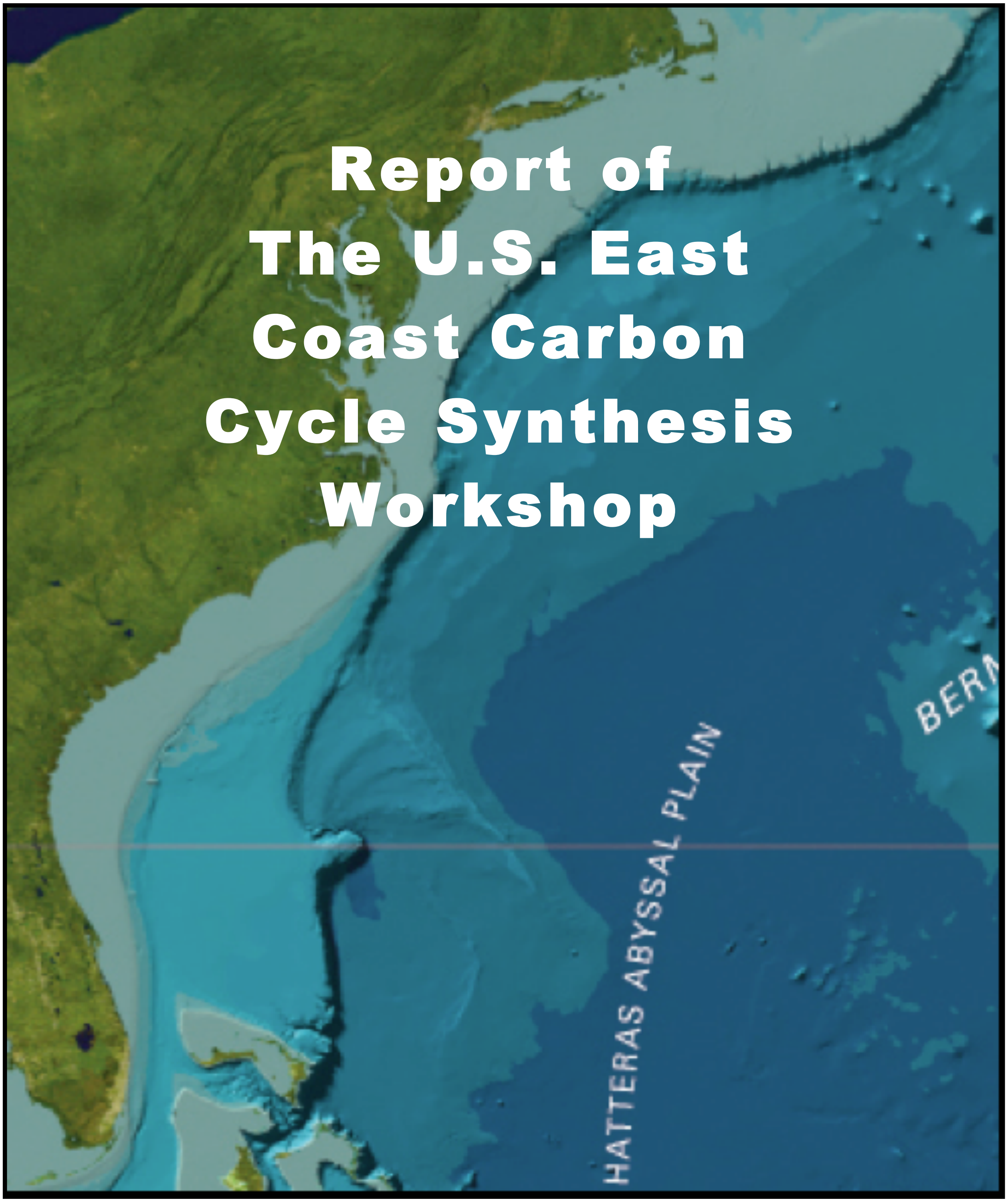
Report of The U.S. East Coast Carbon Cycle Synthesis Workshop



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Report of the U.S. East Coast Carbon Cycle Synthesis Workshop

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Raymond G. Najjar, Marjorie A. M. Friedrichs, and Wei-Jun Cai

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Executive Summary

Coastal regions, despite covering a small fraction of the earth's surface, are important in the global carbon cycle because rates of carbon fixation, remineralization, and burial are much higher than their global averages. While a significant amount of research relevant to the carbon cycle has been conducted in coastal regions, it has tended to fall along disciplinary and regional lines, creating a need for synthesis. In 2009, the Ocean Carbon and Biogeochemistry Program and the North American Carbon Program began a synthesis activity with a focus to develop carbon budgets for the five main coastal regions of North America: the Arctic Coast, the Atlantic Coast, the Gulf Coast, the Pacific Coast, and the Great Lakes. The main goal of this NASA- and NSF-funded workshop was to bring together carbon cycle scientists studying the Atlantic coast of the United States to develop a carbon budget for the region.

The workshop hosted 35 scientists, who were organized ahead of time into eight teams, each corresponding to major terms in the regional carbon budget: riverine input (at the head of tide), estuarine fluxes, tidal wetland fluxes, air-sea exchange, sediment-water exchange, exchange at the ocean boundary (roughly the shelf break), photosynthetic primary production, and respiration and net community production. These flux teams synthesized literature and, in several cases, made greatly improved flux estimates before the workshop. At the workshop, flux syntheses were presented and discussed, short-term (6-12 months) plans to improve flux estimates were formulated, and long-term recommendations for research were made. A preliminary, revised overall carbon budget for the region was developed at the end of the workshop, which provided a greatly improved set of carbon budget terms.

Primary production is perhaps the best-studied term in the U.S. east coast carbon budget and occurs at a rate of about 140 Tg C yr^{-1}, with about 10-20% attributable to tidal wetlands, which make up only 2% of the study domain. Four distinct estimates of riverine input of dissolved and particulate carbon were made, and it now appears that coastal waters of the eastern U.S. receive 4-11 Tg C yr^{-1} from land via rivers, a greatly improved estimate over previous syntheses. For the first time, a tidal wetlands carbon budget for the U.S. east coast was developed, including terms for net primary production, burial, and carbon export to estuaries. A preliminary synthesis suggests that tidal wetlands of the U.S. east coast remove 5-10 Tg C yr^{-1} of CO_2 from the atmosphere, bury 10-40% of it, and export the remainder to adjacent estuaries. Three estimates of coastal air-sea CO_2 exchange were made from: (1) an observational synthesis, (2) a statistical model using remotely sensed data, and (3) a 3-D biogeochemical-circulation model. This synthesis indicates that coastal waters of the U.S. east coast (excluding tidal wetlands and estuaries) remove 0-8 Tg C yr^{-1} as CO_2 from the atmosphere (best estimate: 1-4 Tg C yr^{-1}). The cross-shelf carbon flux, estimated using a coupled biogeochemical-circulation model and observational analyses, averages 2-10 Tg C yr^{-1} offshore and has significant interannual variability. Finally, the first regional estimates were made for sinking particle fluxes out of the surface layer (>8 Tg C yr^{-1}), sediment remineralization (13 Tg C yr^{-1}), and burial (1 Tg C yr^{-1}). Resuspension rates are high (up to 11 Tg C yr^{-1}) and provide the potential for substantial lateral export of particulate organic carbon to the open ocean.

Practical plans were made to further refine and improve flux estimates, including uncertainties, in the eight categories over the next 6-12 months. Numerical models will be used to estimate interannual variability of several fluxes, including cross-shelf exchange, which is very difficult to measure directly at the regional scale. Fluxes in tidal wetlands and estuaries will be scaled up to the region as a whole using existing data sets that characterize these systems.

Remote sensing algorithms will be used to further improve primary production and air-sea flux estimates.

Several overarching themes emerged from the workshop and led to specific long-term recommendations for improving our understanding of carbon cycling in coastal waters of the eastern U.S. and elsewhere. First, it was clear that discussions and interactions at the workshop were synergistic, with knowledge being created as a result of sharing information across disciplines. Therefore, continued cross-disciplinary interaction is essential for a comprehensive understanding of the carbon fluxes in coastal systems. Second, while all fluxes of the carbon cycle in coastal waters of the eastern U.S. need their uncertainty reduced, there are clear areas where improvement is essential: exchange of CO_2 between the atmosphere and estuaries; lateral advective fluxes at the interfaces between tidal wetlands, estuaries, shelf waters, and the open ocean; and respiration in shelf waters. Third, it was found that the strong heterogeneity and variability within coastal systems demands innovative methods for scaling up local flux estimates. Fourth, because of the difficulty in quantifying flux errors in coastal systems (resulting, in part, from their heterogeneity), it behooves us to make as many independent estimates of a given flux as possible. And lastly, mechanistic numerical models are a powerful complement to observations for constraining carbon fluxes in the coastal zone and identifying important data gaps. The development (and application to the regional scale) of mechanistic models of tidal wetland and estuarine biogeochemistry is a particularly high priority.

1. Introduction

Contributors: R. Najjar, W.-J. Cai, M. Friedrichs, and P. Griffith

As part of an effort to better understand the role of the coastal zone in the global carbon cycle, the Ocean Carbon and Biogeochemistry Program (OCB) and the North American Carbon Program (NACP) began an activity in 2009 to develop carbon budgets for the five main coastal regions of North America: the Arctic Coast, the Atlantic Coast, the Gulf Coast, the Pacific Coast, and the Great Lakes. The main goal of this workshop, which was organized by M. Friedrichs, R. Najjar, and W.-J. Cai, was to bring together carbon cycle scientists studying the east coast of the United States to develop a carbon budget for this region.

1.1. Workshop development and format

An open invitation to attend this workshop and to participate in the process of developing a carbon budget was sent through the NACP and OCB mailing lists on October 21, 2011. A follow-up email on November 22, 2011 called for volunteers to begin the synthesis ahead of the workshop for a given subregion (South Atlantic Bight, Mid-Atlantic Bight, and Gulf of Maine) or flux (riverine input, estuarine fluxes, tidal wetland fluxes, air-sea exchange, sediment-water exchange, exchange at the ocean boundary, primary production, and respiration and net community production). Two follow-up conference calls were held before the workshop to clarify goals and expectations. Eight teams were organized by flux and these teams synthesized literature and, in some cases, made new flux estimates before the workshop. 35 scientists from 16 institutions attended the workshop (Table 1), which was held at the Virginia Institute for Marine Science.

