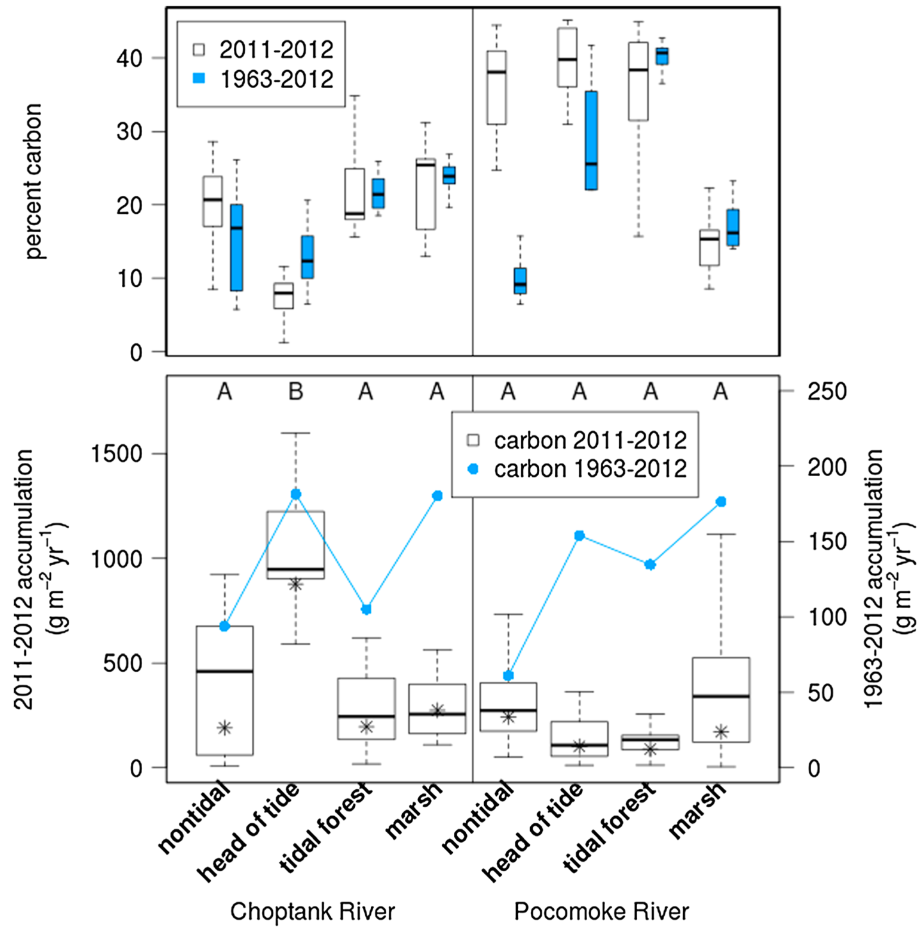


**Figure 2.** Percent C in (top) tile samples and (bottom) sediment and C accumulation. Letters denote groupings from Tukey HSD test on C accumulation rates on tiles; stars represent the geometric mean of the 2011–2012 monitoring data, while bars represent the median, boxes represent the interquartile range, and the dashed lines are the limit of values less than 1.5 times the interquartile range above the third quartile and less than 1.5 times the interquartile range below the first quartile.

Carbon accumulation generally followed the same trend as sediment: deposition was highest at the head of tide on the Choptank likely because of the high load of watershed sediment delivered by the flood-of-record following Hurricane Irene (Tables S1 and S2 and Figures 2 and 3). Decadal C accumulation rates show an identical trend in both rivers, with peaks at the head of tide and oligohaline marsh. Over decades of river flood events and increasing tidal influence, riparian forests at the head of tide accumulated larger amounts of C than nontidal riparian forests upstream due to a combination of high sediment delivery with low percent C (Choptank River), or just C-enriched sediment (Pocomoke River). Downstream the TFFW had higher percent C, but the much lower sediment delivery rate reduced overall C deposition. Higher rates of C accumulation occurred in oligohaline marshes than TFFW. Overall, the tidal freshwater zone accumulated C over decadal time scales at a higher rate than the nontidal riparian zone in this study (similar to shorter-term deposition at other nontidal riparian zones) [*Noe and Hupp*, 2005] but slightly lower than tidal freshwater marshes elsewhere [*Neubauer et al.*, 2002; *Drexler et al.*, 2013].

