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CARBON, NITROGEN, AND PHOSPHORUS ACCUMULATION IN FLOODPLAINS OF ATLANTIC COASTAL PLAIN RIVERS, USA

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Abstract. Net nutrient accumulation rates were measured in riverine floodplains of the Atlantic Coastal Plain in Virginia, Maryland, and Delaware, USA. The floodplains were located in watersheds with different land use and included two sites on the Chickahominy River (urban), one site on the Mattaponi River (forested), and five sites on the Pocomoke River (agricultural). The Pocomoke River floodplains lie along reaches with natural hydrogeomorphology and on reaches with restricted flooding due to channelization and levees. A network of feldspar clay marker horizons was placed on the sediment surface of each floodplain site 3–6 years prior to sampling. Sediment cores were collected from the material deposited over the feldspar clay pads. This overlying sediment was separated from the clay layer and then dried, weighed, and analyzed for its total carbon (C), nitrogen (N), and phosphorus (P) content.

Mean C accumulation rates ranged from 61 to 212 $g \cdot m^{-2} \cdot yr^{-1}$, N accumulation rates ranged from 3.5 to 13.4 $g \cdot m^{-2} \cdot yr^{-1}$, and P accumulation rates ranged from 0.2 to 4.1 $g \cdot m^{-2} \cdot yr^{-1}$ among the eight floodplains. Patterns of intersite variation in mineral sediment and P accumulation rates were similar to each other, as was variation in organic sediment and C and N accumulation rates. The greatest sediment and C, N, and P accumulation rates were observed on Chickahominy River floodplains downstream from the growing metropolitan area of Richmond, Virginia. Nutrient accumulation rates were lowest on Pocomoke River floodplains that have been hydraulically disconnected from the main channel by channelization and levees. Sediment P concentrations and P accumulation rates were much greater on the hydraulically connected floodplain immediately downstream of the limit of channelization and dense chicken agriculture of the upper Pocomoke River watershed. These findings indicate that (1) watershed land use has a large effect on sediment and nutrient retention in floodplains, and (2) limiting the hydraulic connectivity between river channels and floodplains minimizes material retention by floodplains in fluvial hydroscapes.

Key words: carbon; coastal plain; connectivity; floodplain; geomorphology; land use; nitrogen; phosphorus; sediment.

Introduction

Wetlands are generally known to be important locations for material sinks, sources, and transformations in landscapes (Johnston 1991, Mitsch and Gosselink 1993). Located at the confluence of transport pathways for reactive constituents from both terrestrial and aquatic systems, wetland ecosystems can serve as biogeochemical ''hotspots'' in landscapes (McClain et al. 2003). This biogeochemical function is particularly true for nutrients, because wetlands often have high productivity and decomposition rates, high nutrient loading rates, and dynamic oxidation–reduction interfaces that facilitate nutrient processing. In addition, wetland vegetation reduces water velocity, making wetlands important sites for the deposition of suspended sediment and its associated nutrients and contaminants (Gurnell 1997).

Floodplain wetlands, in particular, are widely thought to be important sites for affecting water quality, providing wildlife habitat, and attenuating floods (Conner and Day 1982, Wharton et al. 1982, Junk et al. 1989, Ward 1989, Naiman and Décamps 1997). Flood pulses provide energy and material subsidies to floodplain ecosystems (Junk et al. 1989, Tockner et al. 2000). As a result, floodplains produce, decompose, and export large amounts of organic matter that support riverine metabolism (Brinson et al. 1981, Cuffney 1988, Meyer et al. 1997). It has also been shown that floodplains are important nursery grounds for fisheries (Welcomme 1979), provide a trophic base in landscapes (Junk et al. 1989), and disproportionately support regional biodiversity (Salo et al. 1986).

Floodplains provide opportunities for nutrient uptake during flooding, when most downstream nutrient loading occurs in rivers (Pinay et al. 1992). Floodplains can be sinks for inorganic, organic, dissolved, and particulate fractions of both nitrogen (N) and phosphorus (P) during overbank flooding (e.g., Yarbro 1983, Hamilton and Lewis 1987, Tockner et al. 2002), but they

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PLATE 1. Photo of the Bottoms Bridge floodplain on the Chickahominy River, Virginia, during overbank flooding. The main channel of the Chickahominy River is in the background. Photo credit: G. Noe.

can also be a source or transformer of some nutrient fractions (Conner and Day 1982, Brinson et al. 1983, Elder 1985, Stoeckel and Miller-Goodman 2001). In contrast, large river channels have low nutrient retention rates, with most of their nutrient load passing downstream to receiving water bodies (Alexander et al. 2000). Thus floodplains may limit nutrient loading, or export less-bioavailable nutrient fractions, from rivers to downstream aquatic ecosystems that may be susceptible to eutrophication.

Human management of river–floodplain systems has often disconnected floodplains from river channel hydrology (Sparks 1995, Poff et al. 1997). Levee construction, channelization, flow manipulation by dams, and alteration of hydrology by urbanization are common on rivers (Dynesius and Nilsson 1994) and minimize the frequency and duration of flood pulses on floodplains (Décamps et al. 1988, Ligon et al. 1995). These alterations, in turn, have been shown to effectively reduce sediment deposition in floodplains (Hupp 1992, Kleiss 1996, Ross et al. 2004). By minimizing flood pulses, human management has also reduced nutrient loading to floodplains. Few studies, however, have examined how river regulation affects nutrient accumulation in floodplains. We hypothesize that disconnection from the riverine flood pulse reduces nutrient accumulation rates in floodplains.

Restoring riparian and floodplain function has been proposed as a management tool to reduce nutrient export by rivers (Welcomme 1992, Sparks 1995). For example, Mitsch et al. (2001) proposed restoring 2.1–5.2×10^4 km^2 of wetlands in the heavily agricultural Mississippi River watershed in order to reduce N loading to the Gulf of Mexico. Understanding and quantifying nutrient accumulation rates in floodplains from watersheds with different land use will help elucidate their function in fluvial systems and identify the potential benefits of floodplain restoration. The purpose of this paper is to present a study that measured net carbon (C), N, and P accumulation rates as sedimentation in floodplains of the Atlantic Coastal Plain, USA. Our sites are tributaries to the Chesapeake Bay, the largest estuary in the USA and one of the most productive in the world, where excess nutrient and sediment inputs pose a major water-quality threat (Phillips 2002). Our goal was to quantify nutrient accumulation rates in these floodplains and relate variation in these rates to differences in watershed land use and hydraulic connectivity with the main river channel.

