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Increased Terrestrial to Ocean Sediment and Carbon Fluxes in the Northern Chesapeake Bay Associated With Twentieth Century Land Alteration

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Abstract We calculated Chesapeake Bay (CB) sediment and carbon fluxes before and after major anthropogenic land clearance using robust monitoring, modeling and sedimentary data. Four distinct fluxes in the estuarine system were considered including (1) the flux of eroded material from the watershed to streams, (2) the flux of suspended sediment at river fall lines, (3) the burial flux in tributary sediments, and (4) the burial flux in main CB sediments. The sedimentary maximum in *Ambrosia* (ragweed) pollen marked peak land clearance (~1900 A.D.). Rivers feeding CB had a total organic carbon (TOC)/total suspended solids of 0.24±0.12, and we used this observation to calculate TOC fluxes from sediment fluxes. Sediment and carbon fluxes increased by 138–269% across all four regions after land clearance. Our results demonstrate that sediment delivery to CB is subject to significant lags and that excess post-land clearance sediment loads have not reached the ocean. Post-land clearance increases in erosional flux from watersheds, and burial in estuaries are important processes that must be considered to calculate accurate global sediment and carbon budgets.

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Introduction

River-borne carbon represents a major link in the global carbon cycle between terrestrial sources and oceanic sinks (Sarmiento and Sundquist 1992; McKee 2003). Global carbon budget models estimate the flux of atmospheric carbon carried by rivers to be ~8×10^8 metric tons (t) C year^{-1} (1 metric ton=1,000 kg), about half of which is organic carbon (Schlesinger and Melack 1981; Meybeck 1982; McKee 2003). This value represents a significant proportion of the ~2×10^9 t of anthropogenic carbon taken up annually by the world's oceans (Siegenthaler and Sarmiento 1993; Sabine et al. 2004). Verifying model estimates of the amount of river-borne carbon reaching the ocean is difficult at present due to limited knowledge of spatial and temporal relationships between sub-environments in the watershed–river–estuary–ocean continuum (McKee 2003). Improving estimates of carbon fluxes in these sub-environments represents a critical step toward a more accurate understanding of the global carbon cycle.

Fluvial carbon fluxes are related to sediment loads in rivers (Lal 2003), which vary with watershed geomorphology, soil erodibility, river discharge, land cover, and soil conservation practices (Renard et al. 1997). The relative importance of these factors varies between different river systems, leading to large heterogeneities in terrestrial to ocean fluvial carbon fluxes (Meybeck and Vörösmarty 2005). For example, the total organic carbon (TOC) content of river-borne sediments is thought to range from 1.6% to 6% (Meybeck 1982), and estimates of the annual TOC transport by rivers vary from 1.9×10^8 to 1.0×10^9 t (Lal 2003). Furthermore, determining the fate of fluvial carbon and sediment is complicated by variations in burial, remobilization, and transformation that lead to downstream transport times of months to 10^6 years (Meade 1988; Stallard 1998; Trimble 1999).

In recent centuries, human alteration of river systems has become a major influence on fluvial variability (Meybeck and Vörösmarty 2005), but land clearance is rarely considered in global carbon budgets. Conversion of natural vegetation for agriculture and other land uses can increase fluvial sediment and carbon fluxes (Meade et al. 1990; Houghton et al. 1999; Syvitski et al. 2005). Such increases may be partially or totally offset by reduced sediment and carbon fluxes associated with soil conservation programs (Walling 2006) and burial behind dams (Renwick et al. 2005).

Given the large variations that exist between fluvial systems, accurate estimates of global river-borne sediment and carbon fluxes should be constructed from the sum of fine resolution studies. Furthermore, separating anthropogenic and natural forcings at the watershed scale may help determine the impact of climatic factors on fluvial processes (Howarth et al. 1991; Miller and Russell 1992) and may permit more accurate predictions of future changes in sediment and carbon fluxes. Accurate depictions of river-borne sediment and carbon processes require long records of reliable monitoring data that are rarely available for major world rivers (Milliman and Syvitski 1992; Walling 2006). An exception to this is the Chesapeake Bay (CB), where excellent monitoring of river discharge, sediment loads, and carbon concentrations exists. In this paper, we combine monitoring data with the sedimentary record of northern CB to describe sediment and carbon fluxes across four watershed sub-environments. A sophisticated watershed model and a sedimentary pollen horizon that is indicative of peak colonization allow us to compare natural and anthropogenically altered conditions. Our results suggest marked increases in CB sediment and carbon fluxes since colonial settlement.

