Research Communications

Coastal morphology explains global blue carbon distributions

Robert R Twilley^{1*}, André S Rovai^{1,2}, and Pablo Riul³

¹*Department of Oceanography and Coastal Sciences, College of the Coast and Environment, Louisiana State University, Baton Rouge, LA * (rtwilley@lsu.edu);*

²*Programa de Pós-Graduação em Oceanografia, Universidade Federal de Santa Catarina, Florianópolis, Brazil;* ³*Departamento de Sistemática e Ecologia, Universidade Federal da Paraíba, João Pessoa, Brazil*

Running heads:

RR Twilley *et al.*

Coastal geomorphology and blue carbon

Mangroves store greater amounts of carbon (C) per area than any other terrestrial ecosystems, so that conservation of mangrove forests on a global scale represents a potentially meaningful strategy for mitigating atmospheric greenhouse-gas emissions. However, analyses of how coastal ecosystems influence the global C cycle also require the mapping of ecosystem area across the Earth's surface to estimate C storage and flux (movement) in order to compare how different ecosystem types may mitigate greenhouse gas enrichment in the atmosphere. We propose a new framework based on diverse coastal morphology (that is, diverse coastal environmental settings resulting from how river, tide, wave power, and climate shape coastal landforms) to explain global variation in mangrove C storage using soil organic carbon (SOC) as a model to more accurately determine mangrove contributions to global C dynamics. We present – to the best of our knowledge – the first global mangrove area estimate occupying distinct coastal environmental settings, comparing the role of terrigenous and carbonate settings as global “blue carbon” hotspots. C storage in deltaic settings have been overestimated, while SOC stocks in carbonate settings have been underestimated by up to 50%. We encourage the scientific community, which has largely focused on blue carbon estimates, to incorporate coastal environmental settings to obtain more robust estimates of global C stocks.

Front Ecol Environ 2018;

Coastal landforms at the interface of land and sea are diverse with geomorphology responding to sedimentary processes forming intertidal zones ranging from depositional environments shaped by rivers, waves, and tides, to carbonate sediments formed through biological processes (Woodroffe 1992). Mangroves colonize the intertidal zone of these

diverse coastal landforms in subtropical and tropical climates typically composed of shrubs and trees forming extensive forested wetlands along both muddy and carbonate coasts. Terrigenous coastal settings are sediment-rich depositional coastal environments where terrestrial sediments from rivers form coastal landform patterns depending on influence of tides and waves, forming the intertidal platform that mangroves inhabit. Terrigenous settings include deltas (Fly River delta, New Guinea), estuaries (Ord estuary, Australia), lagoons (Terminos Lagoon, Mexico) and strands (Senegal delta). In contrast, intertidal platforms along carbonate coastal settings are formed by in situ processes of sediment deposition, resulting from a combination of carbonate formation and mangrove productivity, both of which originate largely through carbon fixation. Carbonate settings comprise karstic environments (such as southwestern Florida and many islands in the Caribbean) and Holocene reef tops, including mangroves bordering oceanic islands. Based on local hydrology, geomorphology, and climate, these two sedimentary settings can be classified into several distinct coastal environmental settings, including deltas, estuaries, and lagoons, as well as bedrock (drowned river valley), composite river/wave-dominated, and carbonate settings (Thom 1982; Woodroffe 1992). The ecological processes (e.g. primary productivity, food webs, nutrient cycling) associated with mangroves vary among these coastal environmental settings, which may explain the global diversity of mangrove habitats (Thom 1982). In comparison to terrestrial woodlands, where climate and soil moisture largely control these ecosystem processes (Holdridge 1967; Post *et al.* 1982), mangrove forests thrive in dynamic coastal landforms controlled by physical forcings (e.g. rivers, tides, waves) that controls sedimentary processes (e.g. sedimentation and geochemistry), hydrology, and microtopography of the intertidal zone (Boyd *et al.* 1992; Woodruffe 2002).