METHODS

Net nutrient accumulation rates were quantified by measuring the nutrient content of sediment that accumulated on floodplains over a known time period. Networks of feldspar clay pads were placed on the sediment surface of floodplains (Hupp and Bazemore 1993) on rivers across the Coastal Plain of the Chesapeake Bay watershed. We collected sediment cores from these

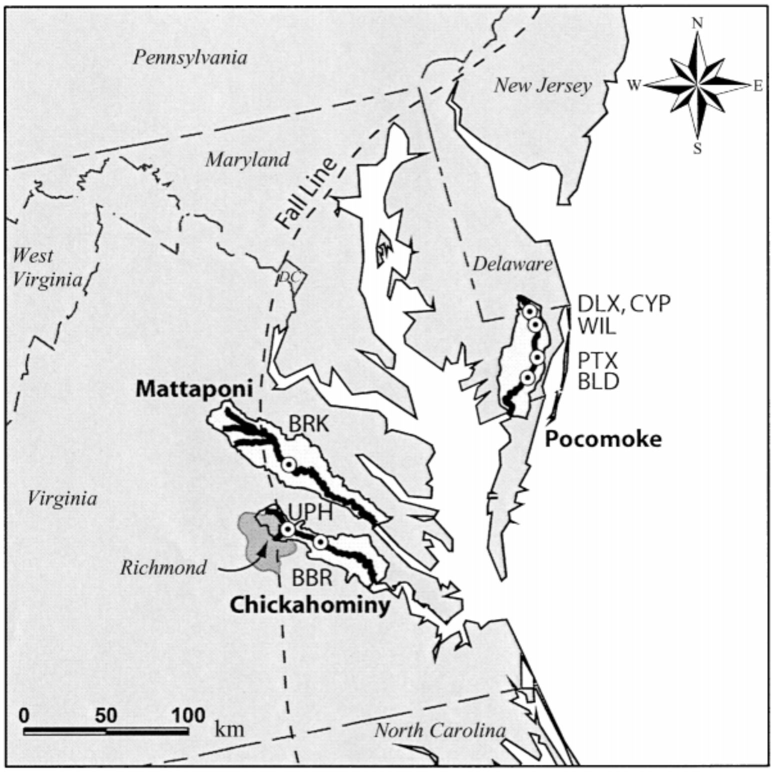

FIG. 1. Map showing the locations of the three rivers and their watersheds, the Fall Line, and the metropolitan area of Richmond, Virginia, on the mid-Atlantic Coastal Plain, USA. Floodplain sites include Upham (UPH) and Bottoms Bridge (BBR) on the Chickahominy River; Burkes (BRK) on the Mattaponi River; and Delaware Crossing (DLX), Cypress (CYP), Willards (WIL), Porters Crossing (PTX), and Blades (BLD) on the Pocomoke River.

pads and quantified the mass and nutrient content of this recently deposited sediment. From these data, sediment and nutrient accumulation rates ($g \cdot m^{-2} \cdot yr^{-1}$) were calculated.

Study sites

The floodplains of three rivers in the Coastal Plain of the Chesapeake Bay watershed were sampled (Fig. 1). These rivers span a range of land-use and geomorphic alteration that is typical of the Coastal Plain. Flooding in this region typically occurs in late winter and early spring. Dominant floodplain forests consist of bottomland hardwoods, including *Acer rubrum*, *Carpinus caroliniana*, *Fraxinus pennsylvanica*, *Liquidambar styraciflua*, *Nyssa biflora*, and *Quercus* spp.; *Nyssa aquatica* and *Taxodium distichum* occur in deep backswamps.

Two floodplain sites were sampled on the Chickahominy River in Virginia. The alluvial Chickahominy River has its source in the Piedmont (30% of the 790-km^2 watershed is in the Piedmont, Hupp et al. 1993). The upper third of the basin has been steadily developing in and around the city of Richmond (Table 1). As a result of increased water withdrawal, soil disturbance, and impervious surface cover associated with urbanization, the water table has been lowered, there is an increased frequency of overbank flash floods, and sediment deposition rates have increased since the 1940s (Ross et al. 2004). The Upham site is located on Upham Brook, which drains the urbanized Richmond area, just above its confluence with the Chickahominy River and about 10 km downstream from the Fall Line, the transition between the Coastal Plain and the Piedmont. The Bottoms Bridge site is located about 40 km downstream from the Fall Line on the main stem of the Chickahominy River (see Plate 1). Both the Upham and Bottoms Bridge floodplains remain hydraulically connected to the main channel.

The Burkes floodplain site is located on the alluvial Mattaponi River in Virginia. This watershed is the least developed of the three watersheds in this study. Land use is a mixture of forest, with some nonintensive agriculture and sparse population centers (Table 1). Like the Chickahominy River, the upper watershed of the Mattaponi River is located in the Piedmont. The Burkes floodplain remains hydraulically connected to the main channel.

Five floodplain sites were sampled on the Pocomoke River in Delaware and Maryland. The Pocomoke River is located entirely in the Coastal Plain and was historically a blackwater system, until the upper half of the Pocomoke River watershed was extensively drained by

TABLE 1. Watershed characteristics of the three rivers.

Characteristic	Chickahominy River	Mattaponi River	Pocomoke River
Area (km)	1217	2362	969
Population	199 089	48 571	23 871
Population density (per km^2)	424	53	64
Developed (%)	12	1	1
Agriculture (%)	16	21	41
Forested (%)	55	68	38
Open water (%)	4	2	1
Wetland (%)	12	6	18
Barren (%)	1	2	1
Slope (m/km)	1.0	0.9	0.2
Main channel length below fall line (%)	78	79	100

Notes: Watershed area, population, and land-use characteristics are from Hopkins et al. (2000). The watershed slopes and percentages of the river main channel occurring below the Fall Line were determined from USGS topographic maps.

ditches and levees in the 1940s to support intensive row crop and chicken production (Table 1). As a result, floodplains in the upper basin have been hydraulically disconnected from the river and are rarely inundated (Ross et al. 2004). Suspended sediment concentrations in river water have also increased and the river–floodplain system is alluvial. In contrast, riverine geomorphology has been modified little in the lower basin, and the floodplains still regularly inundate with overbank flow from the main channel. The Cypress site (Delaware) is a groundwater-dominated *Taxodium* swamp (''headwater'' site). The Delaware Crossing (Delaware) and Willards (Maryland) floodplain sites are located in the upper, drained portion of the watershed and typically do not flood (''disconnected'' sites). Finally, the Porters Crossing and Blades sites (Maryland) occur downstream of the limit of channelization and are regularly flooded (''connected'' sites). The Blades floodplain is a freshwater tidal area, although flow reversals do not occur.