Regional Setting

The physiographically diverse and partially deforested CB watershed (Fig. 1) is uniquely suited for estimating changes in sediment and carbon fluxes after land clearance. CB is the largest estuary in the USA with a length of ~300 km, a surface area of 6,500 km^2, and a watershed area of 166,000 km^2 (Schubel and Pritchard 1986). It is a partially mixed, stratified estuary with a large oceanic influence in the south near its mouth and a terrestrial influence in the north where the Susquehanna River enters the bay (Pritchard 1967; Langland and Cronin 2003). We focused on the northern half of the CB and associated Appalachian Mountain, Piedmont, and Coastal Plain watersheds, which are far removed from any oceanic influence.

Land use in the northern CB before the seventeenth century was influenced only by climate and relatively minor Native American agriculture (Chapelle et al. 1986; Fig. 2). Major European settlement and associated land clearance for timber and agriculture occurred during the seventeenth century (Brugger 1988). By 1840, land clearance had increased in the northern CB to 40–50% (Brush 1984), and reached 80% by ~1900 (Brugger 1988; Brush 1989). Agricultural land use declined during the twentieth century (31% today), while forested and urban land areas increased (58% and 4%, respectively; http://www.chesapeakebay.net/wshed.htm).

Methods

Multiple independent sources of long-term CB data allow sediment and carbon fluxes to be estimated at four distinct stages between their terrestrial sources and estuarine sink. The fluxes considered are (1) the erosional flux from CB watershed land surfaces to rivers and tributaries, (2) the fluvial sediment flux at river fall lines, (3) the flux from fluvial load to deposition in tributaries, and (4) the flux from the water column to burial in the main CB estuary. Hereafter, we refer to these four stages as “watershed,” “fall line,” “tributary,” and “CB estuary.” Our approach first estimates sediment fluxes at each stage and then applies empirical sediment–carbon relationships derived from monitoring data to calculate carbon fluxes.

Sediment Fluxes

To contrast sediment flux under natural forested land cover with more recent partially deforested conditions, we compare fluxes before and after peak land clearance. The pre-land clearance period was defined as 1000–1900 A.D., while the post-land clearance period was defined as the time since 1900 A.D. The division between these intervals was defined as the horizon of maximum *Ambrosia* (ragweed) pollen, which is clearly marked in sediment cores near ~1900 A.D. (Brush 1984; Willard et al. 2003). Radiocarbon dates (Willard et al. 2003; Cronin et al. 2005) constrained the age of sediments that accumulated ≥500 years ago. Annual pre- and post-land clearance sediment fluxes in the northern CB were then computed in metric tons per year (t year^{-1}) for each of the four regions (watershed, fall line, tributary, and CB estuary).

Pre- and post-land clearance watershed fluxes were estimated using Phase 4.3 of the Chesapeake Bay Program