The workshop agenda is provided in the Appendix. Two presentations were given at the beginning of the workshop to provide context and progress to date on constructing a budget for the region. These were followed by presentations by each of the eight flux teams describing their pre-workshop efforts at synthesizing literature and updating the flux estimates of Najjar et al. (2010). The individual flux teams then met in breakout groups to further refine estimates, develop a short-term (6-12 months) strategy to improve flux estimates, and discuss long-term recommendations for research. After the breakout groups reported back to the workshop participants, a revised budget for the region was generated, next steps for the budget synthesis were planned, and long-term recommendations were discussed. Sections 2 through 9 detail the work done by individual flux teams. Section 10 provides overall workshop findings and recommendations.

1.2. Workshop context

The workshop began with a discussion of the recent history of efforts to coordinate carbon cycle research at the U.S. national level. In the late 1990s, The Carbon Cycle Interagency Working Group (CCIWG) requested that a science plan for carbon cycle research be developed. In 1999 such a plan was published (Sarmiento and Wofsy, 1999) and led to the formation of the NACP and OCB[1], sister organizations with overlapping domains in the coastal zone of North America. Both programs recognized the importance of the coastal zone in the global carbon cycle and the relative lack of coordinated research in this area. As a result, a workshop was proposed to the CCIWG to broadly synthesize knowledge of carbon cycling in the North

[1] Originally called the Ocean Carbon and Climate Change (OCCC) program.

American Continental Margins (NACM). The workshop, funded by NASA, NOAA, and NSF, was held in 2005 and made several recommendations, including coastal data synthesis and carbon budget estimation based on a control volume concept (Hales et al., 2008). With the NACM report recommendations in mind, and with an interim synthesis activity underway within the NACP, NASA funded a proposal to synthesize existing knowledge of coastal carbon fluxes through regional workshops and the assistance of a post-doctoral scholar.

Efforts before the initiation of the workshop to develop a carbon budget for the U.S. east coast were then summarized. An informal literature review was organized in 2009, presented at several meetings, and published in a newsletter article (Najjar et al., 2010). The regional boundaries to define the control volume were chosen to be the head of tide at the landward side, the shelf break[2] at the seaward side, the southern tip of Florida to the south, the southern tip of the Scotian peninsula to the north, the air-sea interface at the top, and the sediment-water interface at the bottom (Figure 1). The three main subregions of the domain are, from south to north, the South Atlantic Bight (SAB), the Mid-Atlantic Bight (MAB), and the Gulf of Maine (GoM). All fluxes were found to be in need of substantial improvement, but particularly large uncertainty was found for estuarine and wetland fluxes, groundwater fluxes to the coast, respiration, sediment-water exchange, and exchange at the ocean boundary.

2. Riverine input

Contributors: D. Butman (lead), R. Alexander, E. Boyer, K. Kroeger, E. Mayorga, R. Smith, E. Stets, and H. Tian

Four new estimates of the riverine carbon input to coastal waters of the eastern U.S. were made by the riverine input team (Table 2). The first estimate was from Stets and Striegl (2012), and is based on a United States Geological Survey (USGS) data synthesis known as *The Century of Trends*. Riverine carbon flux estimates were made for monitoring sites at the fall line of 53 large coastal rivers with the USGS Load Estimator (LOADEST), a statistical model that uses constituent concentrations and streamflow as inputs (Figure 2). By comparison, the other three models provide estimates of carbon loadings to tidal (estuarine) waters from all coastal rivers and streams and in the runoff from small coastal drainages. The second estimate was from the Global NEWS (Nutrient Export from Watersheds) model, which exploits data on land use as well as flow and constituent data. A description of the nutrient version of the Global NEWS model is found in Mayorga et al. (2010). The third estimate was from USGS's SPARROW (SPAtially Referenced Regression on Watersheds attributes) model, broadly similar to Global NEWS in its data requirements and recently applied to total organic carbon (TOC, Shih et al., 2010). The ratio of dissolved organic carbon (DOC) to TOC was then used to separate the TOC fluxes into dissolved and particulate fractions. The fourth estimate was from a mechanistic terrestrial biogeochemical model known as the Dynamic Land Ecosystem Model (DLEM, Tian et al., 2010a; Tian et al., 2012; Tian et al., 2010b). SPARROW only estimates fluxes of DOC and particulate organic carbon (POC); the other three models also include dissolved inorganic carbon (DIC).

[2] The exact location of the ocean boundary is shown in Figure 1 and roughly corresponds to the 100-m isobath for most of the domain except for the Gulf of Maine.

Comparing the fluxes between the four models is complicated by the fact that the drainage areas and reference years are different. For the Gulf of Maine, for example, drainage areas vary by up to 60%, in part because some of the models are limited to the U.S. Nevertheless, the results indicate that the total flux of carbon to the east coast is roughly 4-11 Tg C yr^{-1} (mostly in dissolved form), as much as twice that estimated by Najjar et al. (2010).

An attempt was also made to estimate groundwater carbon input to the coastal zone by combining DOC concentration data in coastal groundwater wells with estimates of the groundwater volume flux. The result, 1 Tg C yr^{-1}, is highly uncertain.

<u>*Short-term plans*</u>

There is concern that there may be double counting of carbon fluxes with the tidal wetlands flux team given that the SPARROW, NEWS, and DLEM models provide estimates of carbon exports from tidal wetlands; this will be addressed in future revisions of the tidal wetlands estimates (see Section 3). Fluxes of carbon and nutrients will be provided to the tidal wetlands and estuarine flux teams (Sections 3 and 4) for each of the 64 basins identified by these teams to assist them in their budgeting activities. The riverine input team also identified several short-term goals and activities related to differences among the model estimates. Improvements in the new version of Global NEWS will be identified and the model will likely be used only for comparison because it may be too simplistic and coarse. Watersheds will be chosen from the spatially limited Stets and Striegl (2012) study to directly compare with DLEM and SPARROW. Output layers from DLEM will be incorporated into the SPARROW TOC/DOC model (soil organic matter, leaf litter, etc.). Finally, nitrogen fluxes will be obtained from DLEM and compared with the other models. Two papers are being planned on the following topics: (1) a DLEM-based estimate of riverine carbon fluxes to coastal waters of the eastern U.S. (Tian lead) and (2) a model intercomparison of riverine carbon fluxes to coastal waters of the eastern U.S. (Butman lead).

<u>*Long-term recommendations*</u>

SPARROW is the only one of the four models that does not include DIC, and this should be remedied. A national SPARROW dissolved solids model is being developed by D. Anning (USGS) and connections should be made with this effort to aid in the development of a DIC loading model. Groundwater inputs of dissolved carbon to the coastal zone are a potentially large but poorly constrained flux, and a dedicated research effort is needed to reduce the uncertainty in this flux. Finally, a mechanistic phosphorus model should be explored for possible inclusion into DLEM.

3. Fluxes in tidal wetlands

Contributors: K. Kroeger (lead), I. Anderson, S. Baldwin, W. Brooks, M. Brush, W.-J. Cai, E. Canuel, M. Casso, R. Chen, A. Green, L. McCallister, M. Kemp, C. Schaaf, M. Tzortziou, and R. Zimmerman

Research on carbon cycling in tidal wetlands is motivated by the fact that, despite their small area, they make a substantial contribution to wetland carbon sequestration in North America. Tidal wetlands are present throughout the east coast of the U.S., but more than half of the area is along the SAB coast. Through a literature review, the tidal wetlands team identified some of the important terms in the tidal wetlands carbon budget: CO_2 uptake from the atmosphere (net primary production, NPP), degassing to the atmosphere, respiration, organic carbon burial, and lateral fluxes of DIC, DOC, and POC (e.g., Cai and Wang, 1998; Cai et al., 1999; Cai et al., 2000; Jordan and Correll, 1991; Jordan et al., 1983; Jordan et al., 1986; Megonigal and Neubauer, 2009; Moran and Hodson, 1994; Moran et al., 1991; Neubauer and Anderson, 2003; Tobias and Neubauer, 2009; Tzortziou et al., 2011; Tzortziou et al., 2008). Lateral fluxes involve mainly export of dissolved carbon components via tidal exchange (e.g., Childers et al., 2000; Nixon, 1980), while higher variability has been reported in the rates and direction of particle exchange between wetland and estuarine environments (Tobias and Neubauer, 2009).

The challenge for computing fluxes at the regional scale is the high degree of heterogeneity, the lack of sufficient data across system types, and the incomplete understanding of controls on the rates. The problem can be tackled by using high-resolution, geographically specific information that is now available for many of the key features of coastal ecosystems. One important resource, for example, is the National Wetlands Inventory (NWI) of the U.S. Fish and Wildlife Service. As an example of this data source, Figure 3 shows the distribution of wetland types for a portion of the mid-Atlantic coastal region. Given the time constraints imposed by the workshop, an interim approach was taken in which: (1) the surface area of two wetland types was estimated for each of the three subregions, (2) literature estimates of burial (organic carbon) and lateral flux (of POC, DOC, and DIC) in each wetland type were determined, and (3) the measured rates were integrated over each wetland type and subregion.

Two broad categories of tidal wetlands were defined: tidal fresh wetlands (salinity < 0.5) and brackish and saline wetlands (salinity > 0.5). Areas for each were computed for each subregion using the NWI and compared with literature estimates. Integrated burial rates and lateral fluxes were then computed for each subregion and also compared with literature estimates, where available (Table 3). Preliminary estimates indicate that burial in tidal wetlands is 1-2 Tg C yr^{-1} and lateral export from tidal wetlands to estuaries is 2 Tg C yr^{-1} of DIC and 2-6 Tg C yr^{-1} of DOC. The limited data analyzed thus far suggest that 0.6 Tg C yr^{-1} of POC is exported from tidal wetlands, but wetlands may in fact be a POC sink and thus this estimate is highly uncertain.