Sediment collection

Each floodplain site had three transects established perpendicular to the river, with typically five feldspar pads per transect. Feldspar pads were nonrandomly located to ensure sampling of important geomorphic features and avoid local microtopographic and vegetation irregularities. Pads were installed by pouring 2.3 kg of dry, ground feldspar clay roughly 1 cm deep over a 0.5 m diameter circle of floodplain surface sediments. Feldspar pads in the Mattaponi, Pocomoke, and Chickahominy River sites were installed in 1997, 1998, and 2000, respectively; all sampling occurred in May and June 2004.

Three sediment cores were collected on each feldspar pad that had net sediment accumulation, had a defined feldspar–sediment interface, and was not inundated at the time of sampling. Four cores were collected on those few pads with a small amount of sediment accumulation in order to ensure collection of sufficient material for analysis. The Bottoms Bridge site was mostly inundated, biasing sampling to drier locations. The total number of pads sampled at each site is presented in Fig. 2. Sediment cores were collected by inserting a beveled, 4.85 cm inner diameter, stainless-steel tube through the surface sediment and underlying feldspar layer. Surface leaf litter was sampled, but large branches (>2 mm diameter) were discarded. Cores were then extruded, and surface sediments were separated from the underlying feldspar layer with a knife in the field. Replicate sediment cores were pooled from each pad, placed in a plastic bag, stored on ice, returned to the laboratory, and stored at 4°C until analysis.

Sediment analysis

Samples were dried to a constant mass at 60°C and then weighed. Dried sediment samples were then ground with a mortar and pestle to pass through a 0.5-mm sieve. Coarse organic matter was preground with a Wiley mill (Thomas Scientific, Swedesboro, New Jersey, USA). The organic and mineral content of the sediments was determined by loss-on-ignition at 400°C for 16 h in a muffle furnace (Nelson and Sommers 1996). Total C and total N concentrations were determined with a Carlo-Erba CHN elemental analyzer (Thermo Electron, Milan, Italy). Both C and N were likely in organic fractions because of the relatively acidic sediments. Total P (both inorganic and organic) concentrations were measured in digested sediments by inductively coupled plasma–optical emission spectroscopy analysis. Sediments were digested at high temperature and pressure by repeated microwave-assisted digestion following sequential addition of HNO_3, HCl and HF, and then HBO_3 acids. Differences in parameters among the eight floodplain sites were tested with one-way ANOVA and Tukey post hoc tests. Sediment texture was uniform among the different floodplain sites and was predominantly in the silt + clay and medium sand fractions (means, 31% in the <62 μm size class and 27% in the 250–500 μm size class; G. B. Noe, *unpublished data*).

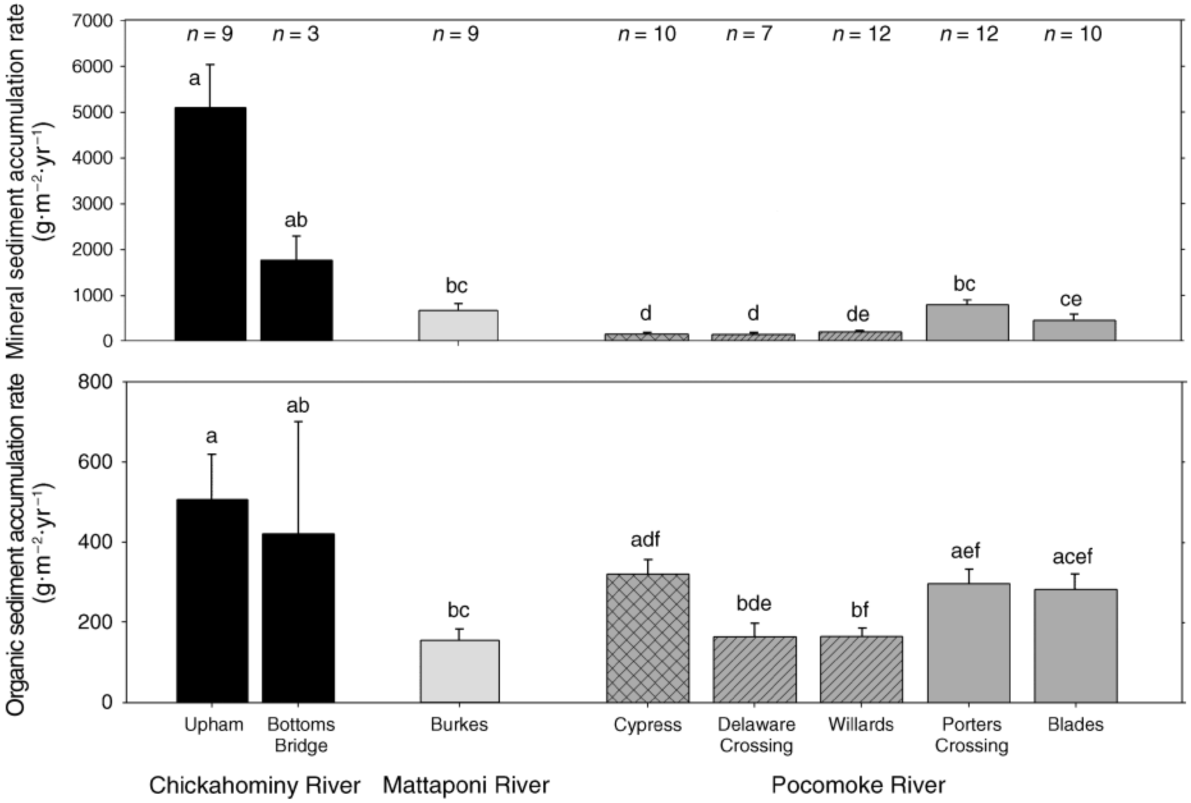

FIG. 2. Mineral and organic sediment accumulation rates (mean + SE). Sites on the Pocomoke River are differentiated into headwater (crosshatch), hydraulically disconnected (slant hatch), and hydraulically connected (no hatch) floodplains. The number (n) of feldspar pads sampled at each site is listed in the top panel. Different lowercase letters above the bars indicate a statistically significant difference ($P < 0.05$) between sites.

RESULTS

The greatest rates of mineral sediment accumulation occurred in the floodplains of the Chickahominy River (urban watershed; Fig. 2). In particular, the Upham site on the Chickahominy River had a rate of mineral sediment accumulation an order of magnitude greater than floodplains on the other rivers. Feldspar pads on the Chickahominy River sites were installed most recently; thus the greater rates of sediment deposition at these sites cannot be attributed to large deposition events during years not sampled at the other sites. Intermediate levels of mineral sediment accumulation were found in the Mattaponi River floodplain (forested watershed) and the hydraulically connected Pocomoke River floodplains (Porters Crossing and Blades; agricultural watershed). Finally, the hydraulically disconnected (Delaware Crossing and Willards) and headwater (Cypress) floodplains of the Pocomoke River had the lowest rates of mineral sediment accumulation.