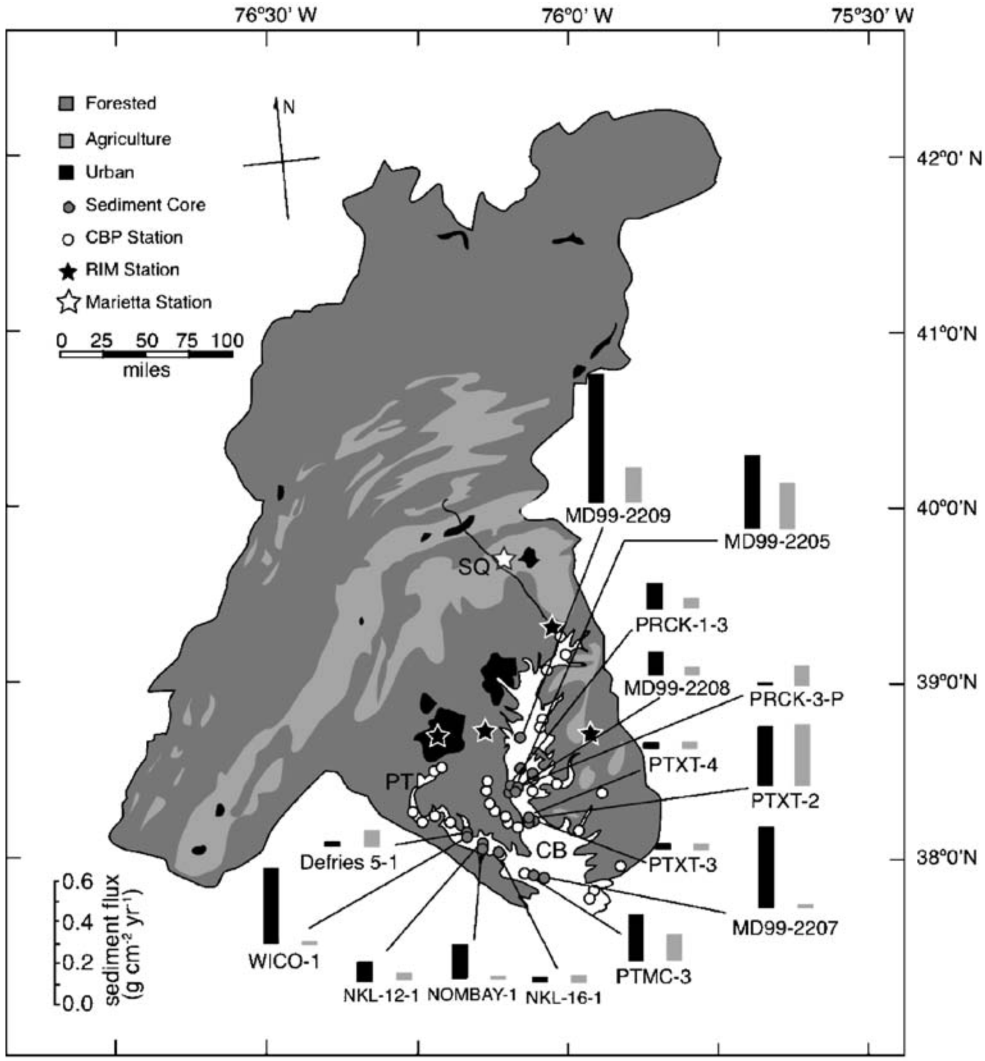

Fig. 1 Generalized land-use map of the northern Chesapeake Bay (*CB*) and its watershed. Shown are the locations of Chesapeake Bay program (*CBP*) monitoring stations (*white circles*), USGS River Input Monitoring (*RIM*) stations (*black stars*), and the locations of sediment cores (*gray circles*) used in pre- and post-land clearance sediment and carbon flux calculations. *Vertical bars* indicate pre-land clearance (*left*, *black*) and post-land clearance (*right*, *gray*) sediment burial flux in g cm year^{-1}. The Susquehanna (*SQ*) and Potomac (*PT*) rivers are also shown

(CBP) Community Watershed Model (CWM4.3; http://www.chesapeakebay.net/temporary/mdsc/community_model/). This model calculates sediment flux to tributaries based on the erosion rates from different CB land surfaces (Linker et al. 2000). The land uses considered in CWM4.3 include cropland, pasture, forests, and urban areas. Forested land in CWM4.3 has a mean erosion rate of 0.02 t ha^{-1} year^{-1} and an erosion rate range from 0.01 to 0.04 t ha^{-1} year^{-1}. Pasture, crop, and hay land erosion rates range from 0.07 to 0.49 t ha^{-1} year^{-1} in CWM4.3, with an area-weighted average of 0.2 t ha^{-1} year^{-1}. We used this average value to represent all agricultural land and did not consider urban lands. All scenarios used a sediment delivery ratio (SDR) of 0.15 (Linker et al. 2000). SDR is a dimensionless term defined as the sediment yield divided by the erosion over a given area and time span (cf. Walling 1983).

