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Understanding Coastal Carbon Cycling by Linking Top- Down and Bottom-Up Approaches

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PAGE 315

The coastal zone, despite occupying a small fraction of the Earth's surface area, is an important component of the global carbon (C) cycle. Coastal wetlands, including mangrove forests, tidal marshes, and seagrass meadows, compose a domain of large reservoirs of biomass and soil C [*Fourqurean et al.,* 2012; *Donato et al.,* 2011; *Pendleton et al.,* 2012; *Regnier et al.,* 2013; *Bauer et al.,* 2013]. These wetlands and their associated C reservoirs (2 to 25 petagrams C; best estimate of 7 petagrams C [*Pendleton et al.,* 2012]) provide numerous ecosystem services and serve as key links between land and ocean.

However, these coastal resources are in jeopardy from a variety of threats. Land use change, nutrient pollution, urbanization, and climate change (e.g., sea level rise) are affecting C cycling in the coastal zone, with the potential to alter exchanges of carbon dioxide (CO_2) with the atmosphere and therefore affect the longer-term stability and function of these and adjacent systems.

While information regarding coastal C cycling is developing rapidly, variation within and among coastal ecosystems contributes to high uncertainties in component stocks and fluxes. For example, the issue of "missing C" in mangrove forests persists [*Maher et al.,* 2013]. That is, the sum of C sinks, including C accumulation, soil respiration, burial, and export, is falling well short of net ecosystem productivity estimates.

The scientific community increasingly recognizes that interdisciplinary teams are essential for synthesis and integration to achieve the goal of constraining and improving C budgets. Despite the broad variation in techniques and their spatiotemporal scopes, there are several common themes on which to base integration and synthesis to reconcile coastal C budgets. Here we develop a coastal C cycle road map to facilitate this goal.

What Is the Coastal Carbon Cycle?

Coastal C cycling, as defined here, is the set of all biogeochemical processes and lateral aquatic fluxes of C that occurs within the coastal domain residing between the terrestrial system and the open ocean. The coastal C domain consists of subdomains of flooded or partially flooded ecosystems, such as tidal freshwater and brackish marshes, mangrove forests and salt marshes, seagrass meadows and the coastal ocean, and estuarine waters and tidal rivers, which form a broad, integrated "biogeochemical reactor." Inputs of terrestrial C enter and are subsequently transformed within the biogeochemical reactor to other forms, including dissolved and particulate organic and inorganic C. Carbon that is not stored via burial in soils and sediments may exit the coastal ocean through CO_2 outgassing or export to the open ocean, with C import across these interfaces also possible.

Establishing a C Accounting Framework and a Complementary Set of Equations

A consistent C accounting framework should clearly define the physical boundaries of the system and identify major routes of C entering or exiting the system. At regional and global scales, mass balance diagrams [e.g., *Cai,* 2011] and an underlying set of mass balance equations have been used to identify physical locations or components of the coastal C budget and to integrate and summarize rates of exchange between these components. Every effort must be made to create internal consistency in all aspects of a C accounting framework. This includes matching between conceptual models, sets of equations, boundary positions, and definition of terms. Such a framework is essential to prevent double counting of C as it enters one subdomain, undergoes biogeochemical processing, and is finally stored in or exported to an adjacent subdomain.

The quality and integrity of regional C budgets rest on mass balance approaches developed at fine scales, such as that of an individual marsh, river, or estuary. At these scales, the net ecosystem C balance (NECB) [*Chapin et al.,* 2006] represents a key term for understanding coastal C cycling and is quantified by summing the annual change in the system's organic C pools.

NECB has become a central theme and rallying point for collaborations aimed at understanding the complexities of C cycling in coastal systems [e.g., *Troxler et al.,* 2013] and has helped to identify several practical challenges. For example, how can components of the C budget be synchronized across space and time? What are effective means for integrating primary productivity and other C fluxes across spatially heterogeneous coastal regions? How do we transition from qualitative observations (e.g., those of forest spatial patterns) to quantitative, scalable, and meaningful integration of spatial variation in regional estimates of C fluxes (e.g., mangrove net primary productivity)?

By answering these types of questions, conceptual models that integrate variability inherent to C cycling can be parameterized, and uncertainties can be reduced to improve predictions of land use impacts in the coastal domain and feedbacks to atmospheric CO_2.

Spatiotemporal Integration and the Future of Regional and Global Coastal C Budgets

Scientists and policy makers are contending with the many complexities of quantifying regional and global C budgets by constructing functional hierarchies that enable interaction and feedback at multiple levels and that can feed to national-scale methodologies and global assessments [e.g., *Intergovernmental Panel on Climate Change,* 2014]. The conceptual hierarchical structure of coastal C cycling science can be envisioned as a pyramid that depicts levels of communication and integration that are required among principal investigators, policy makers, and government and intergovernmental organizations. The foundation of this pyramid is represented by research targeting specific, small-scale fluxes and internal biogeochemical processing of C. These efforts, led by principal investigators, involve small teams of several to tens of people and are limited in scope temporally (i.e., hours to years) and spatially (i.e., square meters to several square kilometers).

The next level of the pyramid, process-based integration, is necessary for piecing together C budgets over several seasons to multiple years at a local scale (e.g., for a single subdomain). Identification of understudied fluxes and processes becomes an opportunity to promote, integrate, and transform small-scale efforts into coordinated research campaigns to satisfy the demand for data that can address environmental drivers at ecosystem scales. For instance, collaborations have vastly improved process-based understanding of C cycling between terrestrial and permafrost sources and adjacent waters of the East Siberian Arctic Shelf [*Semiletov et al.,* 2012].

Of higher order and at the scale of entire continental shelves, C budgets may best be quantified through a systems-level approach. This approach encompasses multiple monitoring platforms operating continuously over years to decades, intelligent and informed sampling across heterogeneous ecosystems, use of large databases, and complementary and synergistic use of measurements and modeling techniques. This systems-level integration has not yet been fully realized, but examples include those for the North American coasts of the Arctic and Atlantic Oceans [*Mathis and Bates,* 2010; *Najjar et al.,* 2012].

Individual studies of integrated, process-based, and system approaches form the basis for the top layer of the pyramid: synthesis and scaling of C budgets. International and multiorganizational teams composed of technical staff and policy makers can address the challenges of integrating results from regional teams by developing a common language for coastal C science and using independent verification of findings as a means to synthesize and constrain C budget data.

Top-down functioning of the pyramid occurs as regional C budgets are derived and critical knowledge gaps in conceptual and numerical models are identified. Knowledge gaps may be identified in any of the top four layers of the pyramid, from process-based integration to development of regional and global C budgets. However, the flow of information and ideas is driven by bottom-up approaches used in smaller-scale experiments and accumulated expertise of individual researchers. Moving forward, linking top-down and bottom-up approaches will implicitly target new questions about coastal C budgets, will quantify the current societal and economic value of coastal ecosystems, and will determine the anthropogenic influences or natural forcings that are likely to modify them.

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