NPP in tidal wetlands was crudely estimated by taking two estimates of it on an areal basis and multiplying them by the estimated tidal wetland area for the study region (1.2×10^{10} m^2). The first estimate is the global-mean salt marsh gross primary production (GPP) estimate of Duarte et al. (2005), 300 mol C m^{-2} yr^{-1}, multiplied by the estimated fraction of GPP that is NPP (0.31, Duarte and Cebrian, 1996), which gives NPP = 93 mol C m^{-2} yr^{-1}. The second estimate of NPP is from Hopkinson (1988), 169 mol C m^{-2} yr^{-1}, used by Cai (2011) for an SAB carbon budget. These two estimates give an NPP range in the study region of 13-24 Tg C yr^{-1}.

If it is assumed that the C supporting this NPP comes from the atmosphere and that 3-8 Tg C yr^{-1} of this organic C formed is buried or exported laterally, then steady state requires 5-21 Tg C yr^{-1} of heterotrophic respiration (DIC production) in tidal wetlands (i.e., respiration = NPP – organic C burial – organic C lateral export). Assuming 2 Tg yr^{-1} of DIC is exported laterally to estuaries, then steady state requires that 3-19 Tg C yr^{-1} of CO_2 are degassed to the atmosphere from tidal wetlands (i.e., degassing = respiration – DIC lateral export). The net removal of CO_2 from the atmosphere by tidal wetlands is simply NPP minus the degassing flux, which is equal to organic C burial + organic C lateral export + DIC lateral export, or about 5-10 Tg C yr^{-1}.

Short-term plans

The tidal wetlands team will extend the existing approach by making it more spatially explicit and by refining estimated C flux rates (lateral export, burial, and NPP) for each wetland type. The resulting lateral export fluxes will be provided to the estuarine flux team for each of the 64 estuaries they are considering in their calculations (Section 4). The double counting issue will be assessed by turning off tidal wetlands in the riverine flux team's version of SPARROW. Non-tidal (freshwater) wetlands will be included in the watershed-river budget, while tidal (freshwater, brackish, salt) will be included in the tidal-wetland budget. Activities between the riverine, tidal wetlands, and estuarine flux teams will be coordinated so that input from the non-tidal watershed and rivers is provided to the tidal tributaries and wetland areas, and the total input from watershed, rivers, and wetlands is provided to the estuaries. In addition to the contribution of this team to the overall east coast carbon synthesis paper, a paper is being planned on carbon fluxes and processing in tidal wetlands.

Long-term recommendations

The rate of carbon burial in wetland soils is relatively straightforward to measure and has been reviewed in the literature. The challenge is that accumulation rates differ in individual systems, making it difficult to extrapolate to the regional scale. Additionally, an increased number of direct measurements are needed of the vertical carbon dioxide exchange between the atmosphere and coastal wetlands and lateral carbon exchanges between wetlands and estuaries. The vertical and lateral fluxes are heterogeneous in space and time, and thus spatially intensive and temporally extended sets of measurements are required to capture the variability and calculate seasonal and annual rates. Furthermore, flux measurements are needed in relation to variables that may influence rates as well as carbon quality, including vegetation type, climate, salinity, pH, and loadings of nutrients and sediment.

Improvements in measurements of tidal wetland fluxes and the analysis and synthesis of such measurements will facilitate the development of mechanistic models of tidal wetland biogeochemistry, which are needed for understanding how carbon fluxes in tidal wetland systems will respond in the future to stressors associated with land use and climate change. Such models need to account for the complex and rapid physical, microbial, and photochemical transformations affecting carbon and nitrogen cycling at the wetland-estuarine interface and be capable of being applied at the regional scale.

4. Fluxes in estuaries

Contributors: M. Kemp and L. McCallister (leads), I. Anderson, M. Brush, E. Canuel, E. Hall, M. Herrmann, K. Kroeger, R. Najjar, M. Tzortziou, and R. Zimmerman

Net community production (NCP) is defined as the excess of gross primary production over community respiration.[3] Estuarine NCP is important because it describes the metabolic status of an estuary and, in combination with other fluxes (inputs from rivers, wetlands, and the atmosphere, and losses to burial), it determines the nutrient and organic matter loads to the

[3] Another commonly used term with the same definition as NCP is net ecosystem production (NEP). New production, export production, and net ecosystem metabolism (NEM) may also be defined in ways that make them equivalent to NCP.

coastal ocean. The estuarine fluxes team described the variety of methods available for estimating NCP in estuaries. These vary considerably and include the following: (1) direct measurements of primary production and respiration for all functional groups of organisms integrated over space and time, (2) measurements of diel variations in dissolved oxygen or DIC in the open water over space and time, and (3) steady-state chemical mass balances with conservative tracers to compute transport and non-conservative elements (e.g., C, O, N, and P) to compute net biogeochemical rates. Recent synthesis studies have related estuarine NCP to a variety of forcing factors, including water residence time and loading of inorganic nutrients and organic carbon, providing a potential basis for statistical modeling of NCP (Figure 4). A recent survey provides quantitative and qualitative data for 64 major estuaries that cover most of the U.S. east coast (Bricker et al., 2007). Key physical and chemical data are available for all of these estuaries, including water residence time, stratification, area, depth, nutrient levels, and nutrient inputs. The estuarine fluxes team's recent survey indicates that about a third (22) have direct or indirect estimates of NCP. Values for organic C burial are also available for a subset of these estuarine systems.

Short-term plans

The initial approach used to estimate NCP for east coast estuaries will involve application of existing areal estimates of NCP and organic C burial and extrapolation to the full list of 64 estuaries by grouping estuaries according to physiographic types and applying the corresponding rates for each type. The estuarine fluxes team will also explore the application of SPARROW estimates of river loading rates for TOC, total nitrogen, and dissolved inorganic nitrogen to use as a predictor for estuarine NCP. GIS data from the NWI and the USGS will be used to calculate the total U.S. east coast area not directly included in the 64 named estuaries. Organic C burial rates will be computed using data on particle deposition rates and sediment organic carbon content where available and from steady-state mass balance calculations. Given the estuarine areas and biogeochemical rates, integrated NCP and organic C burial rates will be determined for each estuary, subregion, and the whole domain.

The estuarine fluxes team will also expand the analysis of estuarine NCP along the U.S. east coast through several parallel and independent approaches. Multivariate statistical models will be developed that relate net metabolism rates to physical factors and to nutrients and organic carbon loading rates for numerous estuaries. Where possible, the team will apply the well-tested LOICZ (Land-Ocean Interaction in the Coastal Zone) method for simple mass balance calculations of net organic carbon production assuming consistent ecological stoichiometry (Smith et al., 2005). These rates will then be compared with those estimated in the initial approach described above. At least one paper is being planned on the carbon budget of estuaries in the study region.

Long-term recommendations

In the long run, the ability to develop reliable estimates for the estuarine compartment requires both increased measurements within individual systems and approaches that allow for broad integration across systems. Development of a broad view of the carbon cycle in estuaries of the eastern U.S. continues to be hampered by the number of estuarine systems and considerable variability within and across these systems. Since individual estuaries have different forcings and responses (e.g., differences in residence time, inorganic nutrient delivery, and the amount and quality of carbon exported from the adjacent watersheds), it is difficult to develop predictive frameworks at the regional level. Much of the focus, to date, has been on large estuarine systems such as Chesapeake Bay and Delaware Bay (e.g., Kemp et al., 1997), which may not be representative of smaller estuaries. Future efforts should be focused on: (1) a synthesis of data on NPP and community respiration for estuarine waters, (2) expanded measurement and modeling of the air-water CO_2 flux in estuaries, (3) investigations of the lability and photoreactivity of POC and DOC derived from wetland and watershed sources, and (4) improving understanding of lateral fluxes or tidal exchange of DIC, DOC, and POC from estuaries to the coastal ocean.

The estuarine fluxes team recommends development of improved estuarine coupled hydrodynamic-biogeochemical models that account for the complex physical, microbial, and photochemical transformations affecting carbon fluxes and dynamics in estuarine waters. Such models will be critical for understanding the impacts of changing climate, land use (e.g., increasing coastal urbanization), and land cover, which will likely affect many dimensions of the carbon cycle in estuaries including carbon loadings, estuarine production, metabolism and burial, and export to the coastal ocean (Canuel et al., 2012).

5. Air-sea exchange

Contributors: Z. A. Wang (lead), B. Cahill, W.-J. Cai, K. Fennel, M. Friedrichs, W. McGillis, J. Salisbury, C. Schaaf, and S. Signorini

The air-sea exchange team provided a global context for the role of continental shelves in the uptake of CO_2 from the atmosphere, summarized previous work on air-sea CO_2 exchange in the study region, and then described a new effort to make improved estimates of CO_2 uptake in the study region. Globally, shelves are about 7% of the ocean surface area and yet may account for as much as one quarter of the CO_2 uptake from the atmosphere. Previous observational studies suggest the GoM is a weak CO_2 source to the atmosphere while the MAB and SAB are atmospheric CO_2 sinks.

The team made revised estimates of the air-sea flux using the air-sea pCO_2 difference in combination with a wind- and temperature-based exchange coefficient. Estuaries and wetlands were not included in the analysis. Three approaches were taken to estimate the surface ocean pCO_2 field: (1) gridding of existing data from various data sources, (2) a multiple regression model based on latitude, longitude and satellite-based estimates of surface ocean temperature and chlorophyll, and (3) a 3-D biogeochemical-circulation model (Fennel et al., 2008; Hofmann et al., 2008; Hofmann et al., 2011) known as the NENA (*N*orth*E*ast *N*orth *A*merica) model. The data sources include large compilations from T. Takahashi and the Surface Ocean CO_2 Atlas (SOCAT) with additional contributions from W.-J. Cai in the SAB and J. Salisbury and D. Vandemark in the GoM. The statistical model, developed by S. Signorini and based largely on NASA remote sensing data, was found to be skillful in the MAB and SAB but not in the GoM and in a subregion combining Georges Bank and Nantucket Shoals (GB + NS). Spatial sampling uncertainty estimates were made using the statistical and biogeochemical models and temporal sampling uncertainties were addressed using buoy measurements in the SAB. The modeled air-sea flux estimates are derived from a four-year simulation (2004 to 2007) of the NENA model without dissolved organic matter (DOM) dynamics (Cahill et al., in preparation).