Nitrogen deposition followed a similar trend as C, with highest long-term accumulation at the head of tide and oligohaline marshes (Tables S1 and S2 and Figures 4 and 5). In the Choptank, the head of tide received higher N over annual and decadal time scales than the nontidal floodplain; the Pocomoke's N accumulation over the long-term was similar to the Choptank, but short-term deposition was not different from the nontidal floodplain. As with C, N accumulation over decadal time scales was higher in the oligohaline marshes than TFFW regardless of the range in percent N. With the exception of the high rates at the head of tide and oligohaline marsh, short-term rates of N deposition were within the range of other Coastal Plain fluvial and estuarine wetlands [*Craft and Casey*, 2000; *Noe and Hupp*, 2005].

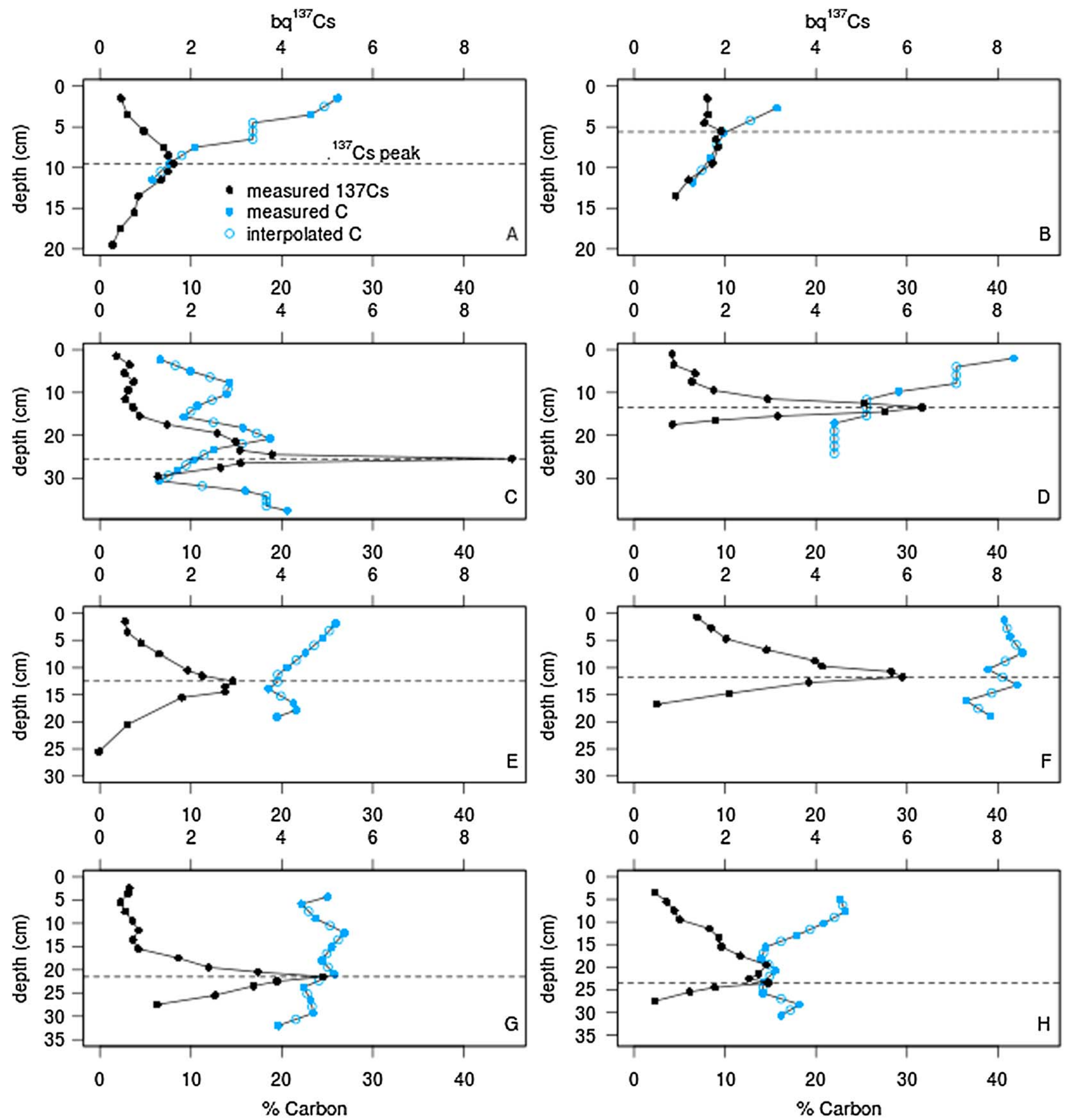


**Figure 3.** Down-core distribution of $^{137}$Cs and percent Carbon in nontidal Choptank River (A) and Pocomoke River (B), head of tide (C and D), tidal freshwater forest (E and F), and oligohaline marsh (G and H).

Short- and long-term rates of P deposition were greatest at the head of tide in the Choptank River, declining to a minimum in the TFFW downstream (Tables S1 and S2 and Figures 5 and 6). The oligohaline marsh on the Pocomoke had significantly greater short-term P deposition than at the head of tide due to greater sediment deposition, not higher percent P. Phosphorus deposition in this study was on par with other tidal freshwater marshes, riparian floodplains, and cypress swamps [*Noe and Hupp*, 2005].

We infer from these data and the mechanisms discussed that the tidal freshwater zone near the head of tide forms a hydrologic transport bottleneck for sediment and associated C, N, and P transport from Coastal Plain watersheds to their saltwater estuaries. We predict that this bottleneck occurs at the landward extent of tidal influence on all alluvial Coastal Plain rivers in which the river valley morphology permits extensive floodplain inundation. The distance downstream that this bottleneck extends from the head of tide and its effectiveness depend on the tidal amplitude relative to the river's stage during storm events: higher tides are more capable of reducing the water surface gradient driving river floods, thereby inducing sediment-laden floodwater to deposit sediment on the floodplain as the flow velocity slows. This bottleneck is so efficient that it creates a sediment shadow that starves the tidal freshwater wetlands downstream from the sediment necessary to help keep pace with sea level rise [*Hupp et al.*, 2015]. Previous studies have found only trace amounts of