Differences in organic sediment accumulation rates among sites were much smaller and were rarely statistically significant compared to the variation in mineral sediment accumulation. Mean organic matter accumulation rates were greatest in the Chickahominy River floodplains, intermediate in the headwater (Cypress) and connected (Porters Crossing and Blades) Pocomoke River floodplains, and lowest in the Mattaponi River floodplain and disconnected (Delaware Crossing and Willards) Pocomoke River floodplains (Fig. 2). Significantly greater rates of organic sediment accumulation occurred on the Upham floodplain on the Chickahominy River compared to the Mattaponi River floodplain and disconnected Pocomoke River floodplains. The headwater Cypress and connected Porters Crossing sites on the Pocomoke River also had significantly greater organic sediment accumulation rates than did the floodplain on the Mattaponi River.

Patterns of nutrient accumulation rates in different floodplains were similar for C and N, and largely mirrored the differences in organic sediment accumulation rates among sites. Accumulation rates of C and N generally were greatest on the floodplains of the Chickahominy River, intermediate in the headwater and connected floodplains of the Pocomoke River, and lowest on the floodplain of the Mattaponi River and on the disconnected floodplains of the Pocomoke River (Fig. 3). As with organic sediment accumulation, the Chickahominy River floodplains at Upham and Bottoms Bridge had significantly greater C and N accumulation than the disconnected Delaware Crossing and Willards

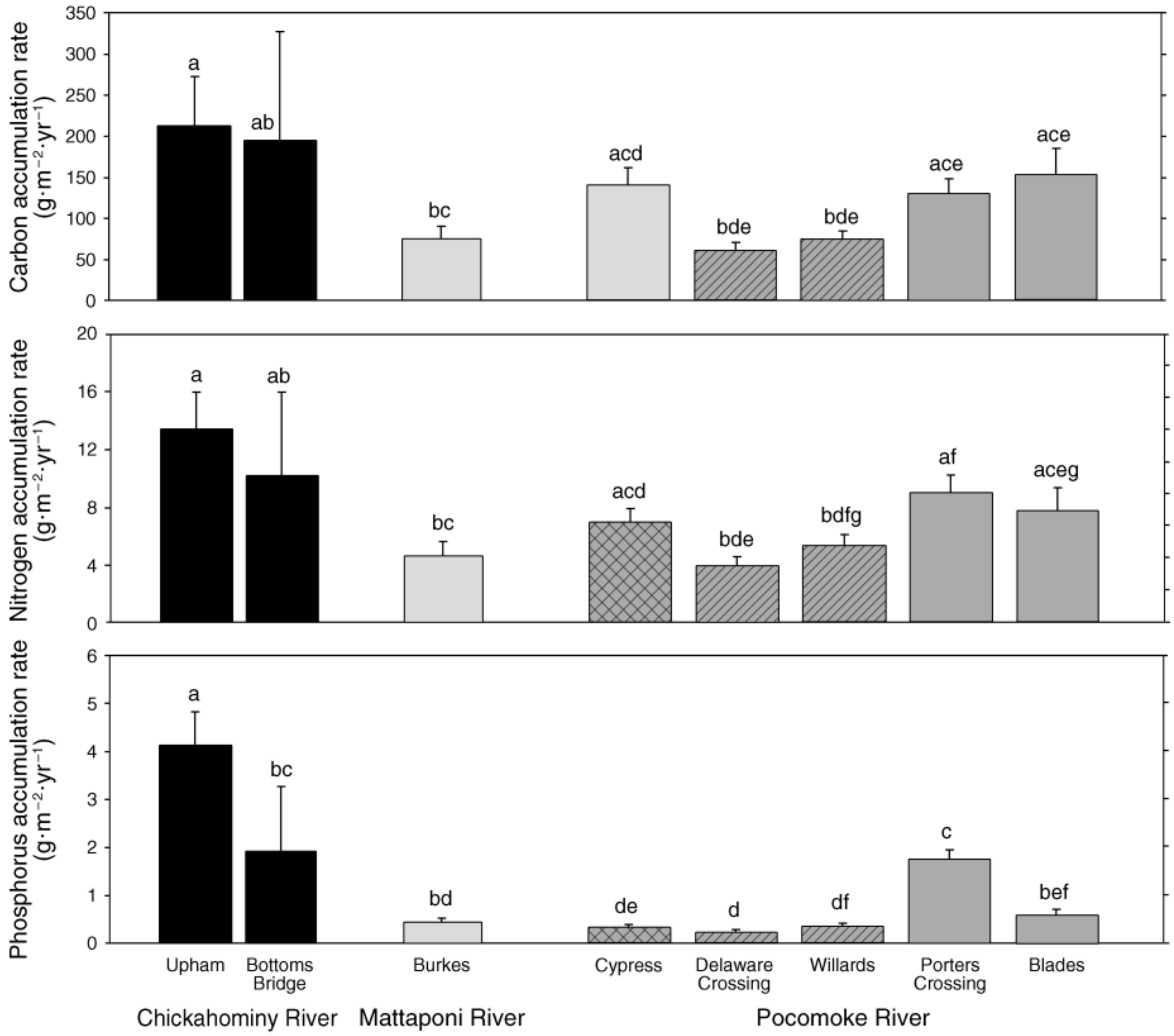

FIG. 3. Carbon, nitrogen, and phosphorus accumulation rates (mean + SE). Sites on the Pocomoke River are differentiated into headwater (crosshatch), hydraulically disconnected (slant hatch), and hydraulically connected (no hatch) floodplains. Different lowercase letters above the bars indicate a statistically significant difference ($P < 0.05$) between sites.

floodplains on the Pocomoke River and the Burkes floodplain on the Mattaponi River. In addition, N accumulation rates were greater at the connected Porters Crossing floodplain on the Pocomoke River, compared to the disconnected Delaware Crossing floodplain on the same river and the Burkes floodplain on the Mattaponi River.