The preliminary results from these approaches are shown in Table 4. The data-gridding approach indicates that the MAB, GB + NS, and SAB subregions are sinks of atmospheric CO_2 and the GoM is a source of CO_2 to the atmosphere; the region as a whole is estimated to be a sink of 1-4 Tg C yr^{-1}. The satellite algorithm results are largely in agreement with those from the data gridding, where applicable (MAB and SAB). The NENA model simulates all subregions to be sinks of atmospheric CO_2, with a total uptake of 5.3 ± 1.9 Tg C yr^{-1}.

The air-sea flux team determined that the uncertainties associated with the air-sea CO_2 flux estimates of Najjar et al. (2010) were underestimated. Considerable uncertainty exists as a result of the lack of historical surface-ocean pCO_2 data, particularly in high-flux conditions (very close to shore and during episodic events). Also notable is the lack of long-term data for capturing the potentially large interannual variability and any long-term trends. Given these uncertainties, the true error in the uptake may be as large as 100%, so that at this time it is estimated that net removal of CO_2 from the atmosphere by coastal waters of the eastern U.S. (excluding tidal wetlands and estuaries) is probably between 0 and 8 Tg C yr^{-1}.

Short-term plans

The team will be adding additional pCO_2 data sources to the study, including MAB data from W. McGillis and Z. A. Wang. The GoM data will be further synthesized by the team and attempts will be made to improve the satellite statistical model for this subregion using other variables and approaches. Three papers are planned on the following topics: (1) seasonal control of CO_2 in the Gulf of Maine (Salisbury lead), (2) CO_2 flux between the atmosphere and coastal waters of the eastern U.S. (Signorini and Wang leads), and (3) the inorganic carbon system of coastal waters of the eastern U.S. (Wang lead).

Long-term recommendations

The air-sea flux team recommends improvements in the two main components of the air-sea flux calculation: surface ocean pCO_2 and the gas transfer velocity. With regard to the former, despite the improvements made during this synthesis effort, the region is still undersampled as a result of its high spatial and temporal variability. Additional measurements are needed as well as further development of satellite algorithms and 3-D numerical models for extrapolating measurements in space and time. Gas transfer coefficient parameterizations are also needed that account for the relevant processes and phenomena in the coastal zone (surfactants, stability, waves, and bottom-generated turbulence); most formulations are calibrated for the open ocean. The team recommends extending the analysis to the Scotian shelf (Figure 1), which is part of the Atlantic coastal domain and has a substantial surface pCO_2 data set from H. Thomas and colleagues. The air-sea flux analysis should also include estuaries and wetlands; because data are very limited (especially problematic given the high diel, tidal and seasonal variability), a program of estuarine and wetland CO_2 flux measurements is a high priority (see also Sections 3 and 4). Other forms of carbon should be looked at as well, as their fluxes may not be small: air-water gas exchange of methane and carbon monoxide, and rainwater DOC and DIC.

6. Sediment-water exchange

Contributors: C. Pilskaln and D. Burdige (leads), W.-J. Cai, E. Canuel, and X. Hu

This team synthesized literature and unpublished measurements of carbon export (e.g., the vertical POC flux between 50-150 m) and near-bottom carbon resuspension flux (Anderson et al., 1994; Benitez-Nelson et al., 2000; Biscaye and Anderson, 1994; Biscaye et al., 1988; Charette et al., 2001; Falkowski et al., 1994; Hayashi, 2012; Packard and Christensen, 2004; Pilskaln, 2009; Pilskaln et al., 2007; Pilskaln and Lehmann, 1998; Walsh, 1994), plus sedimentary rates of carbon remineralization and burial (Burdige, 2007; Burdige et al., 1999; Christensen, 1989; DeMaster et al., 2002; Fennel et al., 2006; Jahnke et al., 2005; Jahnke et al., 2008; Keigwin, 2012; Middelburg et al., 1996; Rowe et al., 1988; Thomas et al., 2002). Calculated mean annual rates of the above fluxes for each of the three sub-regions are provided in Table 5. A fairly reasonable number of data sets for carbon export and the resuspension flux are available for the MAB and GoM but not for the SAB. Sediment remineralization (effectively the upward DIC flux at the sediment-water interface) was estimated by using both a literature-based remineralization rate vs. water depth regression (all sub-regions) and a mass balance calculation based on the nitrogen cycle (MAB only); the two methods yielded comparable results. Preliminary results suggest no significant difference in margin sedimentary remineralization rates between sandy sediments, which dominate the southern MAB and SAB study sub-regions, and muddy silts, which are found in the northern MAB and GoM (Figure 5). A similar regression approach was used for the upward DOC flux. Finally, burial fluxes were estimated using direct measurements of carbon accumulation, as well as carbon burial proxies and an organic C burial efficiency. The latter was based on approximations of the non-accumulating, relict sand content of sub-region sediments (e.g., 70%, 80%, and 90% for the GoM, MAB and SAB, respectively).

The benthic particle resuspension flux, occurring within the benthic nepheloid layer (BNL), represents a two-way particle flux near (10-30 m) the bottom, and was examined as part of the sediment-water synthesis. This flux may be part of a net source or sink of POC to the shelf sediments. Additionally, the shelf BNL likely makes a substantial contribution to the horizontal exchange of carbon with the ocean outside of the domain (Hwang et al., 2009; Thomas et al., 2004); also see Section 7.

In summary, many of the missing water column flux and sediment terms in the Najjar et al. (2010) budget were provided (Table 6). The level of certainty varies largely as a result of spatially and/or temporally limited direct observations. For some fluxes, such as sediment remineralization (weighted towards DIC fluxes), the certainty level is high ($\geq$95%) due to the reasonable agreement between values obtained by different methods. However, very limited data exist on DOC benthic fluxes. Confidence in the near-bottom POC resuspension fluxes is likewise high due to an abundance of time-series data sets in the sub-regions and there is overall moderate certainty ($\geq$60%) in the export fluxes resulting from either limited direct measurements or extremely wide ranges in reported values. Our certainty in the burial fluxes is low ($\leq$20%, MAB and SAB) to moderately low ($\leq$50%, GoM) as a result of large uncertainties in burial efficiencies, steady-state assumptions with respect to organic carbon input, burial and remineralization, and lack of spatially well-constrained information on depositional vs. erosional state of the sediments.

Short-term plans.

Budget terms from this synthesis will be refined and included in a planned GoM carbon budget paper that will include a section comparing the sediment-water exchange fluxes of the three study sub-regions (Pilskaln lead).

Long-term recommendations.

Despite the substantial improvements made as a result of this synthesis, the quantification of POC flux to the sediments in the region is weak in spatial and temporal coverage and additional measurements are needed. The fate of this flux, particularly as it is resuspended and transported laterally, is also minimally understood. Research should focus on quantifying the linkage between water column production (which is relatively well known), the sinking particle flux, lateral advection, and remineralization in sandy sediments. These linkages could be exploited for improving regional estimates of the POC flux to the sediments and sediment remineralization. Improvements are also needed in estimates of benthic algal production, which are currently limited (outside of estuaries) to the SAB, plus assessments of the contribution of chemoautotrophy to sediment carbon budgets (Middelburg, 2011).

7. Exchange at the ocean boundary

Contributors: P. Vlahos (lead), M. Friedrichs, and J. Xue

This flux team emphasized the importance of understanding the circulation of the region in order to constrain fluxes of carbon at the ocean boundary. The MAB, SAB, and GoM are very distinct dynamically with different advective processes dominating in different regions and at different times of the year. These advective processes include wind-driven currents and gyres, thermohaline currents (due, in part, to riverine freshwater input), warm- and cold-core rings, and filaments. Cross-shelf fluxes are dominated by cyclonic eddies in the GoM, the shelf-slope front in the MAB, and the Gulf Stream in the SAB. An argument was made for having the ocean-side boundary vary with time depending on the meandering of the current boundaries.

Approaches to constrain fluxes across the ocean boundary include analysis of observed tracer distributions and 3-D biogeochemical-circulation models. Tracer-based approaches suggest the MAB is a source of DOC and sink of DIC (Vlahos et al., 2002; Vlahos et al., 2012). In contrast, the NENA biogeochemical circulation model suggests, that at least for the year 2004, the MAB, SAB and GoM are all sources of POC and DIC (Hofmann et al., 2011). A revised version of this model including DOM dynamics was run for a four-year time period (2004-2007) and indicates that, on average, the shelf is a source of POC, DOC and DIC with fluxes ranging from 2-10 Tg C y^{-1} (Table 7); however, the temporal and spatial variability in these fluxes is large, particularly for DIC. Throughout this time period, the SAB is generally a sink for DIC, whereas in some years the MAB acts as a sink and in other years as a source.

Short-term plans

Work will continue on estimating carbon fluxes at the ocean boundary using the two approaches (tracers and numerical models). The tracer approach will be extended to include DIC and DOC data from the Ocean Margins Project (OMP). Two papers are planned on the following topics: (1) the carbon budget of a 3-D biogeochemical-circulation model of eastern

U.S. coastal waters (Friedrichs lead), and (2) an analysis of DIC and DOC observations from the OMP (Vlahos and Cai leads).

Long-term recommendations

Constraining carbon fluxes at the ocean boundary requires the water budget to be well known. Whereas the annual water budgets are reasonably well constrained, more work is needed to determine seasonal and interannual variability in these budgets with particular emphasis on the water fluxes between the subregions. Measurements of the velocity field and carbon concentrations at the ocean boundary in combination with a 3-D modeling system with data assimilation are needed to fully constrain water and carbon fluxes at the ocean boundary and between subregions. Models should be used to identify dominant areas of exchange and targeted sampling. Physical oceanographers who understand the mechanisms of water, salt, and heat transport between the coastal and open ocean are essential to the success of any effort to constrain the associated fluxes of carbon. Studies at subregional scales may be necessary in order to develop a successful methodology.