Watershed sediment fluxes were calculated by multiplying erosion rates described above by the appropriate area of forested or agricultural land (Table 1). The pre-land clearance scenario assumed 100% forest cover, which is

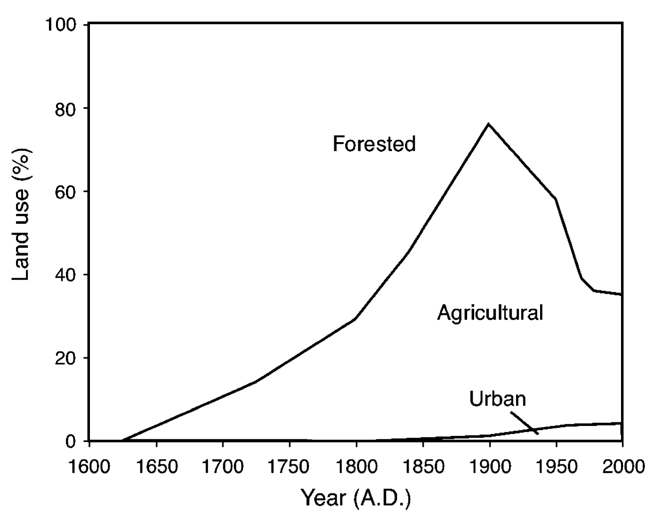

Fig. 2 Generalized CB land use history expressed as the percentage of total watershed area

Table 1 Northern Chesapeake Bay land areas used in sediment flux calculations

	Total area (km^2)	Total area (ha)	Forested (ha)	Agricultural (ha)	Wetlands and tributaries (km^2)	Fine sediment accumulation (km^2)
Pre-land clearance	1.29×10^5	7.86×10^7	7.86×10^7	0	2,830	1,840
Post-land clearance	1.29×10^5	7.86×10^7	4.45×10^7	2.45×10^7	2,830	1,840

Northern CB areas used to calculate sediment fluxes. Total area, forested area and agricultural area are used for calculations in the watershed region. The area of wetland and tributaries is used for calculations in the tributary region. The area blanketed by fine sediment is used for calculations in the CB estuary region. Total, forested, agricultural, wetland, and tributary areas are from http://www.chesapeakebay.net/wspv31/(psuw1d55upnl1e55rc2i55ie)/WspAbout.aspx?basno=1&topic=5. The area accumulating fine sediment uses data from (Cronin 1971; Kerhin et al. 1988).

equivalent to 7.86×10^7 ha. The post-land clearance scenario summed data from five northern CB sub-watersheds (Susquehanna, Potomac, Maryland western shore, Patuxent, and Maryland eastern shore) to estimate modern watershed land areas of 4.45×10^7 forested hectares and 2.45×10^7 agricultural hectares (http://www.chesapeakebay.net/wshed.htm). Furthermore, we estimated the uncertainty of pre- and post-land clearance watershed sediment fluxes by multiplying each period's forested and agricultural land areas by maximum and minimum forested (0.01 and 0.04 t ac^{-1} $year^{-1}$) and agricultural (0.07 and 0.49 t ha^{-1} $year^{-1}$) erosion rates (Table 2).

Fall line sediment fluxes were determined from monitoring of total suspended solids (TSS) in major CB rivers and smaller tributaries (Darrell et al. 1999). Pre-land clearance TSS loads at the fall line were estimated by Brown et al. (1988) from ^{10}Be accumulation in soils and were crosschecked with TSS data from 45 US Geological Survey (USGS) monitoring stations. Brown et al. (1988) determined pre-colonial sediment yield to be 1.0 ± 0.2 mg cm^{-2} $year^{-1}$ in mid-Atlantic Piedmont regions (Table 2). This value was multiplied by the CB watershed land area (Table 1) and converted to units of t $year^{-1}$. Our post-land clearance fall line sediment flux was calculated by adding the average annual TSS load measured in Susquehanna, Potomac, Patuxent, and Choptank Rivers for the period 1985–1996 (Darrell et al. 1999). The variability of post-land clearance fall line sediment flux was estimated from the mean TSS load during the 3 years of highest (1993, 1994, and 1996) and lowest (1988, 1991, and 1995) total river discharge. Seasonal extremes in discharge and TSS were not considered.

Tributary sediment fluxes were computed from the stratigraphy of cores dated by radiogenic isotopes (^{14}C, ^{210}Pb, and ^{137}Cs) and by pollen abundance tied to historical land use change (Brush 1984). The linear sediment accumulation rate during the pre-land clearance period below the *Ambrosia* pollen horizon was estimated to be 0.14 cm $year^{-1}$ (Brush 1984). Multiplying this sedimentation rate by a mean bulk density 0.54 g cm^{-3} for sediment stratigraphically below the *Ambrosia* pollen peak (Zimmerman and Canuel 2000) yielded a mean pre-land clearance mass accumulation rate (MAR) of 0.076 ± 0.027 g cm^{-2} $year^{-1}$ (Table 2). The mean post-land clearance MAR was estimated to be 0.200 ± 0.015 g cm^{-2} $year^{-1}$ under 40–50% cleared conditions (Brush 1984). Pre- and post-land clearance MARs were multiplied by the modern northern CB tributary and wetland area (2,830 km^2) estimated by the CBP and converted to units of t $year^{-1}$ (Table 1).