Phosphorus accumulation patterns were similar to the variation in mineral sediment accumulation rates among the different floodplains. The Upham floodplain on the Chickahominy River had the greatest mineral sediment accumulation rate (Fig. 2) and also accumulated P at the fastest rate (Fig. 3). The other Chickahominy River site (Bottoms Bridge) and a connected (Porters Crossing) floodplain on the Pocomoke River gained intermediate amounts of P relative to the other sites. The Porters Crossing site accumulated 3–8 times more P than the other Pocomoke River sites, including the other connected floodplain (Blades), the headwater floodplain (Cypress), and the disconnected floodplains (Delaware Crossing and Willards). Finally, the Blades floodplain had a greater P accumulation rate than the Delaware Crossing floodplain.

Sediment C concentrations were greatest in the floodplains of the Pocomoke River (Fig. 4). In particular, the headwater Cypress floodplain had the most concentrated C in sediment, whereas the Porters Crossing sediment was least concentrated in C among the Pocomoke River floodplains. Carbon concentrations were the lowest in the Chickahominy and Mattaponi Rivers floodplain sediments.

Trends in N concentrations generally followed the trends in C concentrations. Sediment N concentrations were greatest in Pocomoke River floodplains and lowest in the floodplains of the Chickahominy and Mattaponi River floodplains (Fig. 4). Unlike for C con-

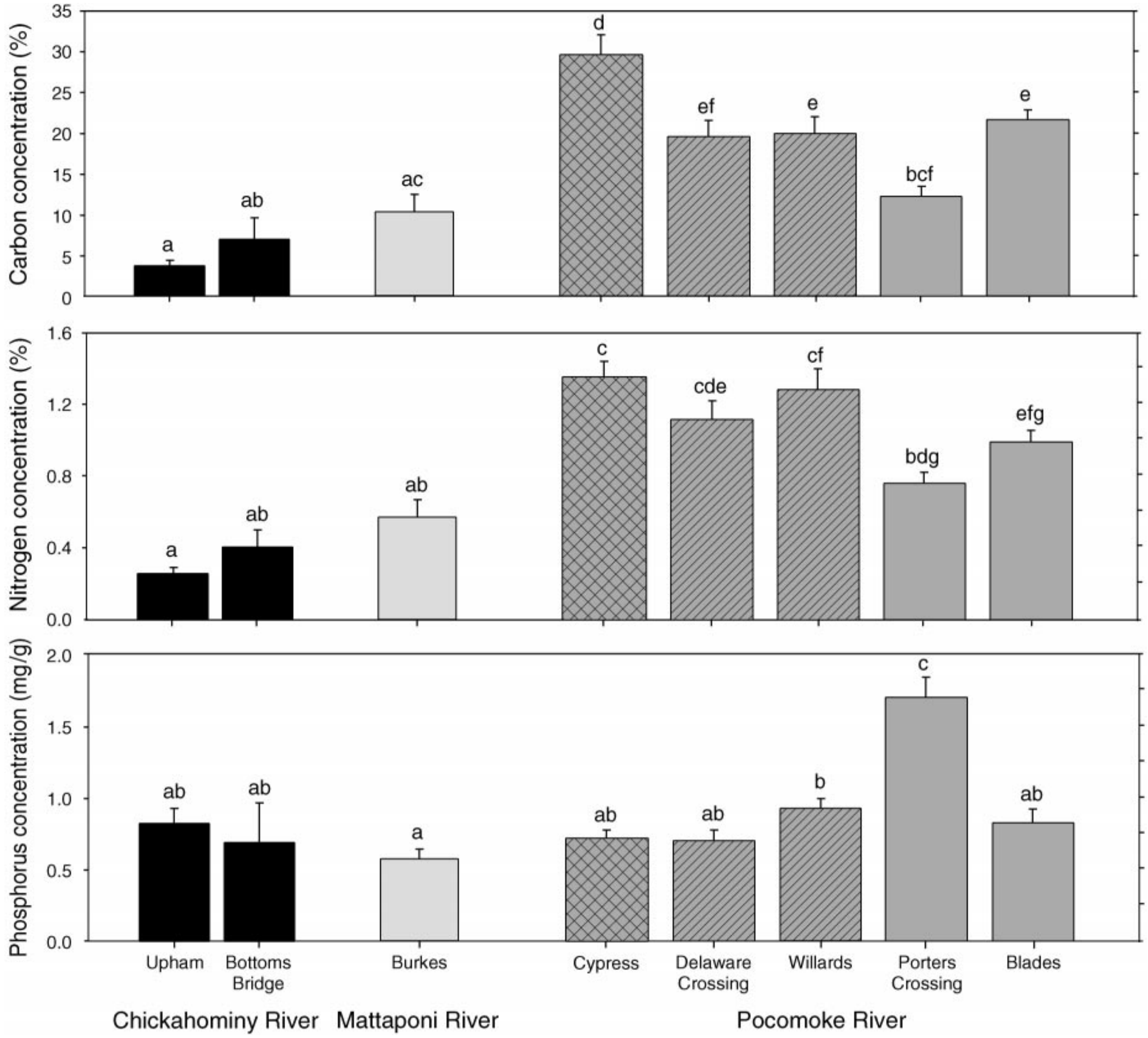

FIG. 4. Total carbon, nitrogen, and phosphorus concentrations in accumulated sediment (mean + SE). Sites on the Pocomoke River are differentiated into headwater (crosshatch), hydraulically disconnected (slant hatch), and hydraulically connected (no hatch) floodplains. Different lowercase letters above the bars indicate a statistically significant difference ($P < 0.05$) between sites.

centrations, the headwater site on the Pocomoke River had N concentrations similar to the disconnected floodplains of the Pocomoke River.

The P concentration of sediments in the Porters Crossing floodplain of the Pocomoke River was twice that of the other sites (Fig. 4). Sediment P concentrations were generally similar among the other floodplains. However, the Willards floodplain on the Pocomoke River had significantly greater sediment P concentrations than the Burkes floodplain on the Mattaponi River.

Sediment C:N ratios were generally similar among the different floodplains. Two sites had greater C:N ratios, the connected, microtidal floodplain at Blades and the headwater floodplain at Cypress, both on the Pocomoke River (Fig. 5). Otherwise, C:N ratios in the recently deposited sediment did not differ among sites.

Floodplains with higher mineral sediment accumulation rates also had lower sediment C:P ratios. The connected floodplains of the Chickahominy and Mattaponi Rivers and the connected Porters Crossing floodplain on the Pocomoke River had the lowest C:P ratios (Fig. 5) and were also sites of greater mineral sediment deposition (Fig. 2). Sediment at the headwater Cypress floodplain was most enriched in C relative to P, whereas the disconnected and microtidal floodplains on the Pocomoke River had intermediate C:P ratios.