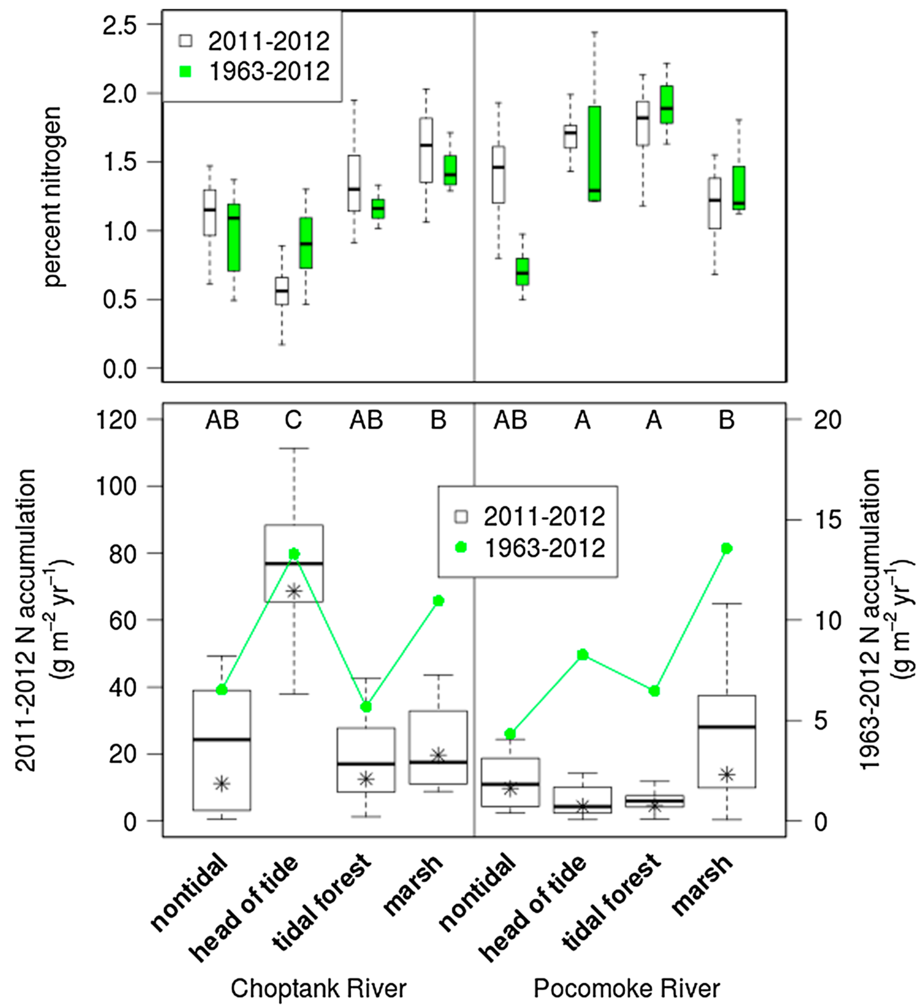


**Figure 4.** Percent N in (top) tile samples and (bottom) N accumulation. Letters denote groupings from Tukey HSD test on N accumulation rates on tiles, and data are represented as described in Figure 2.

watershed-derived clay-sized particles in coastal plain river estuaries, providing further evidence for this bottleneck effect [*Phillips*, 1997; *Benedetti et al.*, 2006]. The watershed material that does slip through the bottleneck is diluted with coastal sediments in the lower estuary and may be moved back upstream to brackish marshes in estuaries with the appropriate tidal hydrodynamics [*Guézennec et al.*, 1999; *Ganju et al.*, 2015]. This bottleneck creates a sediment shadow that starves the TFFW downstream from the sediment necessary to help keep pace with sea level rise [*Hupp et al.*, 2015].

Given the likelihood of sediment trapping in the tidal freshwater zone bottleneck, under what conditions does particulate matter from Coastal Plain watersheds reach saltwater estuaries? A short tidal freshwater zone may allow floods to push suspended material through to the saltwater estuary in a single ebb tide and bypass the head of tide bottleneck; this may be the case where contemporary watershed sediment loads lead to saltwater wetland accretion [*Mattheus et al.*, 2009]. Alternatively, low-amplitude, diurnal tides may be overwhelmed by river floods which push fluvial material to a bayhead delta, while large rivers are capable of moving material to their deltas regardless of tidal influence. Developing these scenarios with scaling relationships between hydrology and river morphology would enable prediction of the relative throughput of material from watersheds to estuaries, a valuable tool for identifying where saltwater wetlands will be affected by declining river sediment loads [*Weston*, 2014].

This sediment and associated nutrient bottleneck in tidal rivers has important implications for management of watershed loads to improve estuarine water quality. For example, the Chesapeake Bay has been impaired

