Net Ecosystem Production and Organic Carbon Balance of U.S. East Coast Estuaries

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Abstract

The present study is part of the Coastal Carbon Synthesis Activity coordinated jointly by the Ocean Carbon and Biogeochemistry Program (OCB) and the North American Carbon Program (NACP), aimed at synthesizing individual small-scale studies across broader spatial and temporal scales in order to develop carbon budgets for the coastal regions of North America, which is a vital step towards improving the overall understanding of the role of the coastal zone in the global carbon cycle.

We present organic carbon budgets for the estuaries of the eastern U.S., focusing on net ecosystem production (NEP) as a key process. Statistical models were developed for NEP and burial in the sediment, whereas riverine input was taken from a data-constrained USGS statistical water quality model. Export of organic carbon to the coastal ocean was computed by difference, assuming steady state.

Our results indicate that the U.S. East Coast estuaries are net heterotrophic, respiring between 0.61 and 2.5 TgC yr^{-1} in excess of primary production, with the maximum likelihood NEP estimate (MLE) of -1.9 TgC yr^{-1}. Approximately 3.4 TgC yr^{-1} are delivered to the estuaries in river inflow. Between 0.60 and 2.2 TgC yr^{-1} are buried in the sediment, with MLE of 0.95 TgC yr^{-1}. Estimates of carbon export from the estuaries to the coastal ocean range from -0.74 TgC yr^{-1} (import to estuaries) to 1.9 TgC yr-1, with MLE of 0.63 TgC yr^{-1}.

Introduction

Coastal regions cover a small fraction of the earth's surface yet play a major role in the global carbon cycle because coastal rates of carbon fixation, remineralization, and burial tend to be much higher than the global averages. In the estuarine systems, riverine loadings of nutrients and carbon are not delivered directly to the coastal ocean but first undergo transformations in the estuaries; thus, NEP is an important component of the overall coastal carbon budget because it regulates the fluxes of nutrients and carbon from land to the coastal ocean. NEP is the gross primary production minus community respiration, and thus describes the net metabolic status of a given system: the systems where NEP is positive are net autotrophic (i.e., a net source of organic carbon) and the systems where NEP is negative are net heterotrophic (i.e., a net sink of organic carbon).

A box-model view of a hypothetical estuarine system adopted in this study is illustrated in Fig. 1, where the major fluxes across the box boundaries are input from land (*I*), export from the estuary to the shelf (*E*), and burial in the sediment (*B*); the net ecosystem production (*NEP*) is the internal source term.

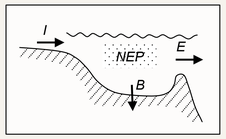
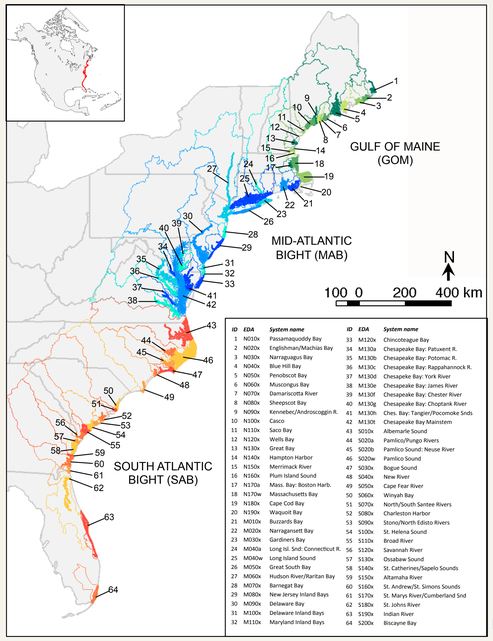


Fig. 1. Estuarine organic carbon balance.