As with sediment C:P, floodplains accumulating mineral sediment also had lower N:P ratios in this deposited sediment. The Upham floodplain on the Chicka-

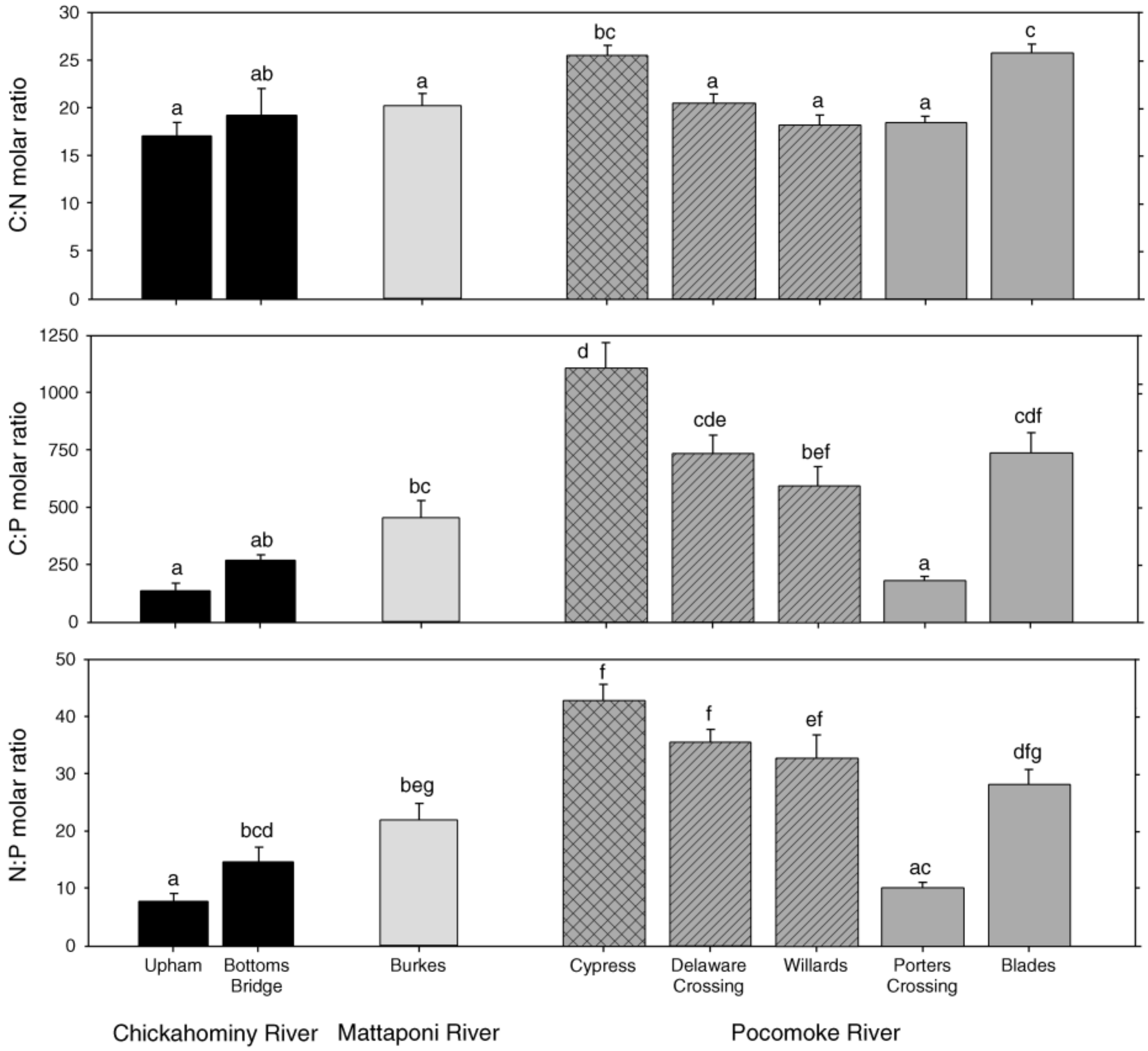

FIG. 5. Carbon:nitrogen (C:N), carbon:phosphorus (C:P), and nitrogen:phosphorus (N:P) molar ratios in accumulated sediment (mean + SE). Sites on the Pocomoke River are differentiated into headwater (crosshatch), hydraulically disconnected (slant hatch), and hydraulically connected (no hatch) floodplains. Different lowercase letters above the bars indicate a statistically significant difference ($P < 0.05$) between sites.

hominy River and Porters Crossing floodplain on the Pocomoke River had the smallest N:P ratio, and the Bottoms Bridge floodplain on the Chickahominy and Burkes floodplain on the Mattaponi River had intermediate N:P ratios (Fig. 5). The remaining Pocomoke River floodplains (headwater, disconnected, and microtidal) were enriched in N relative to P.

DISCUSSION

Methodological issues

This research successfully identified links between nutrient accumulation rates in floodplains and both watershed land use and floodplain–river hydraulic connectivity. However, the technique of quantifying nutrient accumulation by collecting sediment over feldspar marker horizons has various methodological issues. First and foremost, only the net accumulation of sediments and their associated nutrients is estimated. Gross rates of nutrient fluxes in and out of the deposited sediments are unknown, but could have large magnitudes relative to net flux.

Our estimates for medium-term nutrient accumulation may not hold for longer time horizons. First, alluvial floodplain geomorphology can be reworked by river channel migration, resulting in the downstream export of sediment and associated nutrients. For example, Arp and Cooper (2004) documented relatively equal rates of sediment deposition in floodplains and sediment erosion from riverbanks in a relatively pristine montane river system. In the Atlantic Coastal

Plain, however, sediment remobilization and lateral channel migration rates are low (Hupp 2000). Therefore, our estimates of net nutrient accumulation are likely sustainable over longer time periods, particularly for the mineral-associated forms of P. Second, the decomposition of organic matter and resultant lowering of redox potential in buried sediment likely reduce net nutrient accumulation over time. The mineralization of organic C, N, and P and desorption of inorganic P from reduced Fe minerals likely result in inorganic nutrient export to the atmosphere, groundwater, or surface water during flooding (Baldwin and Mitchell 2000). Thus under similar conditions, sites with older feldspar pads likely had lower net nutrient accumulation rates than sites with more recently installed feldspar pads. However, floodplain leaf litter decomposes rapidly ($\bar{x} = 36\%$ mass remaining after one year, calculated from Lockaby and Walbridge 1998). Thus most remaining organic matter in these three- to six-year accumulations of surficial sediments was likely recalcitrant, and the C and N were relatively stable for long time periods.