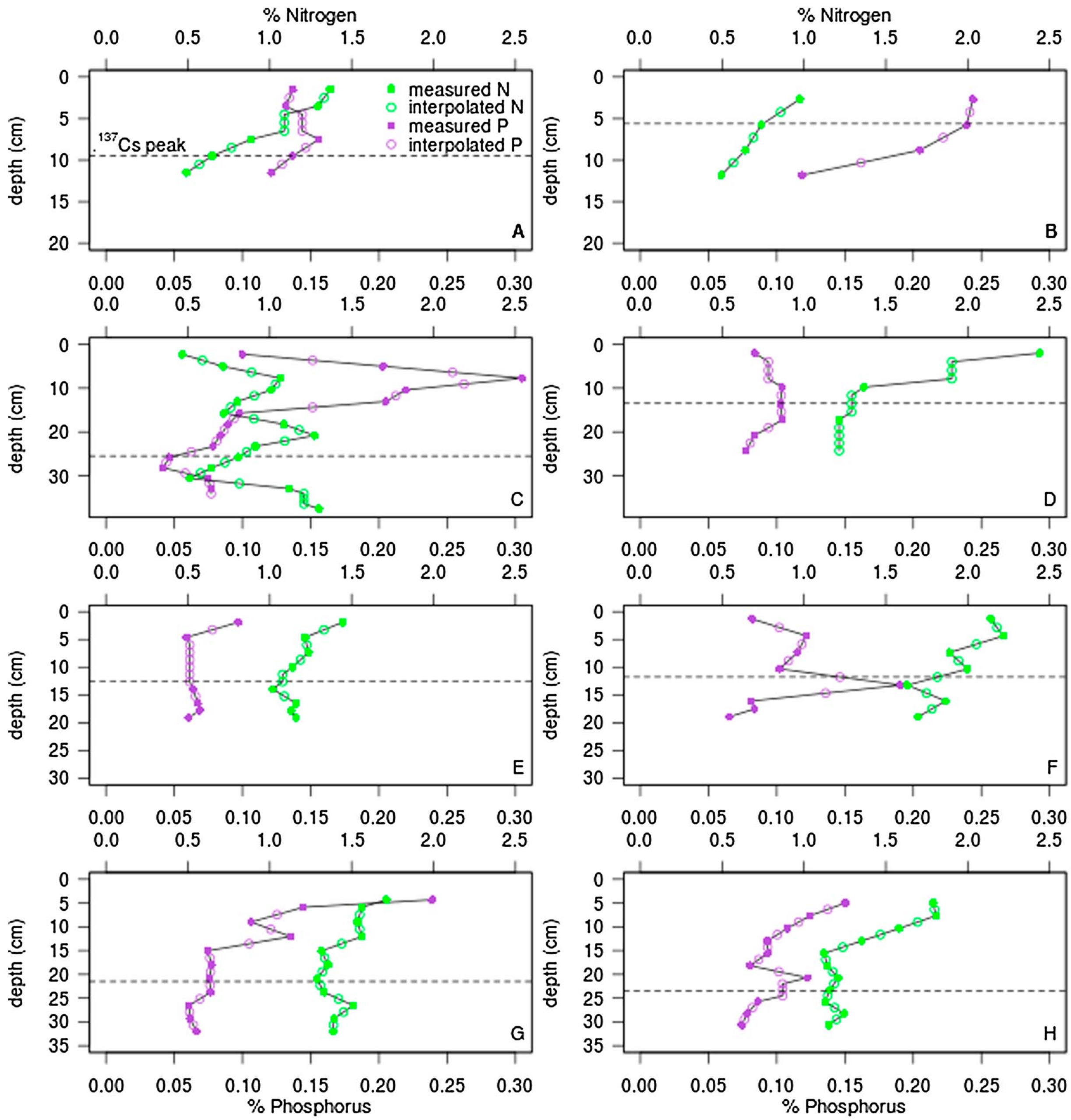


**Figure 5.** Down-core distribution of percent P and percent N in nontidal (a) Choptank River and (b) Pocomoke River, (c and d) head of tide, (e and f) tidal freshwater forest, and (g and h) oligohaline marsh.

by decades of elevated sediment, N, and P inputs that have resulted in the implementation of a Total Maximum Daily Load restriction on loading estuarine waters [*Shenk and Linker*, 2013]. Models of watershed-to-estuary transport may be overestimating delivery of Coastal Plain watershed inputs to the Chesapeake Bay by not considering hydrodynamic processes (i.e., a transport bottleneck) unique to the tidal freshwater zone.