Global estimates of carbon dioxide (CO₂) fluxes based on landform classifications provide insights into Earth system dynamics associated with how land-use change contributes to CO₂ enrichment in the atmosphere. The present rate of atmospheric CO₂ enrichment represents a positive balance between industrial sources that contribute CO₂ and net continental and oceanic (ie Earth surface) sinks that remove CO₂ from the atmosphere (Houghton 2007). One flux that is often omitted in annual updates of the global carbon (C) budget is C transport across the land–ocean aquatic continuum (ie the coastal zone; Le Quéré *et al.* 2016). As forested wetlands at the terrestrial–aquatic interface, mangroves have long been recognized for their potential role as a major global C sink, thereby helping to mitigate atmospheric CO₂ enrichment (Twilley *et al.* 1992).

Although studies focusing primarily on local and regional C stocks have increased greatly in number over recent decades, only a handful have attempted to provide estimates of global mangrove C budgets (Chmura *et al.* 2003; Bouillon *et al.* 2008), even though mangroves are generally considered to be the most C dense forests in the tropics (Donato *et al.* 2011). Moreover, only recently have specific models been developed to account for global variation in mangrove soil organic carbon (SOC) stocks, where most

of the C in mangrove systems is stored (Jardine and Siikamäki 2014; Atwood *et al.* 2017). Here, we propose a novel framework, based on coastal morphology, to explain the differences among observed data as a means of improving global estimates of mangrove SOC stocks.

Several attempts have been made to describe how ecological processes vary with classifications of coastal morphology (Ewel *et al.* 1998; Day *et al.* 2008; Twilley *et al.* 2017), but global analyses of how different coastal morphologies are distributed in the tropics to determine global estimates of ecological processes, such as C sinks, are scarce. Recently, however, a spatially explicit global typology (ie classification scheme) for nearshore coastal systems – based on numerical analyses of river basin run-off, tidal ranges, and coastal lithology – provided a robust spatial representation of dominant coastal environmental settings worldwide (Dürr *et al.* 2011). Similar to earlier attempts at classifying coastal environmental settings (Thom 1982; Woodroffe 1992), this global typology of coastal morphology recognizes large rivers and small deltas (grouped as “deltaic” by Thom [1982]), tidal systems (estuaries, bedrock), lagoons (including composite settings, as defined by Thom [1982]), and carbonate coastal settings, but also includes dry coastlines, referred to as “arheic”. The dry coast of Peru, the Gulf of California, the Red Sea, and the Persian Gulf are examples of locations where mangroves can be found in an arheic coastal setting (Dürr *et al.* 2011). Overall, this modeled global distribution of coastal environmental settings may provide the necessary scaling factor to estimate global biogeochemical analyses as influenced by coastal morphology. Improving the accuracy of estimates of the contribution of coastal zones to CO₂ dynamics in the atmosphere is critical given the elevated rates of CO₂ exchange in these ecosystems and the rates of land-use change associated with coastal zones that may affect these C fluxes (Friess and Webb 2014).

Each type of coastal environmental setting has unique sedimentary processes, nutrient loads and limitations (eg nitrogen [N]-to-phosphorus [P] stoichiometric ratio), organic matter decomposition, and, ultimately, C storage in vegetation (above- and belowground biomass) and soil (Twilley *et al.* 2017) (Figure 1). These environmental drivers promote nutrient exchange and aeration of soil layers, which largely control how microbial communities decompose organic matter in mangrove soils. River discharge, a proxy for P load to coastal oceans (Harrison *et al.* 2005), is an especially important driver of C partitioning between aboveground (trunk, branches, leaves) and belowground (roots) compartments in mangrove ecosystems (Figure 1). In river-dominated coastlines, given more suitable soil conditions for plant development in terms of resources (ie reduced N:P ratios due to high river-borne P supply), regulators (low salinity), and hydroperiod (frequent inundation, low water residence time), more C is allocated to aboveground biomass than to roots (Twilley *et al.* 2017). In contrast, in carbonate settings, where river discharge is negligible (or absent), P may be a strong limiting nutrient (ie high N:P ratios), increasing allocation to roots to enhance P foraging, which in turn increases C

density in these mangrove soils (McKee *et al.* 2007; Adame *et al.* 2013). In tide- and wave-dominated coastlines, where river expression is less pronounced, C partitioning between above- and belowground biomass is more balanced. The feedback of the biophysical environment (ie soil) with mangrove vegetation along coastal environmental settings explains how ecological processes can be expressed in distinct soil nutrient composition (ie C:N:P stoichiometry) and C stocks. It could therefore be assumed that hemispheric variation in SOC stocks responds to local and regional geomorphic and geophysical drivers.