The inability to sample inundated plots potentially added bias to the estimates of nutrient accumulation. Standing water prevented collection of intact sediment cores at some locations, and these lower elevation plots may have had different sedimentation rates and nutrient concentrations than the higher, dry plots that were sampled. Sedimentation rates can be either greater or smaller in lower elevation floodplain surfaces compared to higher surfaces, with the delivery of sediment-rich water to a location strongly affecting sedimentation rates (Hupp 2000, Ross et al. 2004). Further, lower elevation surfaces are more likely to have groundwater seepage that could either add or remove nutrients from sediments. Fortunately, only a small proportion of feldspar pads were inundated at the time of sampling in most floodplain sites. At the Bottoms Bridge floodplain on the Chickahominy River, however, only three plots were exposed and could be sampled, potentially biasing the measured rates as underestimates of true nutrient accumulation. Nonetheless, the greatest coefficient of variation in nutrient accumulation rates, compared to the other floodplain sites, was observed at Bottoms Bridge (G. Noe, *unpublished data*), indicating that a broad range of conditions was sampled there.

In addition, our samples are biased toward locations with sediment deposition and avoid locations with sediment erosion; sediments could not accumulate on eroding feldspar pads. This bias skews the estimates of nutrient accumulation upward. However, only 6% of the feldspar pads were eroded, and 9% could not be located (and may have been eroded) among all the sites. Therefore nutrient accumulation rates in these Coastal Plain floodplains are only slightly affected by this bias. Sediment accumulating on feldspar pads could be derived from either the river channel or from remobilized floodplain sediments. The low frequency of eroding pads and relatively small variability in sediment deposition rates within a site indicate that the accumulating sediments came from the river channel and not sediment eroded from within the floodplain.

Last, organic matter deposited on floodplain surfaces can have both allochthonous and autochthonous origins. Identifying the relative importance of internal vs. external inputs of organic matter is difficult without concurrent estimates of litter deposition. However, differences in total organic sediment accumulation between hydraulically connected and disconnected floodplains are indicative of the relative magnitude of allochthonous organic matter inputs to floodplains. This comparison assumes that litter deposition and decomposition rates are similar in hydraulically connected and disconnected floodplains, which is unlikely given the differences in nutrient content between these types of floodplains. Regardless, organic sediment accumulation rates in the connected floodplains ranged from one (Mattaponi River), to two (Pocomoke River), to three times (Chickahominy River) that of the rates in the disconnected floodplains (Fig. 2). Patterns were similar for both C and N accumulation rates, whereas P accumulation rates in connected floodplains vastly exceeded rates in their unconnected counterparts (Fig. 3). Therefore allochthonous inputs of nutrients, nutrients captured by floodplains that otherwise would have increased nutrient loading downstream, vary from small to large amounts in different hydraulically connected floodplains.

Nitrogen vs. phosphorus accumulation

Phosphorus accumulated faster in floodplains that were capturing more mineral sediment. Sediment P concentrations did not covary with mineral sediment accumulation rates; rather, the increased P accumulation rates occurred because of the increased quantity of mineral sediment that accumulated. Phosphorus dynamics in wetlands are largely controlled by interactions between PO_4^{3-} and minerals, particularly Fe and Al (Richardson 1985, Walbridge and Struthers 1993, Axt and Walbridge 1999, Bridgham et al. 2001, but see Wright et al. 2001). In fact, total P and Fe concentrations were significantly positively correlated in the floodplain sediments ($r = 0.70$, $P < 0.001$, J. Bae and G. Noe, *unpublished data*). Other studies have also found a positive association between mineral sediment and P accumulation in floodplain wetlands (Cooper and Gilliam 1987, Johnston et al. 2001, Stoeckel and Miller-Goodman 2001).

Nitrogen accumulation, in contrast, was controlled by organic matter accumulation rates. Intersite variations in N accumulation rates were also similar to patterns of C accumulation. The small range of C:N ratios in the deposited sediment implies that N accumulation was tied to organic matter deposition and not microbial biomass uptake. Uptake and storage of inorganic N by sediment microbes during overbank flow would enrich the sediment with N relative to C, which was not observed. Brunet and Astin (1997) and Stoeckel and Miller-Goodman (2001) also found that N accumulation in floodplains was associated with organic matter deposition. In summary, this study reinforces the generalization that floodplain and wetland retention of P is associated with mineral sediment, whereas N retention is associated with organic matter.

Land-use effects

Mineral sediment accumulated faster in the floodplains of the river with an urbanizing watershed and partial Piedmont source. The Chickahominy River drains the densely populated and expanding Richmond, Virginia, metropolitan area. The greater sedimentation rates in the Chickahominy River floodplains could result from either urbanization or from the Piedmont geomorphology of its upper watershed. However, sedimentation rates in floodplains of other partial-Piedmont watersheds in the Coastal Plain that have less developed watersheds are much lower than in the urban Chickahominy watershed (C. R. Hupp, *personal observation*). In addition, the overall topography of the Chickahominy watershed is similar to the Mattaponi watershed (Table 1), which had much lower sedimentation rates. Therefore we attribute much of the increase in sediment accumulation rates to urbanization. Others also have found greater rates of mineral sediment deposition in floodplains downstream from developing areas on the Chickahominy River (Hupp et al. 1993, Ross et al. 2004) and in other watersheds (Langland and Cronin 2003). The enhanced sediment trapping on the Chickahominy floodplains indicates their importance to improving water quality in fluvial systems. This function may be of particular importance in the watersheds of the Chesapeake Bay. Submerged aquatic vegetation in the Chesapeake Bay is being strongly negatively affected by increased turbidity from suspended sediments (Carter et al. 1994, Langland and Cronin 2003). Floodplain wetlands, especially those downstream of large sediment sources such as urbanizing areas, may minimize impacts to estuarine ecosystems through their sediment-trapping function.

The effect of agricultural land use was evident in the high nutrient (particularly P) accumulation rates in the floodplain immediately downstream of the channelized Pocomoke River reach. The upper watershed of the Pocomoke River is the location of intensive poultry farms that produce large amounts of manure, a problem general to many areas of the Atlantic Coastal Plain of the United States. Disposal of this manure has been a large management issue with important water-quality implications (Sharpley et al. 2001). At the first location where overbank flow can occur on Pocomoke River floodplains (Porters Crossing site), large rates of N and P accumulation were measured. Phosphorus concentrations were particularly high, and ratios of C:P and N:P were also low in these deposited sediments, compared to other floodplain sites in the Pocomoke River watershed. The high P content of these sediments could arise from high P loading from the intensive agriculture upstream and sorption of PO_4^{3-} to abundant Fe discharged from local groundwater seeps (Bricker et al. 2003).