Tidal freshwater forested wetlands are among the estuarine habitats most threatened by sea level rise due to their low vertical accretion rates [*Conner et al*., 2009; *Craft*, 2012; *Ensign et al*., 2013b, 2014], but our data indicate that forest inundation may trigger farther-reaching effects. Forest inundation occurs in tandem with the changes in vegetation, and initial losses of C, N, and P from tidal freshwater forest soils [*Marton et al*., 2012; *Neubauer*, 2013; *Noe et al*., 2013] are followed by higher accumulation rates in brackish marshes. Yet as the

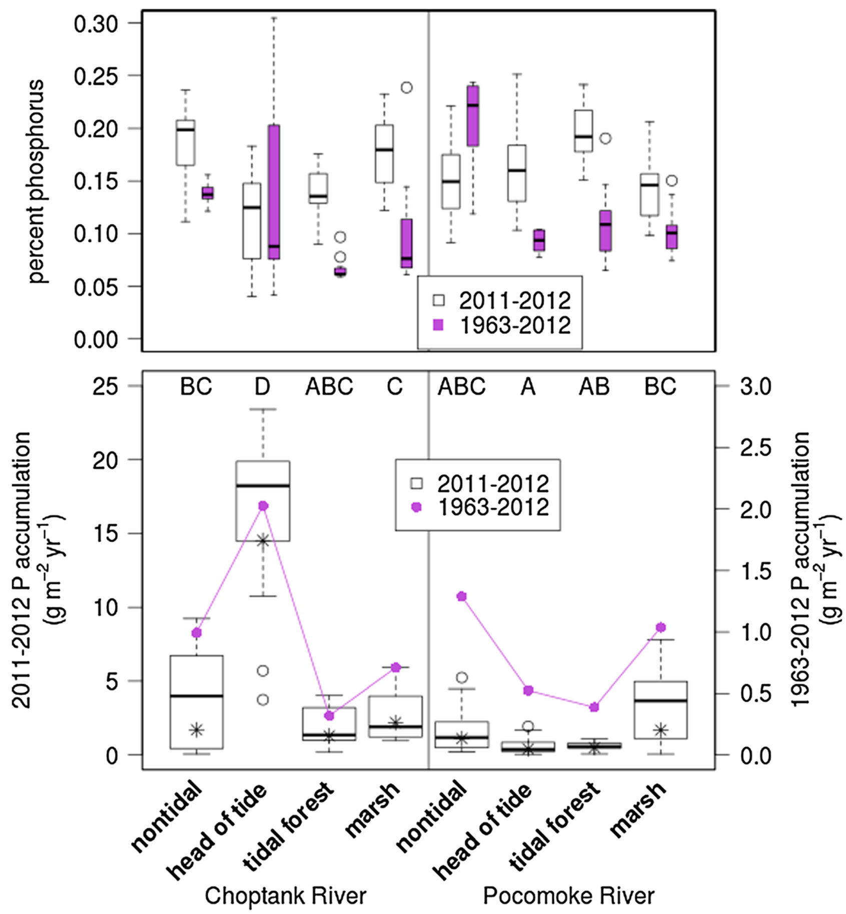


**Figure 6.** Percent P in tile samples (top) and P accumulation (bottom). Letters denote groupings from Tukey HSD test on P accumulation rates on tiles and data are represented as described in Figure 2.

banks of TFFW retreat [*Doyle et al*., 2007], the larger channel volume allows saltwater farther upstream toward the head of tide, triggering ecosystem state change and release of the larger stores of C, N, and P. Mobilization of this watershed-derived material into the atmosphere and estuary is a deferred contribution of watershed-derived material to the estuary elemental budget. Discovery of this locus of C, N, and P trapping at the head of tide revealed an unexpected hydrologic complexity along the estuarine continuum which sea level rise and intertidal wetland modeling must incorporate.

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