8. Primary production

Contributors: R. Vaillancourt (lead), W. J. Cai, M. Friedrichs, Z. Lee, A. Mannino, and C. Schaaf

The primary production (PP) team synthesized PP estimates in the study region (except for estuaries and wetlands) using data derived from published *in-situ* measurements, satellite-based algorithms, and the NENA model with DOM dynamics. Estimates based on *in-situ* measurements (^{14}C uptake) were compiled by the team from the literature, but have not yet been weighted spatially and temporally. The difference between net and gross primary production (which is due to autotrophic respiration) was emphasized, with longer incubations probably reflecting net PP and shorter incubations probably more representative of gross PP. The bulk of the literature PP values lie somewhere between net and gross rates, but probably closer to net. Benthic primary production (BPP) was also discussed and may be significant in the SAB and in nearshore environments throughout the region. For the SAB, Jahnke et al. (2008) found the earlier BPP estimates of Jahnke et al. (2005) to be too high. Mean BPP in the SAB is likely 1-2 mol C m^{-2} yr^{-1}, which integrates to about 1 Tg C yr^{-1}.

The PP team's estimates of regional internal C fluxes due to PP are summarized as follows (Table 1). For *in-situ* estimates, only those published reports where PP was measured on a seasonal basis (or at least seasonally from the beginning to the end of the growing season) were used. Two time-series studies provided robust estimates for PP in the greater GoM (including Georges Bank) and for Massachusetts and Cape Cod Bays, with areal estimates averaging 25 mol C m^{-2} yr^{-1}. Assuming this represents PP throughout the entire GoM region, a total regional estimate of about 47 Tg C yr^{-1} is found. For the MAB, literature estimates based on quasi-seasonally synoptic field studies provide an areal PP estimate of 33 mol C m^{-2} yr^{-1}, which integrates to 34 Tg C yr^{-1}. The SAB region's PP flux was based on the results of only one published field study, which provide an average areal PP estimate similar to the GoM and MAB of 32 mol C m^{-2} yr^{-1}, and a total regional estimate of 35 Tg C yr^{-1}.

Two satellite algorithms were considered and applied to the MAB: the Vertically Generalized Production Model (VGPM) and the Absorption Based Model (ABM). The models show similar results in the MAB except in summer, when the ABM estimates PP to be about 30% higher than the VGPM. The satellite algorithms often predict higher rates than the limited observations in the MAB would suggest. Rates simulated by the NENA model are lower than those derived from the satellite models and the limited observations. NENA estimates that between about 80 and 90% of the PP is in particulate form (depending on the subregion), with the remainder going to DOC.

It was concluded that PP is known relatively well in the study area (GoM + MAB + SAB ~120 Tg C yr^{-1}), with a subjective error estimate of ±25%. But the fluxes are large and therefore small fractional errors can have a large impact on the overall budget

Short-term plans

Several tasks were proposed for the near term, including a benthic PP literature review and the application of improved satellite PP algorithms to the whole region (not just the MAB). Thus, the PP team will continue its literature review and provide data for calibrating the PP algorithms. For example, an on-going NASA-funded project has measured *in situ* PP (^{13}C uptake) throughout the continental margins of the MAB and the GoM (including Georges Bank, GB). Seasonally and regionally averaged PP for these regions is about 23 mol C m^{-2} yr^{-1} with PP on GB (30 mol C m^{-2} yr^{-1}) consistently higher than in other areas. Preliminary results demonstrate strong seasonal and regional variability in PP. These estimates will be incorporated into the data synthesis and satellite algorithm calibration. Also, smaller subregions will be used for aggregating data and the DOC:POC ratio in PP will be estimated from the literature.

Long-term recommendations

A more exhaustive literature review, particularly for the SAB, is needed. Field studies that measure PP on a seasonal basis are rare and limited in spatial coverage, and this will lead to sub-regional biases when simple averaging is used for PP estimates. Ideally, regional PP estimates should be weighted for their relative areas whose boundaries are delimited by sub-mesoscale physical features that are known to cause smaller-scale spatial heterogeneity, such as tidal fronts, shelf-break fronts, and horizontal current shears. These fluid boundaries vary spatially and temporally, and this should be taken into account. PP estimates other than pelagic plankton should also be considered, such as the contribution by benthic macro- and micro-algae, and sub-aquatic vegetation (e.g., Duarte et al., 2005). Care must be taken to assure that the shoreward boundaries for the regional estimates do not overlap with (or produce spatial gaps) with PP estimates of estuaries.

In addition to better retrieval of biogeochemical properties of these coastal regions from satellite observations, improvements in the understanding of the temporal and spatial change of quantum yield are necessary. Also, how phytoplankton functional groups and their different photosynthetic efficiencies change temporally in this region should be studied and characterized. More seasonal studies of internal carbon fluxes should be proposed, but particularly those that utilize field data to tune satellite or numerical models for PP to achieve full spatial and temporal coverage, which is impossible using field studies alone.

9. Respiration and net community production

Contributors: W.-J. Cai (lead), M. Friedrichs, R. Najjar, P. Vlahos, and J. Xue

Respiration measurements are rare in the study region[4], with the exception of the SAB, where there are several published studies. As discussed in Section 4, NCP can be estimated by spatially and temporally integrating respiration and PP measurements. The most recent study to estimate NCP in the SAB suggests that community respiration is in excess of GPP in the SAB (not including wetlands and estuaries), indicating that NCP < 0, though the errors may be large enough as to make NCP indistinguishable from zero (Jiang et al., 2008).

Tracer-based, mass-balance approaches are another means for estimating NCP (Section 4). Knowledge of the residence time in a coastal system as well as the departure of a tracer, such as DIC, from the conservative mixing line, can be combined to compute NCP. Recent estimates using this approach suggest NCP < 0 in the SAB (net heterotrophic) and NCP > 0 in the MAB (net autotrophic).

Finally, NCP can be computed from coupled biogeochemical circulation models. For example, recent NENA runs suggest that on average NCP is greater than zero in all three regions, with total NCP for all three regions being roughly 14 ± 5 Tg C yr^{-1}.

Short-term plans

Seasonal nutrient drawdowns are another means of estimating NCP (e.g., Louanchi and Najjar, 2000); they provide a lower-bound estimate of NCP. This method is being used in the USECoS project and will be summarized in a paper along with NENA-based estimates (Najjar and Friedrichs leads). For the SAB, historical and recently measured respiration and primary production rates will be evaluated and synthesized together with DIC, O_2, and nutrient data.

Long-term recommendations

Because water column respiration is a dominant term in the overall carbon budget for the region, direct measurements of it are a high priority. Changes in DIC, oxygen, and nutrients in the seasonal thermocline may also put constraints on respiration. The importance of NCP also makes improved estimates of it a high priority in the study region. Approaches more common in the open ocean, such as the O_2/Ar method, should be adopted in the study region as well as the continuation of direct measurements of the respiration rate using bottle incubations. Care must be taken to define the depth of integration for computing NCP, with possible zones being the mixed layer, the euphotic zone, and the whole water column (including sediments). These measurement approaches should be combined with efforts to model NCP from space. There have been some advances in satellite-based particle export estimates for the open ocean (Dunne et al., 2005; Laws et al., 2000), and these should be extended to particle export and NCP in coastal waters.

[4] The paucity of the respiration measurements is due, in part, to the success of the ^{14}C method for measuring primary production; the previously used O_2 incubation method, which included a respiration measurement, was less accurate and more time consuming for measuring PP and became outdated

10. Workshop summary and overall recommendations

Contributors: Workshop participants

This workshop made substantial advances in our knowledge of the carbon budget of the coastal zone of the eastern U.S. Most notable were the creation of first estimates of sedimentary and tidal wetland budgets for the region as well as significantly improved estimates of riverine carbon inputs to the coastal zone, CO_2 exchange between shelf waters and the atmosphere, and model-based estimates of advective carbon exchange with the open ocean. Figure 6 summarizes the state of knowledge of the U.S. east coast carbon budget at the end of the workshop. Primary production is easily the largest measured term in the overall budget, with a best estimate of about 150 Tg C yr^{-1}. About 20% of the primary production in the study area takes place in tidal wetlands, which account for only 2% of the total area. Respiration (non-algal) is probably comparable to (net) primary production but it has not been measured adequately with the exception of some selected systems (e.g., the South Atlantic Bight and Chesapeake Bay).

Short-term plans

Strategies were developed to make substantial improvements in all of the fluxes over the short term (6-12 months). These include:

- Intercomparsion of the four different models of riverine carbon fluxes and elimination of any double counting of carbon fluxes with the tidal wetlands flux team.
- Extension of the existing approach for estimating tidal wetlands fluxes (net primary production, burial, and lateral export) by making it more spatially explicit and by refining estimated C flux rates for each tidal wetland type.
- Estimation of estuarine net community production and organic C burial in the region's estuaries through an observational synthesis and application of statistical and mass balance box models.
- Incorporation of additional pCO$_2$ data and further development of the satellite-data-based air-sea CO_2 flux model using additional variables and approaches.
- Refinement of the sediment C budget and a detailed Gulf-of-Maine carbon budget that will include comparison of the sediment-water fluxes of the three study subregions.
- Estimation of carbon fluxes at the ocean boundary using (a) the tracer approach with dissolved inorganic and organic carbon data from the Ocean Margins Project and (b) a 3-D biogeochemical-circulation model.
- Development of improved satellite primary productivity algorithms using available data for calibration and application of the algorithms to continental shelf waters in the region.
- A more complete literature review of benthic primary production throughout the study area.
- Estimation of net community production in coastal waters using a 3-D biogeochemical model and observed seasonal nutrient drawdowns determined from historical data.
- Evaluation and synthesis of historical and recently measured respiration and primary production rates in the SAB.