Study Area



ID	EDA	System name	ID	EDA	System name
1	N010c	Passamaquoddy Bay	33	M120c	Chincoteague Bay
2	N020c	Englishman/Machias Bay	34	M130a	Chesapeake Bay: Patuxent R.
3	N030c	Narraguagus Bay	35	M130b	Chesapeake Bay: Potomac R.
4	N040c	Blue Hill Bay	36	M130c	Chesapeake Bay: Rappahannock R.
5	N050c	Penobscot Bay	37	M130d	Chesapeake Bay: York River
6	N060c	Muscongus Bay	38	M130e	Chesapeake Bay: James River
7	N070c	Damariscotta River	39	M130f	Chesapeake Bay: Chester River
8	N080c	Sheepscot Bay	40	M130g	Chesapeake Bay: Choptank River
9	N090c	Kennebec/Androscoggin R.	41	M130h	Ches. Bay: Tangier/Pocomoke Snds
10	N100c	Casco	42	M130i	Chesapeake Bay Mainstem
11	N110c	Saco Bay	43	S010c	Albemarle Sound
12	N120c	Wells Bay	44	S020a	Pamlico/Pungo Rivers
13	N130c	Great Bay	45	S020b	Pamlico Sound: Neuse River
14	N140c	Hampton Harbor	46	S020w	Pamlico Sound
15	N150c	Merrimack River	47	S030c	Bogue Sound
16	N160c	Plum Island Sound	48	S040c	New River
17	N170a	Mass. Bay: Boston Harb.	49	S050c	Cape Fear River
18	N170w	Massachusetts Bay	50	S060c	Winyah Bay
19	N180c	Cape Cod Bay	51	S070c	North/South Santee Rivers
20	N190c	Waquoit Bay	52	S080c	Charleston Harbor
21	M010c	Buzzards Bay	53	S090c	Stono/North Edisto Rivers
22	M020c	Narragansett Bay	54	S100c	St. Helena Sound
23	M030c	Gardiners Bay	55	S110c	Broad River
24	M040a	Long Isl. Snd: Connecticut R.	56	S120c	Savannah River
25	M040w	Long Island Sound	57	S130c	Ossabaw Sound
26	M050c	Great South Bay	58	S140c	St. Catherines/Sapelo Sounds
27	M060c	Hudson River/Raritan Bay	59	S150c	Altamaha River
28	M070c	Barnegat Bay	60	S160c	St. Andrew/St. Simons Sounds
29	M080c	New Jersey Inland Bays	61	S170c	St. Marys River/Cumberland Snd
30	M090c	Delaware Bay	62	S180c	St. Johns River
31	M100c	Delaware Inland Bays	63	S190c	Indian River
32	M110c	Maryland Inland Bays	64	S200c	Biscayne Bay

- To delineate the study area we used NOAA's national estuarine eutrophication assessment survey (NEEA, Bricker et al., 2007) that relies on NOAA's Coastal Assessment Framework (CAF).
- Fig. 2 shows the extent of the study region and defines the three sub-regions.
- Each estuarine system is identified according to its EDA (estuarine drainage area) code.
- The total water surface area of the U.S. East Coast estuaries is 38,000 km^2. The MAB sub-region is the largest, covering 54% of the total water area, followed by SAB (32%), and GOM (14%).
- The total land area draining into the estuaries is 714,000 km^2, with SAB drainage area covering 46% of the total, followed by MAB (42%), and GOM (12%).

Fig. 2. Map of the study area.

Organic Carbon Input

- A simplifying assumption was made that the organic carbon input to estuaries is dominated by riverine fluxes; thus, a limitation of our analysis is that it does not explicitly include organic carbon input form tidal wetlands.
- To constrain riverine input of organic carbon we used riverine total organic carbon (TOC) load estimates from the USGS SPARROW water quality model (Spatially Referenced Regression on Watershed Attributes; Smith et al.,1997; Shih et al., 2010).

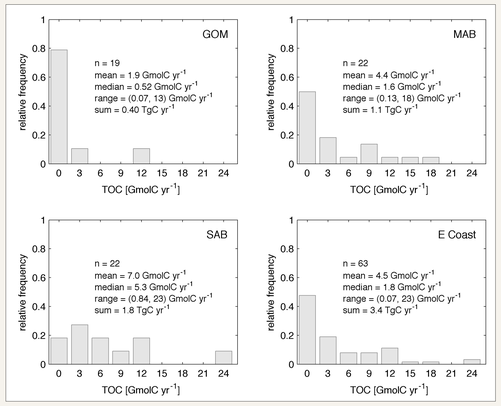


Fig. 3 Estimated riverine loadings of TOC from SPARROW.