CB estuary sediment fluxes were calculated using 15 sediment cores in the CB main channel and larger tributaries (Potomac, Patuxent, and Pocomoke Sound; Langland and Cronin 2003; Fig. 1). Pre-land clearance mean sediment accumulation rates were calculated in each core from the thickness of sediment between the *Ambrosia* horizon and the radiocarbon age closest to 1,000 years BP (Cronin et al. 2000, 2005; Colman et al. 2002). If calibrated radiocarbon dates near 1,000 A.D. were not available, the 1,000 A.D. core depth horizon was estimated by linearly interpolating between depths dated nearest 1,000 years B.P. Multiplying the mean pre-land clearance sedimentation rate of the 15 cores by a mean bulk density of 0.54 g cm^{-3} (Zimmerman and Canuel 2000) yielded a mean pre-land clearance MAR of 0.104 g cm^{-2} $year^{-1}$. A mean post-land clearance sediment accumulation rate was calculated from the average thickness of sediment above the *Ambrosia* peak. This sedimentation rate was multiplied by a mean dry bulk density of 0.34 g cm^{-3} for sediment stratigraphically above the *Ambrosia* peak (Zimmerman and Canuel 2000) to estimate a post-land clearance MAR of 0.288 g cm^2 $year^{-1}$. Shoreline contributions can significantly alter CB sediment accumulation (Langland and Cronin 2003), and we adjusted MARs assuming shoreline contributions of 0–40%. Final pre- and post-land clearance MARs were 0.083 ± 0.021 g cm^2 $year^{-1}$ and 0.230 ± 0.058 g cm^2 $year^{-1}$ (Table 2). Pre- and post-land clearance MARs were multiplied by the area of the northern CB blanketed by fine-grained sediment (1,840 km^2) and then converted to units of t $year^{-1}$ (Table 1). The area blanketed by fine-grained sediment was calculated by multiplying the northern CB area of deep channels capable of accumulating fine sediment (3,479 km^2) by the 53% of the northern CB mapped as silt, clay, and sand–silt–

Table 2 Data used to calculate sediments fluxes for watershed, fall line, tributary, and CB estuary regions

	Watershed		Fall line				Tributary		CB estuary	
	Pre-land clearance	Post-land clearance	Pre-land clearance	Post-land clearance: 1985–1996 average	Post-land clearance: Wet year average (1993, 1994, 1996)	Post-land clearance: Dry year average (1988, 1991, 1995)	Pre-land clearance	Post-land clearance	Pre-land clearance	Post-land clearance
Flux from forested land (t $year^{-1}$)										
Best	1.59×10^6	0.92×10^6								
Upper	2.86×10^6	1.66×10^6								
Lower	0.64×10^6	0.37×10^6								
Flux from agricultural land (t $year^{-1}$)										
Best	0	4.94×10^6								
Upper	0	11.90×10^6								
Lower	0	1.68×10^6								
Total watershed sediment flux (t $year^{-1}$)										
Best	1.59×10^6	5.86×10^6								
Upper	2.86×10^6	13.50×10^6								
Lower	0.64×10^6	2.05×10^6								
Sediment yield (mg cm^{-2} $year^{-1}$)										
Best			1.0							
Upper			1.2							
Lower			0.8							
TSS load (t $year^{-1}$)										
Susquehanna				1.18×10^6	2.82×10^6	4.13×10^6				
Potomac				1.84×10^6	3.26×10^6	8.59×10^5				
Patuxant				2.52×10^4	3.45×10^4	1.54×10^4				
Choptank				2.29×10^3	4.16×10^3	9.78×10^2				
Total fall line sediment flux (t $year^{-1}$)										
Best			1.29×10^6	3.05×10^6	–	–				
Upper			1.54×10^6	–	6.12×10^6	–				
Lower			1.03×10^6	–	–	1.29×10^6				
MAR (g cm^{-2} $year^{-1}$)							0.076±0.027	0.200±0.015	0.0832±0.021	0.2304±0.058
Total tributary sediment flux (t $year^{-1}$)										
Best							2.15×10^6	5.66×10^6		
Upper							2.91×10^6	6.08×10^6		
Lower							1.39×10^6	5.24×10^6		
Total CB estuary sediment flux (t $year^{-1}$)										
Best									1.53×10^6	4.24×10^6
Upper									1.84×10^6	5.09×10^6
Lower									1.22×10^6	3.39×10^6