Long-term recommendations

Several overarching themes emerged from the workshop and led to specific long-term recommendations for improving our understanding of carbon cycling in coastal waters of the eastern U.S. and elsewhere:

- Discussions and interactions at the workshop were synergistic, with knowledge being created as a result of sharing information among scientists that do not normally go to the same meetings and publish in the same journals. Therefore, continued and enhanced cross-disciplinary interaction is essential for a comprehensive understanding of carbon fluxes in coastal systems.
- Though all fluxes of the carbon cycle in coastal waters of the eastern U.S. need their uncertainty reduced, improvement is essential for the following fluxes for which very little is known: exchange of CO_2 between the atmosphere and estuaries; net primary production and respiration in respiration in tidal wetlands and estuaries; lateral advective fluxes between estuaries and the coastal ocean, and between the coastal ocean and the open ocean; and respiration in shelf waters.
- The strong heterogeneity and variability within coastal systems demands innovative methods for scaling up local flux estimates. Remotely sensed data have already proven to be effective for estimating air-sea CO_2 fluxes and primary production in the coastal ocean. Techniques are needed for exploiting remotely sensed and other high-resolution data sets for scaling up other carbon fluxes in the coastal zone, including the estuarine air-sea CO_2 flux and primary production, exchange with the open ocean, sedimentary fluxes, and net community production.
- Because of the difficulty in quantifying flux errors in coastal systems (resulting, in part, from their heterogeneity), it behooves us to make as many independent estimates of a given flux as possible. This approach has already proven fruitful for more robustly estimating errors in riverine and air-sea CO_2 fluxes and should be attempted for other fluxes in the coastal zone.
- Mechanistic numerical models of coastal zone biogeochemistry, with their strong physical basis and internal consistency, are a powerful complement to observations for constraining carbon fluxes in the coastal zone. Such models have witnessed rapid development for terrestrial systems upstream of the head of tide and in shelf waters, and are now commonly applied at the regional scale. In contrast, there is a need for the development and regional application of biogeochemical models of tidal wetlands and estuaries in order to link the land to the sea.
- Transcending many of the above recommendations is the recurring need for small- to large-scale field studies that address physical fluxes and biogeochemical processes, and are suitable for the development and evaluation of mechanistic models and satellite retrievals.

Table 1. Workshop participants.

Name	Institution
Richard B. Alexander	U.S. Geological Survey
Iris C. Anderson	Virginia Institute of Marine Science
Elizabeth Boyer	The Pennsylvania State University
David Burdige	Old Dominion University
David Butman	Yale University
Wei-Jun Cai	The University of Georgia
Elizabeth A. Canuel	Virginia Institute of Marine Science
Robert F. Chen	University of Massachusetts Boston
Cathy Feng	Virginia Institute of Marine Science
Marjorie A. M. Friedrichs	Virginia Institute of Marine Science
Peter C. Griffith	NASA GSFC / Sigma Space
Eric Hall	Virginia Commonwealth University
Maria Hermann	NASA GSFC / Sigma Space
Victoria Hill	Old Dominion University
Eileen Hofmann	Old Dominion University
Xinping Hu	The University of Georgia
Michael Kemp	University of Maryland
Kevin D. Kroeger	U.S. Geological Survey
Zhongping Lee	University of Massachusetts Boston
Antonio Mannino	NASA GSFC
S. Leigh McCallister	Virginia Commonwealth University
Wade McGillis	Lamont-Doherty Earth Observatory
Raymond G. Najjar	The Pennsylvania State University
Diego A. Narváez	Old Dominion University
Cynthia Pilskaln	University of Massachusetts Dartmouth
Joe Salisbury	University of New Hampshire
Crystal B. Schaaf	University of Massachusetts Boston
Sergio Signorini	NASA GSFC / SAIC
Richard A. Smith	U.S. Geological Survey
Hanqin Tian	Auburn University
Maria Tzortziou	University of Maryland
Robert Vaillancourt[a]	Millersville University
Penny Vlahos	University of Connecticut
Zhaohui Aleck Wang	Woods Hole Oceanographic Institution
Yongjin Xiao	Virginia Institute of Marine Science
Richard C. Zimmerman	Old Dominion University

[a]Was unable to attend but organized workshop presentation and contributed to the writing of this report.

Table 2. Estimates of riverine input to coastal waters (Tg C yr^{-1}). The ranges are based on the four models that were employed (see text).

	DIC	DOC	POC	Total
GoM	0.2-0.8	0.3-2.1	0.1-0.2	0.6-3.1
MAB	1.4-1.8	0.5-2.3	0.1-0.3	2.0-4.4
SAB	0.4-1.4	0.9-1.6	0.1-0.2	1.4-3.2
Total	**2.0-4.0**	**1.7-6.0**	**0.3-0.7**	**4.0-10.7**

Table 3. Estimates of tidal wetland fluxes (Tg C yr^{-1}).

	NPP	Burial	Lateral DIC export	Lateral DOC export	Respir-ation[b]	Degas-sing[c]	Uptake from atom-sphere[d]
GoM	NA	0.1	0.1	0.1	NA	NA	NA
MAB	NA	0.8	0.9	0.8	NA	NA	NA
SAB	10.1[a]	1.2 (0.3[a])	1.2 (0.8[a])	1.0 (5.5[a])	7.9 (5.0[a])	6.7 (1.6[a])	3.4 (6.6[a])
Total	**13-24**	**1-2**	**2**	**2-6**	**5-21**	**3-19**	**5-10**

[a]Cai (2011)
[b]Computed from NPP – Burial – Lateral DOC export
[c]Computed from Respiration – Lateral DIC export
[d]Computed from Burial + Lateral DIC export + Lateral DOC export

Table 4. Estimates of air-to-sea CO_2 fluxes for the different subregions made using different techniques (Tg C yr^{-1}).

	Data[a]	**Data**[b]	**Algorithm**[b]	**NENA**[c]
GoM	-0.9 ± 0.5	-0.8 ± 0.4	-	2.5 ± 1.0
GB + NS	0.3 ± 0.3	0.2 ± 0.1	-	1.0 ± 0.4
MAB	2.2 ± 0.4	1.5 ± 0.3	2.2	1.2 ± 0.2
SAB	1.0 ± 0.4	1.3 ± 0.3	1.3	0.6 ± 0.3
Total	**2.6 ± 1.6**	**2.2 ± 0.9**	**-**	**5.3 ± 1.9**

[a]Uses T. Takahashi 2010 pCO_2 synthesis with additional data from W. J. Cai, J. Salisbury, and D. Vandemark.
[b]Uses SOCAT with above additional data.
[c]Cahill et al. (in preparation).

Table 5. Mean (and range) estimates of particle and sedimentary fluxes (mol C m^{-2} yr^{-1}).

	Surface water POC export	**Resuspension flux**	**Benthic DIC + DOC flux**	**POC burial**	**POC available for lateral exchange**[a]
GoM	3.0 (0.3-6.0)	2.4 (0.4-4.6)	2.7 (2.6-4.1)	0.2 (0-2.1)	2.2
MAB	1.7 (0.5-1.9)	5.0 (1.8-13.3)	3.7	0.2 (0-1.2)	4.8
SAB	NA	1.8 (0.4-3.1)	4.3	0.1 (0-1.3)	1.7

[a]Resuspension flux – POC burial

Table 6. Integrated particle and sedimentary fluxes (Tg C yr^{-1}).

	Surface water POC export	Resuspen-sion flux	Benthic DIC + DOC flux	POC burial	POC available for lateral exchange[a]
GoM[b]	6.1	4.8	5.4	0.5	4.3
MAB	1.7	5.1	3.9	0.24	4.9
SAB	NA	1.7	4.7	0.15	1.6
Total	**>7.8**	**11.6**	**14.0**	**0.9**	**10.5**

[a]Resuspension flux – POC burial
[b]Includes Nantucket Shoals and Georges Bank

Table 7. Cross-shelf carbon fluxes computed from a revised version of NENA (Tg C yr^{-1}). Uncertainties are computed as two standard errors of the mean. Positive numbers indicate that the shelf is acting as a source of carbon.

	DIC	POC	DOC
GoM[a]	7.7 ± 1.9	1.0 ± 0.1	2.1 ± 0.2
MAB	1.6 ± 0.9	0.6 ± 0.2	1.8 ± 0.2
SAB	-3.3 ± 1.1	3.9 ± 0.2	4.1 ± 0.4
Total	**5.9 ± 3.0**	**5.5 ± 0.3**	**8.1 ± 0.6**

[a]Includes Nantucket Shoals and Georges Bank

Table 8. Water-column primary production estimates (Tg C yr^{-1}).

	Data	Satellite	NENA
GoM[a]	47 ± 20	-	32
MAB	34 ± 10	44 - 48	18
SAB	35 ± ?	-	27
Total	**120 ± 30**	-	**67**