- The SPARROW model provides a means to estimate long-term average riverine inputs directly at the mouths of the estuaries, where monitoring station observations are non-existent.
- Estimates of riverine TOC input are summarized in Fig. 3. EDA inputs ranged from < 0.1 GmolC yr^{-1} to 23 GmolC yr^{-1}. The integrated TOC input for the East Coast region was 3.4 TgC yr^{-1}.
- Integrated TOC inputs were the lowest in GOM and increased towards the south.
- Per unit estuary surface area, the highest TOC fluxes were in SAB (0.47 molC m^2 yr^{-1}), followed by GOM (0.42), and MAB (0.32).

Net Ecosystem Production

- NEP has been shown to correlate with the ratio of riverine inputs of dissolved inorganic nitrogen (DIN) to total organic carbon (TOC) (Kemp and Testa, 2011). DIN fuels photosynthesis and pushes the system towards net autotrophy, while TOC fuels decomposition and pushes the system towards net heterotrophy.
- We assembled a database of existing NEP estimates and developed an algorithm based on statistical modeling of NEP as a function of DIN:TOC loading ratios ($R_{DIN:TOC}$) to scale up sparse local NEP estimates to regional scales (Fig. 4).
- $R_{DIN:TOC}$ estimates were derived using TOC fluxes from SPARROW and DIN fluxes that were calculated by combining the available SPARROW total nitrogen (TN) flux output with the range of DIN to TN ratios ($R_{DIN:TN}$) that we estimated using TN and DIN concentration measurements from USGS monitoring stations.

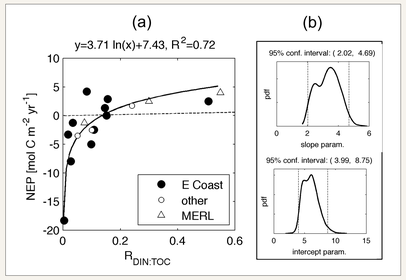


Fig. 4 (a) The statistical model of NEP vs. $R_{DIN:TOC}$. (b) PDFs of model parameters, with 95% confidence intervals shown as dashed lines (derived using 10,000 bootstrap samples).

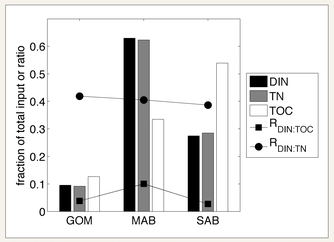
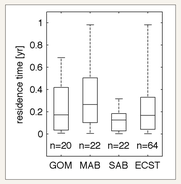


Fig. 5 Summary of sub-regional point estimates of integrated riverine input (DIN, TN, TOC) and loading ratios ($R_{DIN:TOC}$ and $R_{DIN:TN}$)

- $R_{DIN:TN}$ ranged from 0.06 to 0.8, with the point estimate (ratio of regional mean DIN and TN fluxes) for the U.S. East Coast of 0.4. Sub-regional point estimates decreased slightly form north to south (Fig. 5), indicating increased inputs of organic material towards the south (consistent with integrated TOC input).
- $R_{DIN:TOC}$ ratios ranged from <0.01 to 0.5, with the regional East Coast point estimate of 0.05. SAB had the lowest ratios, not exceeding 0.05, with the sub-regional point estimate of 0.03 (Fig. 5). In both GOM and MAB, we found several EDAs where the ratios reached up to 0.5, but while the central tendency in GOM (point estimate of 0.04) was close to the SAB value, the MAB distribution was centered on a substantially higher value of 0.10. The latitudinal pattern of $R_{DIN:TOC}$ followed the latitudinal variation in integrated DIN (and TN) input, with the maximum in MAB, rather than TOC, which increased from north to south (Fig. 5).
- Integrated NEP for the East Coast was -1.9 TgC yr^{-1}, with 95% confidence interval (-2.5, -0.61) TgC yr^{-1}.
- Integrated NEP estimates were the lowest in SAB (most heterotrophic) and increased towards the north.
- Per unit estuary surface area, the lowest NEP fluxes were in SAB (-9.2 molC m^2 yr^{-1}), followed by GOM (-3.75), and MAB (-1.14).
- Spatial variability of sub-regional NEP estimates followed the latitudinal variation of TOC inputs (Fig. 5).