Data used to calculate pre- and post-land clearance sediment flux in each of the four regions. Watershed fluxes multiply CBP4.3 forested and agricultural erosion rates by total watershed area (Table 1) and sum them. Pre-land clearance fall line fluxes multiply the accumulation rates of Brown et al. (1988) by total watershed area. Post-land clearance fall line fluxes sum the annual-average TSS loads of the Susquehanna, Potomac, Patuxant and Choptank rivers (Darrell et al. 1999). Tributary fluxes multiply the MAR of Brush (1984) by the CB wetland and tributary area. CB estuary fluxes multiply sediment core MAR by the area blanketed by fine sediment. "Best" total sediment fluxes use central input parameter values, while "Upper" ("Lower") sediment fluxes are calculated from maximum (minimum) input parameters values.

clay (Cronin 1971; Kerhin et al. 1988; http://www.mgs.md.gov/coastal/vmap/baysed.html).

Carbon Fluxes

We estimated organic carbon fluxes (g C year^{-1}) from sediment fluxes using empirical relationships between organic carbon and TSS. Dissolved, particulate, and total organic carbon (DOC, POC, and TOC, respectively) and TSS data were compiled from annual averages of CBP data between 1984 and 2002 (http://www.chesapeakebay.net). Mean POC/TSS was 0.04±0.02, while DOC/POC was 5.71±3.11. TOC/TSS was 0.24±0.12, which is similar to a value of 0.25±0.24 estimated from USGS River Input Monitoring (RIM) stations between 1979 and 2002 (n= 3,626; Fig. 1). TOC fluxes were estimated by multiplying pre- and post-land clearance watershed, fall line, tributary, and CB estuary sediment fluxes by 0.24±0.12.

Results

Independent sediment fluxes for watershed, fall line, tributary, and CB estuary regions were remarkably consistent during both pre- and post-land clearance intervals (Table 2; Fig. 3). Best estimates of pre-land clearance sediment flux ranged from 1.53×10^6 to 2.15×10^6 t year^{-1}, whereas post-land clearance values were between 3.05×10^6 and 5.86×10^6 t year^{-1}. The range in sediment flux estimates was typically ±40–50% of the best estimate. Post-land clearance sediment fluxes were greater than those for pre-land clearance at all four locations. Our best estimates of fall line, tributary, and CB estuary sediment flux increased by 138%, 163%, and 177%, respectively. The increase from pre- to post-land clearance periods was greatest (269%) for watershed sediment fluxes, though this region also had the greatest range of sediment fluxes during both pre- and post-land clearance intervals.

Carbon fluxes in the four regions ranged from 0.31 to 0.52×10^6 t year^{-1} during the pre-land clearance period and from 0.73 to 1.41×10^6 t year^{-1} during the post-land clearance period. (Table 3; Fig. 2). Our method leads to increases in carbon fluxes from pre- to post-land clearance periods that are proportional to increases in sediment fluxes. Converting carbon fluxes to unit area contributions for the entire CB watershed yielded pre- and post-land clearance values of 3.1±1.1 and 8.8±4.4 t C km^{-2} year^{-1}.

Discussion

Several sources of uncertainty contribute to the range in sediment and carbon flux estimates obtained by the different methods at each of the four stages. For the pre-land clearance period, watershed erosion values may underestimate actual sediment accumulation if an SDR of 0.15 is conservative but may overestimate sediment accumulation if the average global SDR of 0.10 (Walling 2006) is representative of CB. The relative paucity of radiocarbon-dated cores from tributaries, as compared to the main CB estuary, also adds to the uncertainties in the pre-land clearance sediment flux estimate for these habitats.