Effects of hydraulic connectivity

Hydraulic connectivity between main channels and floodplains clearly has a large effect on ecological processes in floodplains (Heiler et al. 1995, Mertes 1997, Tockner et al. 1999, Hupp 2000, Amoros and Bornette 2002). Hydraulic connectivity is a limiting process in determining how much floodplains can affect riverine nutrient transport. The loading rate of material onto floodplains determines the upper bound on potential nutrient processing and accumulation rates by floodplains. This loading rate is determined by both hydraulic connectivity and material load in the main channel. Hydraulic connectivity, in turn, is controlled by flood hydrology and floodplain-channel geomorphology. Mertes (1997) presents the concept of the perirheic zone as the area of floodplain inundated by river water during flooding. The geomorphology of floodplain levees and backswamps, and the flood hydrograph, control which areas of floodplains are inundated by river water vs. groundwater or local runoff (ibid.). Thus sediment accumulation rates in floodplains should be strongly affected by the size and location of the perirheic zone. In fact, sedimentation rates in floodplains are highest in areas with a direct flow path to the river (Hupp 2000, Piégay et al. 2000, Ross et al. 2004).

In the case of the Pocomoke River, anthropogenic reductions in the perirheic zone have reduced nutrient and sediment accumulation rates in floodplains. The floodplain sites that were hydraulically disconnected from the river by channelization and levees tended to have lower mineral sediment, organic sediment, C, N, and P accumulation rates compared to the hydraulically connected sites along the Pocomoke River. Similarly, Ross et al. (2004) and D. E Kroes and C. R. Hupp (*unpublished manuscript*) found that sediment deposition in Pocomoke River floodplains was focused in the nonchannelized section of the watershed. These findings strongly support our hypothesis that reduced hydraulic connectivity would decrease nutrient accumulation rates in floodplains. Similarly, Craft and Casey (2000) found that floodplain wetlands sequester 1.5 times more P than nonfluvial wetlands. The empirical evidence indicates that decoupling floodplains from flooding minimizes the capacity of floodplains to remove nutrients and sediments from riverine systems and thus mediate water quality.

The headwater site on the Pocomoke River, with a largely groundwater-dominated hydrology, also had low mineral sediment and P accumulation rates, compared to the hydraulically connected floodplains lower in the watershed. The high C:P ratio and moderately

TABLE 2. Nutrient accumulation rates (g·m^{-2}·yr^{-1}) in floodplains and mineral-soil wetlands.

Study	Wetland type	Nutrient accumulation (g·m^{-2}·yr^{-1})		
		Carbon	Nitrogen	Phosphorus
This study	hydraulically connected alluvial floodplain	74–212	4.2–13.4	0.44–4.13
This study	hydraulically disconnected alluvial floodplain	61–74	3.5–4.8	0.22–0.35
Craft and Casey (2000)	blackwater floodplain	18	1.4	0.12
Yarbro (1983)	blackwater floodplain	···	···	0.17
Brinson et al. (1980)	alluvial floodplain†	278	7.3	0.54
Brown (1978)	alluvial floodplain	···	···	3.2
Mitsch et al. (1979)	alluvial floodplain	···	···	3.6
Johnston (1991)	mineral soil wetlands	···	14.6	1.5

† Nutrient accumulation as litterfall.

high C:N ratios indicate that nutrient availability is lower in the sediments of the headwater site, compared to the other hydraulically connected floodplains downstream. Thus we conclude that the downstream hydraulically connected floodplains of the Pocomoke River have received P subsidies deposited from overbank flow.

River nutrient load reduction

The nutrient-trapping function of floodplains may contribute to a moderate reduction of nutrient loading to the Chesapeake Bay. A sufficient number of sites were sampled on the Pocomoke River to roughly estimate total nutrient load accumulation in floodplains along the length of the main channel between the upstream and downstream sites. Total floodplain annual N and P accumulation along the Pocomoke River channel was estimated from mean N and P accumulation rates at each site, estimates of floodplain width at each site and channel length between sites (measured from topographic maps), and linear interpolation of nutrient accumulation rates between sites. Annual river loads of N and P are not measured in the Pocomoke River; instead, they were estimated using SPARROW (SPAtially Referenced Regression On Watershed Attributes; *available online*)[2] predictions (see Smith et al. 1997). Floodplains along the Pocomoke River currently remove an estimated 8% of the annual riverine load of both N and P. If the floodplains of the upper Pocomoke River basin were hydraulically reconnected to the river channel (estimated by applying nutrient accumulation rates from the hydraulically connected sites), we predict that annual N and P load removal would increase to 9% and 10%, respectively. The relatively small increase in nutrient load reduction following hydraulic reconnection is due to the narrower width of floodplains in the upper Pocomoke River watershed. Nonetheless, restoring the hydraulic connectivity of disconnected floodplains would reduce riverine nutrient loading to the Chesapeake Bay and other water bodies.

[2] ⟨http://water.usgs.gov/nawqa/sparrow/⟩

Nutrient accumulation rate comparisons

The rates of nutrient accumulation that we observed in alluvial floodplains of the Atlantic Coastal Plain of Virginia and Maryland are similar to rates in other floodplains. The range in mean P accumulation rates at our hydraulically connected sites is higher than measured values for blackwater floodplains but spans the range of values for alluvial floodplains and mineral-soil wetlands, in general (Table 2). Nitrogen accumulation rates in the connected floodplains of this study were also greater than rates in a blackwater floodplain and similar to those in an alluvial floodplain, but lower than for mineral-soil wetlands in general. Likewise, C accumulation rates in the connected floodplains of this study were greater than in a blackwater floodplain and similar to an alluvial floodplain. Nutrient accumulation rates in our hydraulically disconnected sites were much lower than in other alluvial floodplains, but still greater than in blackwater floodplains (Table 2).

CONCLUSIONS

This study documented rates of nutrient accumulation in the floodplains of rivers with different watershed land use and anthropogenic alterations in hydrology. Patterns of N accumulation were strongly correlated with organic matter deposition, whereas P accumulation was strongly correlated with mineral sediment deposition. In addition, floodplains downstream from an urbanizing watershed had the highest rates of sediment and nutrient deposition. The floodplain immediately downstream from intensive agriculture was the location of the highest rate of P accumulation in the watershed, mostly due to greater sediment P concentrations. Furthermore, reduced hydraulic connectivity between floodplains and rivers limited sediment and nutrient accumulation rates in floodplains. These findings indicate that floodplains function as an important nutrient sink in fluvial hydroscapes. Hydrologic disconnections put in place for flood control reduce the magnitude of this water-quality function, indicating that restoring flood pulses to floodplains can reduce downstream nutrient loading from rivers.

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