[a]Includes Nantucket Shoals and Georges Bank

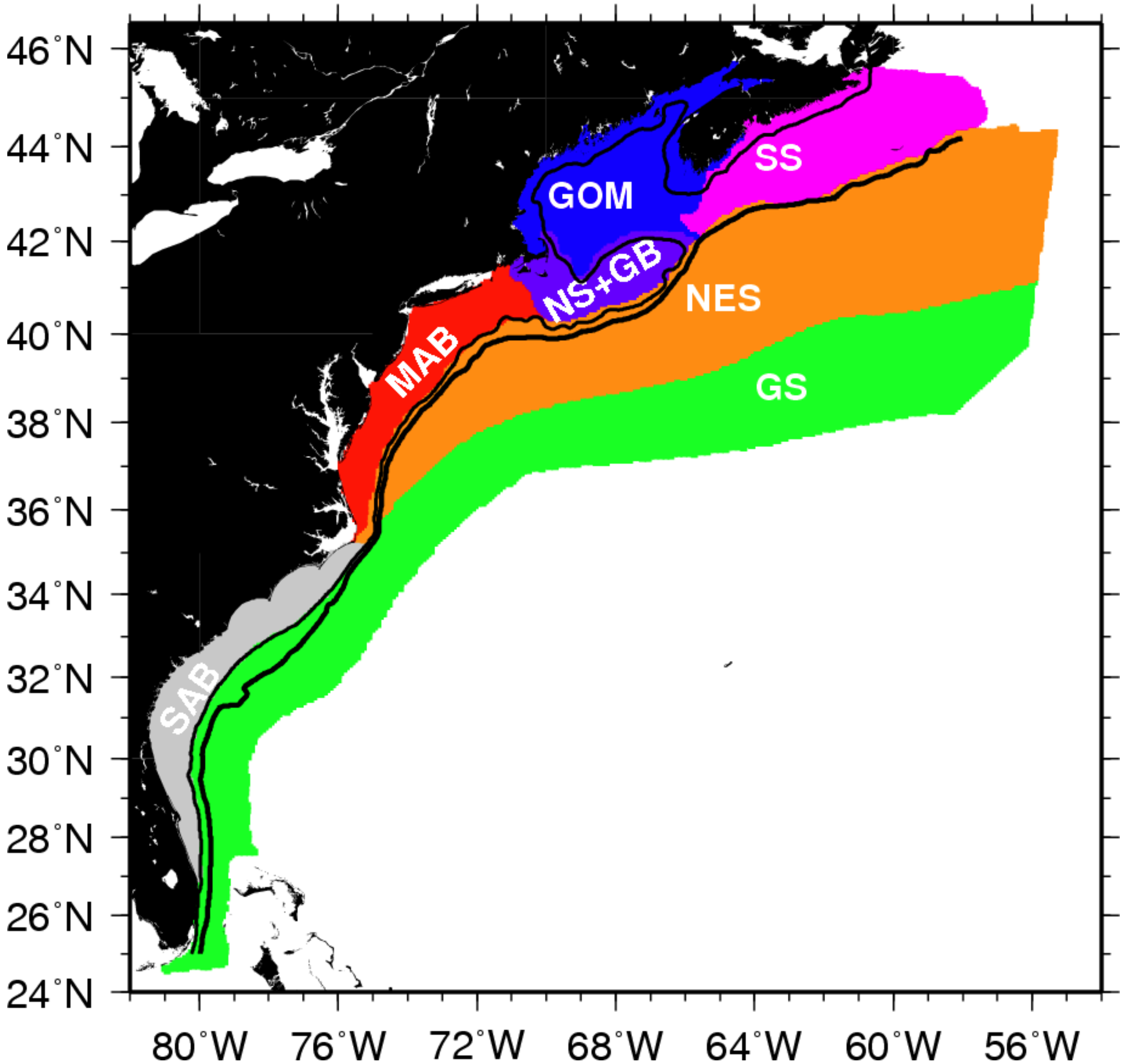

Fig. 1. Map showing seven large subregions in the western North Atlantic Ocean and the 100-m (thin black line) and 500-m (thick black line) isobaths. Four of the subregions are inside the study area: the Gulf of Maine (GoM), Nantucket Shoals and Georges Bank (NS + GB), the Mid-Atlantic Bight (MAB), and the South Atlantic Bight (SAB). The subregions are aggregates of smaller subregions defined in Hoffmann et al. (2008). Their respective areas are 11.5, 5.2, 8.6, and 9.2×10^{10} m^2. In many analyses in this report, the GoM is taken to include NS + GB, with a total area of 16.7×10^{10} m^2. Subregions outside the study domain are the Scotian Shelf (SS), the Northeast Slope (NES), and the Gulf Stream (GS). Figure courtesy of S. Signorini.

Fig. 2. Map depicting the 53 gauging stations along the U.S. east coast used for making riverine carbon flux estimates at the fall line. Blue, pink, and yellow shading depict the watersheds associated with these gauging stations in the SAB, MAB, and GoM, respectively. Green indicates the rest of the watershed that drains to the east coast and the eastern Gulf of Mexico. From Stets and Striegl (2012).

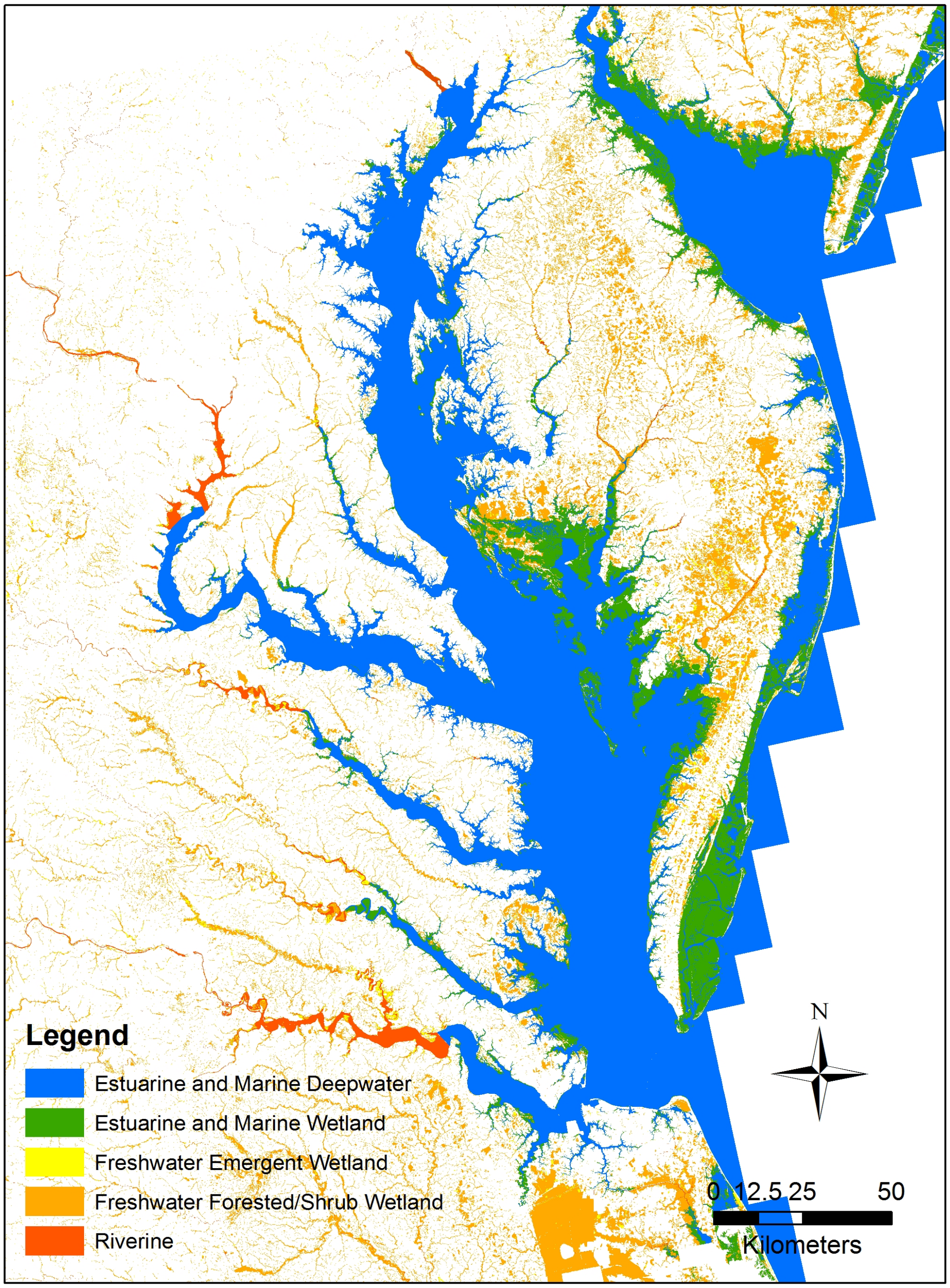

Fig. 3. Distribution of wetland types for a portion of the mid-Atlantic coastal zone that includes Chesapeake Bay (center) and Delaware Bay (upper right). Source: National Wetlands Inventory, U.S. Fish and Wildlife Service.

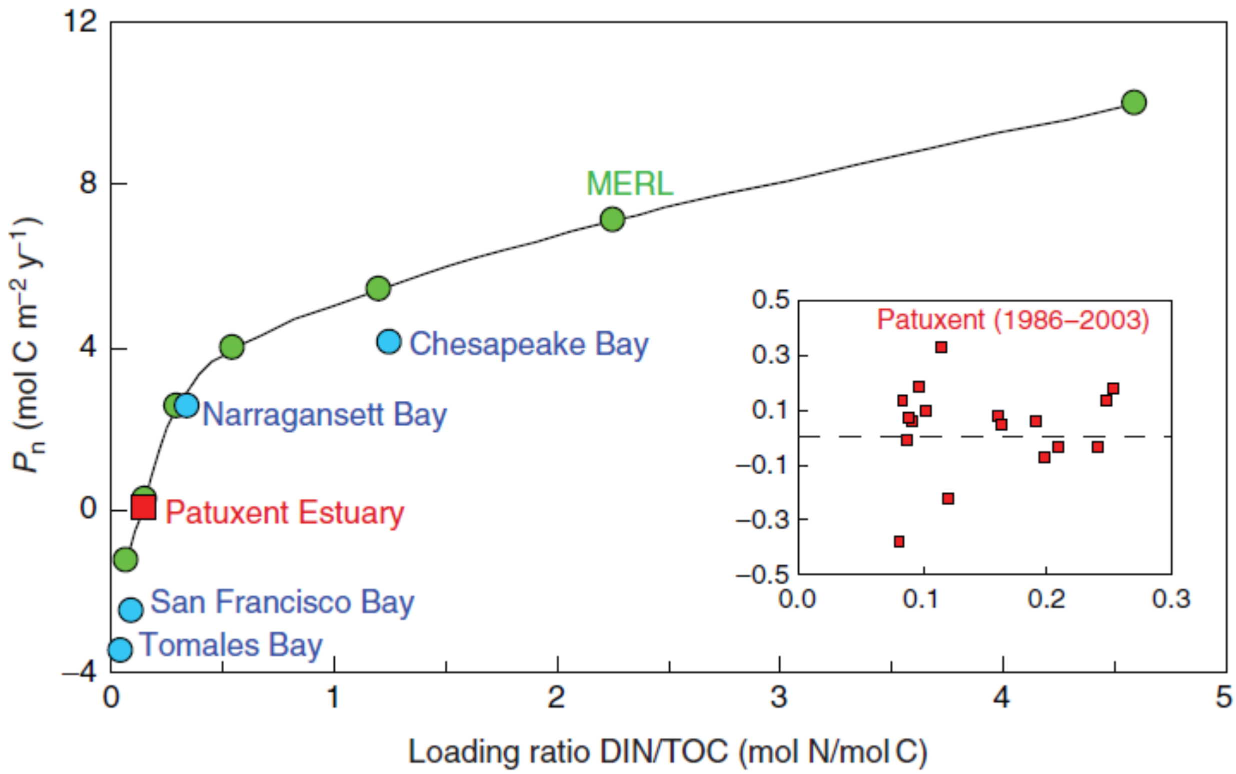

Fig. 4. Relationship between net community production (given by the symbol P_n here) and the loading ratio of dissolved inorganic nitrogen (DIN) to TOC. Blue circles (Kemp et al., 1997) and the red square (Testa et al., 2008) are mean values from individual estuaries and the green circles are from mesocosm experiments (Oviatt et al., 1986). The inset shows the relationship between P_n and the loading ratio for individual years in the Patuxent estuary (Testa et al., 2008). Reproduced from Kemp and Testa (2011).