Within the post-land clearance period, sediment loads may be underestimated if a greater proportion of eroded sediment is stored in uplands or if early twentieth century fall line TSS was greater than the 1985–1996 mean because of greater agricultural land use. Additionally, fall line sediment fluxes may not accurately reflect the entire post-land clearance period if 1985–1996 monitoring data are not representative of twentieth century climatic and hydrologic variability. Tributary post-land clearance sediment flux estimates exceeded watershed and fall line values, suggesting that sediment transport from the coastal plain province below the fall line was not captured by our method. Furthermore, a large but unknown quantity of sediment eroded during early colonial land clearance is trapped in low-lying coastal areas and causes lagged sediment delivery to tributaries (Defries 1986). Within the main CB estuary, post-land clearance sediment burial may be overestimated at near-shore core sites where shoreline erosion contributes more than 20% of the sediment (Langland and Cronin 2003).

It must be emphasized that pre- and post-land clearance sediment flux estimates represent mean conditions for the intervals from ~1000 to 1900 A.D. and from 1900 A.D. to present. On annual timescales sediment fluxes are strongly influenced by extreme precipitation events such as floods and hurricanes as illustrated by the sevenfold increase in sediment flux associated with Hurricane Agnes in 1972 (Langland and Cronin 2003). Sediment fluxes are also affected by decadal variability in twentieth century reforestation/urbanization and lags in sediment transport. Our method smoothes out annual to decadal variability and is not able to assess the causes of high-frequency changes in sediment and carbon flux.

Nonetheless, our results indicate that sediment flux after land clearance was ~2.4 to 3.7 times greater than mean pre-land clearance flux. While both climate and land use changes can influence sediment fluxes (Howarth et al. 1991), CB paleoclimate reconstructions suggest slightly wetter conditions before 1900 A.D. (Cronin et al. 2003, 2005; Saenger et al. 2006) that are inconsistent with lower sediment transport at that time. Changes in land use are a more likely mechanism for the increase in sediment flux, and our results are consistent with previous studies suggesting land clearance increased sediment flux to tributaries and the estuary (Defries 1986; Meade et al.

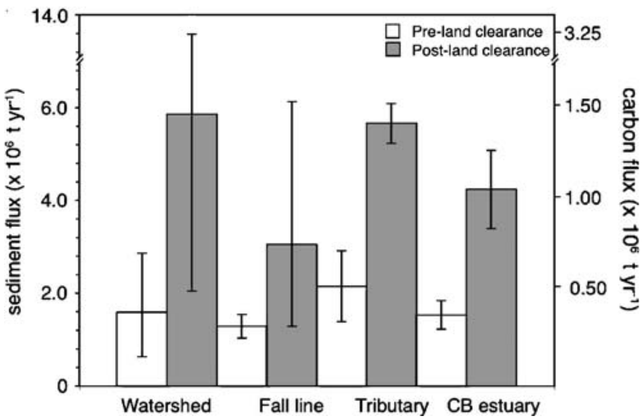

Fig. 3 Pre-land clearance (*light gray*) and post-land clearance (*dark gray*) sediment and carbon fluxes (*left* and *right y*-axis, respectively) in watershed, fall line, tributary, and CB estuary regions. *Vertical bars* reflect the potential range in sediment fluxes described in "Methods." Conversion to TOC assumes TOC/TSS is 0.24

1990). Furthermore, the magnitude of our post-land clearance sediment flux increase generally agrees with evidence for a tenfold increase in northern CB sediment accumulation due to anthropogenic land alteration (Barros and Gordon 2002).

Sediment fluxes increase from the pre- to post-land clearance period in all regions despite recent reforestation, dam construction, and soil conservation efforts. This trend supports evidence for multi-decadal lags in sediment delivery to the main estuary due to burial in alluvium, colluvium, and lakes (Stallard 1998; Trimble 1999). Furthermore, the uniform increase in sediment flux across all regions indicates that the volume of sediment trapped behind dams (Langland 1998) is far outweighed by larger sediment fluxes associated with land clearance.

Monitoring data from other river systems supports the accuracy of our conversion of sediment fluxes to carbon fluxes. Global fluvial carbon data indicate that the POC/TSS value of 0.04 found in northern CB broadly represents major rivers, which have values ranging from 3.5 to 6.5% (Ittekkot and Laane 1991). Our DOC/POC of 5.71 is also typical for systems such as the CB in which POC comprises ~1.3 to 8.4% of TSS (Meybeck 1982; Ittekkot and Laane 1991). Propagating the uncertainties in sediment fluxes and TOC/TSS relationships yields carbon flux errors that are equivalent to differences between pre- and post-land clearance periods. However, both pre- and post-land clearance estimates are subject to the same TOC/TSS calibration errors, and we consider the relative differences between the periods to be meaningful.