Burial in the Sediment

- There are very few direct estimates of carbon burial in estuaries but factors controlling the cycling of nitrogen are reasonably well understood. Nixon et al. (1996) showed that the rates of estuarine denitrification and TN export were linked to estuarine water residence time (τ), suggesting that TN burial is also dependent on residence time.
- We used τ, TN export, and denitrification data from Nixon et al. (1996) to develop a regression model of TN burial as a function of τ (Fig. 6). The model was then used to estimate carbon burial from τ estimates (Fig. 7) and an assumed burial C:N ratio of 10.
- τ for the study area (Fig. 7), were calculated as: $\tau = V/Q\left(1 - S_{ESR}/S_{OCN}\right)$, where *V* is the volume, *Q* is the net freshwater input, S_{ESR} is the average salinity of the estuary, and S_{OCN} is the average salinity on the adjacent shelf; we used river inflow form SPARROW and all other parameters from Bricker et al. (2007).
- Integrated burial for the East Coast was 0.95 TgC yr^{-1}, with 95% confidence interval (0.6, 2.22) TgC yr^{-1}.
- Per unit estuary surface area, the highest burial fluxes were in MAB (2.4 molC m^2 yr^{-1}), followed by SAB (1.64), and GOM (1.34).
- Spatial variability of sub-regional burial estimates was similar to the latitudinal variation of DIN inputs (Fig. 5).



Each box is bounded by the upper and lower quartiles of the data; the bar locates the median; the whiskers show the range of the data, excluding extreme values (N170w: τ=2.81 yr, N180x: τ=3.20 yr, S020w: τ=1.79 yt).

Fig. 7 Boxplot summary of residence time (τ) estimates.

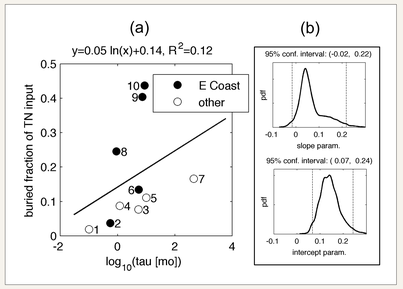


Fig. 6 (a) The statistical model of TN burial vs. residence time (τ). (b) PDFs of model parameters, with 95% confidence intervals shown as dashed lines (derived using 10,000 bootstrap samples). 1=Ochlockonee Bay, 2=Boston Harbor, 3=Scheldt Estuary, 4=Guadalupe Estuary: wet year, 5=Guadalupe Estuary: dry year, 6=Delaware Bay, 7=The Baltic Sea, 8=Narragansett Bay, 9=Potomac Estuary, 10=Chesapeake Bay.

Summary: Organic Carbon Balance

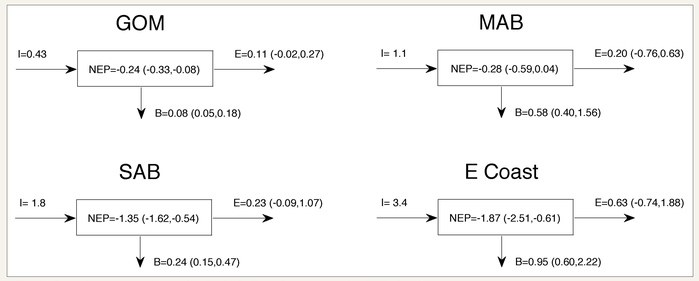


Fig. 8 Organic carbon balance for the U.S. East Coast estuaries in TgC yr^{-1}.

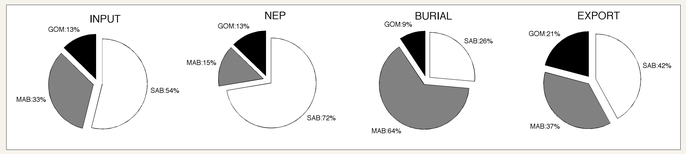


Fig. 9 Relative contribution of the sub-regions to the U.S. East Coast organic carbon fluxes.

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