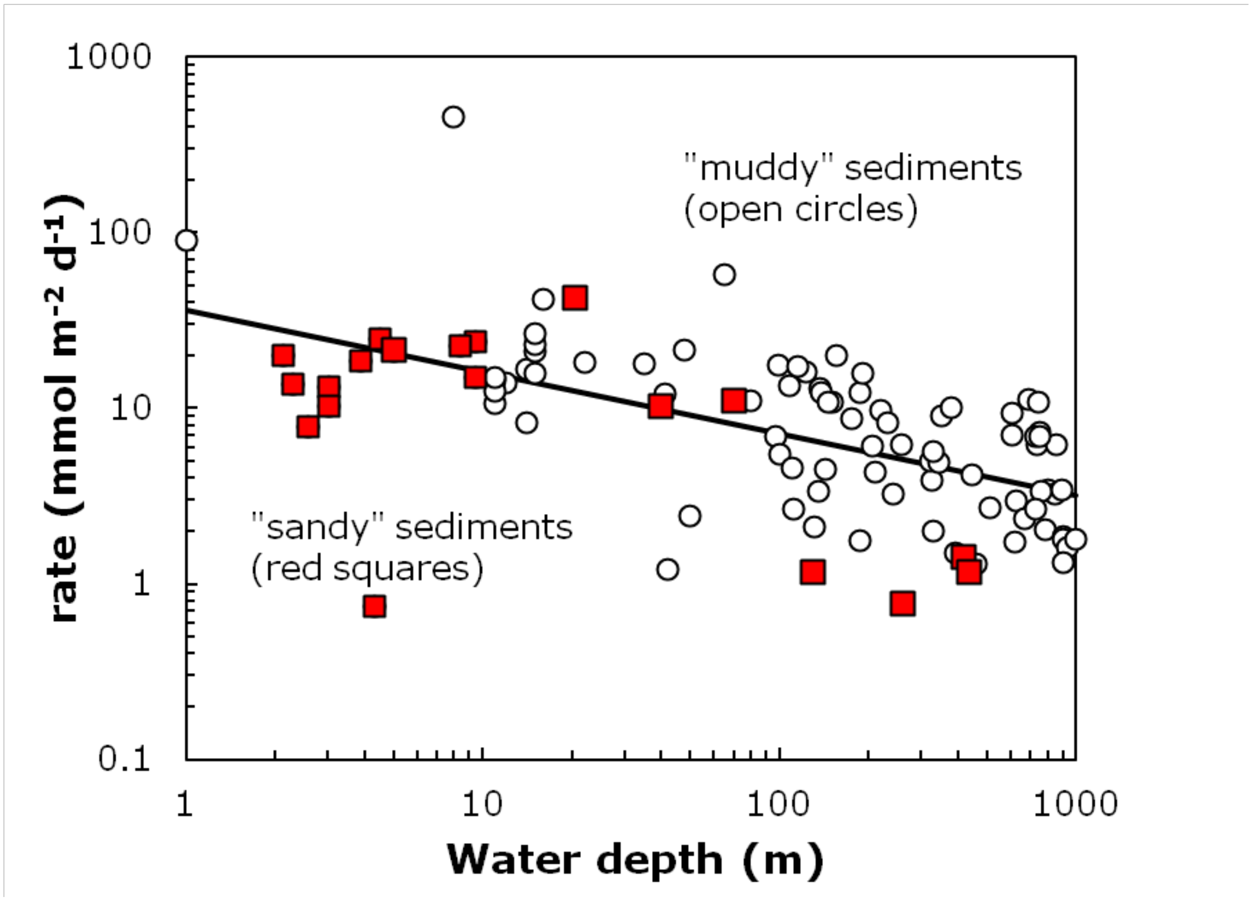

Fig. 5. Sedimentary organic carbon remineralization rate as a function of water depth. Data are summarized in Burdige (2007) with additional data from Rowe et al. (1988) and Anderson et al. (1994).

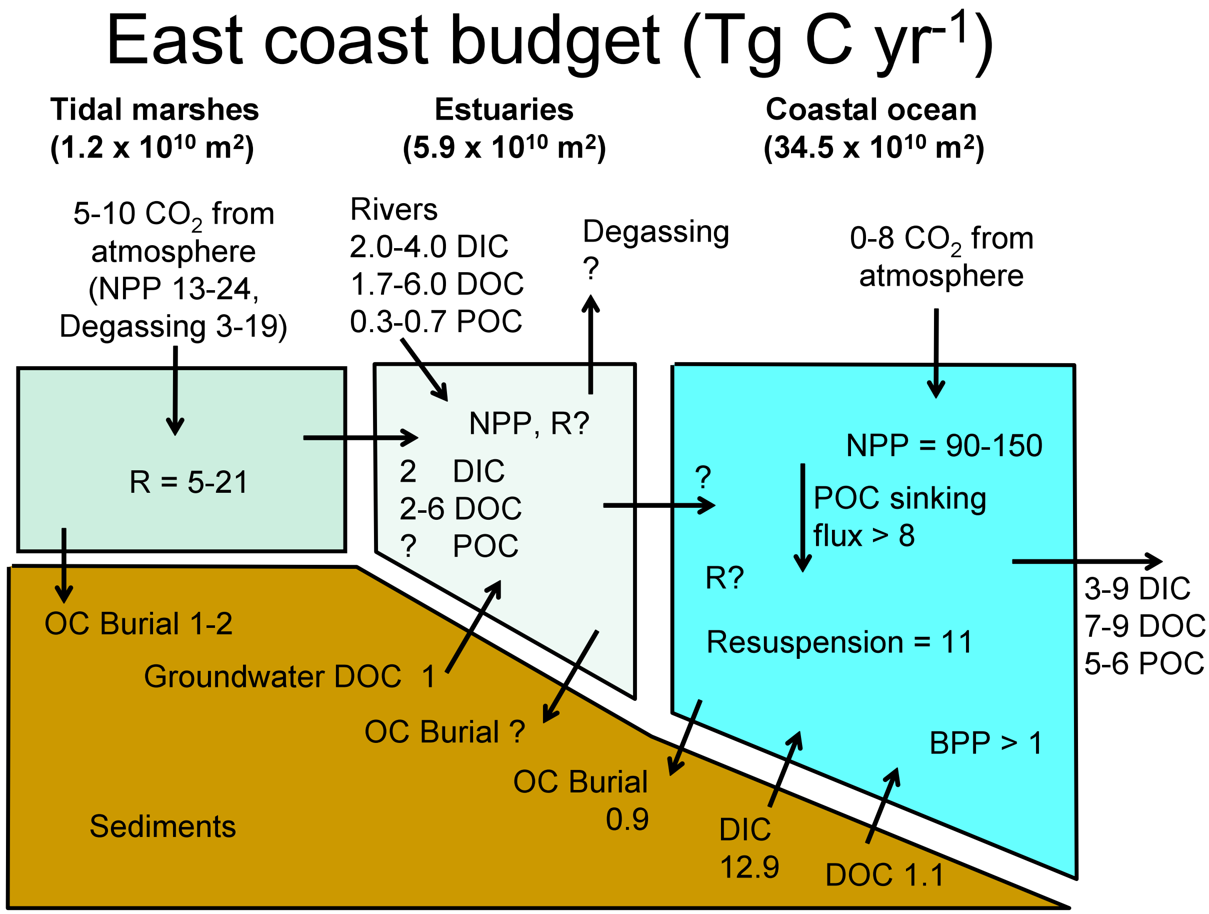

Fig. 6. Preliminary carbon budget for the coastal zone of the eastern U.S. based on synthesis activities conducted in preparation for the workshop and shortly thereafter. R = respiration, OC = organic carbon, BPP = Benthic primary production.

Appendix

U.S. East Coast Carbon Cycle Synthesis Workshop Agenda

Classroom A/B, Waterman's Hall

Virginia Institute of Marine Science

Rte. 1208 Greate Rd, Gloucester Point VA

Thursday, 19 January 2012

0745 Continental Breakfast

0830 Welcome (*M. Friedrichs*)

0835 Overview of the Coastal Carbon Cycling project (*P. Griffith*)

0850 East Coast Carbon Budget: progress to date (*R. Najjar*)

Budget outlined in 2010

Discussion of choices for regional areas/boundaries

9:15 Group updates (15-20 min presentations followed by 10-15 min discussion)

Air-sea interface (*A. Wang*)

Cross-shelf fluxes (*P. Vlahos*)

10:15 Morning Break

10:30 Group updates cont. (15-20 min presentations followed by

10-15 min discussion)

Primary production (*M. Friedrichs*)

NCP/respiration (*W.-J. Cai*)

Sediment-water interface (*C. Pilskaln* & *D. Burdige)*

12:00 Lunch (catered at VIMS)

13:00 Group updates cont. (15-20 min presentations followed by

10-15 min discussion)

Rivers (*D. Butman*)

Tidal wetlands (*K. Kroeger*)

Estuaries (*M. Kemp*)

1430 Group discussion (*M. Friedrichs, R. Najjar, W. Cai*)

1500 Break-out groups

Cross-shelf fluxes (3:00-4:15); PP + NCP (4:15-5:30)

Tidal wetlands/estuaries

Rivers

Sediment-water interface

Air-sea interface

1730 Adjourn, dinner on own

Friday, 20 January 2012

0745 Continental Breakfast, optional breakout discussions

0830 Breakout Reports (15 minutes)

Air-sea interface

Cross-shelf fluxes

Primary production and NCP/respiration

Sediment-water interface

Rivers

Tidal wetlands/estuaries

1000 Morning Break

1015 East coast carbon budget: revisited (*R. Najjar*)

1130 Final plenary discussion; where do we go from here?

1230 Adjourn (*box lunches provided to those who placed orders)*

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