Our estimated post-land clearance increase in TOC flux is consistent with carbon isotopic evidence for greater terrestrial input to CB since ~1750 A.D. (Bratton et al. 2003) and with an up to fivefold increase in bay TOC since ~1915 (Zimmerman and Canuel 2002). However, these increases in TOC cannot be attributed entirely to land use changes. Recent increases in sediment and carbon fluxes have been accompanied by more frequent CB eutrophication and hypoxia (Cooper and Brush 1991; Karlsen et al. 2000; Colman and Bratton 2003; Kemp et al. 2005), which could increase TOC by increasing aquatic productivity and preservation of organic matter. Attempts to account for these influences still estimate a 150–300% increase in TOC since ~1915 A.D. (Zimmerman and Canuel 2002), which agrees well with our calculated increase of 138–269%.

The increased post-land clearance fluxes in the CB estuary suggest that sediment and carbon mobilized by land alteration largely remains trapped in the bay. CB sediment budgets indicate that the central bay is a sediment sink (Hobbs et al. 1992; Langland and Cronin 2003), and it is likely that post-land clearance POC is also buried in this region. On the other hand, CB water has a residence time of 7.6 months (Dettman 2001), suggesting that DOC could be exported relatively rapidly from the estuary. However, the actual residence time of DOC is likely somewhat longer than that of water due to carbon cycling associated with autochthonous production, bacterial respiration, flocculation, burial, and resuspension (Raymond and Bauer 2001). Uncertainties in these processes prevent the residence time of CB carbon from being estimated robustly, but it is likely that post-land clearance carbon is sequestered, at least temporarily, rather than being directly transported to the ocean.

Globally, anthropogenic land clearance has also increased fluvial sediment flux but not sediment delivery to coastal regions (Syvitski et al. 2005). This suggests that other coastal environments respond to human land disturbance in a similar way as CB. If this is the case, increases in

Table 3 Total organic carbon fluxes for watershed, fall line, tributary, and CB estuary regions

	Carbon flux ($\times 10^6$ t year^{-1})		
	Best	Upper	Lower
Watershed			
Pre-land clearance	0.38	0.69	0.15
Post-land clearance	1.41	3.24	0.49
Fall line			
Pre-land clearance	0.31	0.37	0.25
Post-land clearance	1.73	1.47	0.31
Tributary			
Pre-land clearance	0.52	0.70	0.33
Post-land clearance	1.36	1.46	1.26
CB estuary			
Pre-land clearance	0.37	0.44	0.29
Post-land clearance	1.02	1.22	0.81

TOC fluxes for watershed, fall line, tributary, and CB estuary regions calculated from total sediment fluxes (Table 2) assuming TOC/TSS is 0.24.

erosional fluxes and estuarine storage after land clearance should be incorporated into global sediment and carbon budgets. However, fluxes in anthropogenically altered watersheds are often underestimated due to a paucity of sediment and carbon data (Syvitski 2003). In lieu of long-term global monitoring data, the observed changes in CB may provide a useful first approximation of the global response to land alteration. While extreme caution is necessary in extrapolating CB results to other regions, our results suggest that global terrestrial to ocean sediment and carbon fluxes are underestimated. Trapping in estuaries likely causes a significant lag in these fluxes, and the bulk of sediment and carbon mobilized by human land alteration probably has not reached the ocean.

Conclusions

Though subject to several sources of uncertainty, the data presented in this paper suggest an approximately twofold increase in sediment and carbon transported to CB since ~1900 A.D. Climate change cannot fully account for the observed changes, and we attribute the increased fluxes to human land clearance. Increased fluxes in regions from upstream watershed erosion to downstream estuarine deposition suggest that the influences of dam construction and soil conservation are outweighed by the effect of land alteration. Sediment and carbon mobilized after land clearance appears to be trapped in estuarine sediments rather than being exported directly to the ocean. Assuming CB is indicative of how other coastal systems respond to land use change, estuaries represent an increasingly important buffer between the ocean and increased terrestrial sediment and carbon fluxes. Further monitoring of sediment and carbon loads in altered watersheds will help confirm our results and may result in more accurate global sediment and carbon budgets.

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