Methods

Local and regional estimates of SOC linked to coastal environmental settings can provide a more realistic spatial representation of global mangrove SOC stocks. We focus on SOC stocks because most of the C in mangrove ecosystems is stored in this compartment, where it remains stable for much longer than the C stored in aboveground biomass. To demonstrate the utility of the coastal environmental setting approach to scale up mangrove properties from site to global level, we used a dataset that combines published and unpublished data representing the diversity of coastal settings where mangrove thrive (Rovai *et al.* 2018). This dataset consisted of depth-integrated (top meter) mangrove SOC density values derived from 107 studies reporting on 551 sites in 43 countries (WebTable 1). In contrast to previous studies (eg Jardine and Siikamäki 2014; Atwood *et al.* 2017), this dataset only included soil profiles that were at least 0.3 m in depth and mangrove SOC density estimates obtained via elemental analyses or chemical determination (ie wet oxidation). Each site in this dataset was previously classified into distinct coastal environmental settings according to a conceptual model (Thom 1982; see Rovai *et al.* [2018] for details); Thom's (1982) conceptual model took into consideration prevailing coastal geomorphological features such as the presence or absence of rivers, embayments, lagoons, barrier islands, chenier plains (longshore sandy or shelly beach ridges), and carbonate substrates. These categories were assigned to sites based on information specified in independent studies, or based on visual inspection using Google Earth when classification was not provided (see Rovai *et al.* [2018] for details). We assigned categories to these sites based on an independent modeled global classification of nearshore coastal system typologies described above (Dürr *et al.* 2011).

To calculate the total mangrove area per type of coastal morphology, we overlaid a high-resolution map of mangrove forest cover (Hamilton and Casey 2016) to a worldwide typology of nearshore coastal systems classifications (Dürr *et al.* 2011). Mangrove SOC stock estimates per coastal environmental setting were calculated by multiplying the mangrove area within each type of coastline by the mean SOC stock (Mg ha⁻¹) value computed from all sites located in that same coastline type. All statistics and graphics were performed using R (R Development Core Team, www.r-project.org).

Results

Coupling mangrove forest cover with coastal environmental settings revealed that nearly one-half of the global mangrove area occurs as estuaries, followed by deltaic (small deltas and large rivers combined), lagoon, carbonate, and arheic coastal settings (Figure 2, a–c). Mangrove SOC density varied substantially across these coastal environmental settings, ranging from $14.9 \pm 0.8 \text{ mg cm}^{-3}$ (mean $\pm$ standard error) in river-dominated (deltaic) soils to $53.9 \pm 1.6 \text{ mg cm}^{-3}$ and $60.1 \pm 11.3 \text{ mg cm}^{-3}$ in carbonate and arheic settings, respectively (Figure 3a). In contrast to previous work (eg Twilley *et al.* 1992), we detected no relationship between mangrove SOC and latitude ($R^2 = 0.0035$, degrees of freedom [df] = 550, $P = 0.09$). The global mangrove SOC budget was determined to be 2.3 Pg C (Figure 4). Although total mangrove SOC storage (ie expressed in Pg) per environmental setting increased with area, as expected, on a per unit area basis (ie expressed in Mg ha^{-1}) these stocks were about twice as large in carbonate and arheic coastal settings than in terrigenous coastal settings. Despite mangroves in carbonate coastal settings accounting for less than 5% of the world's total mangrove area, they represent almost 10% (213 Tg) of global mangrove SOC stocks (Figure 4). Similarly, mangroves in arheic coastlines only compose $\sim 0.2\%$ of the total global mangrove surface area, but the ratio of SOC stocks to mangrove area was greater than two, underscoring the potential of these coastal environmental settings as major C stores despite the stunted architecture of the vegetation. For terrigenous coastal settings, the ratio of SOC to mangrove area decreased from 1.3 in lagoons, to 0.9 for both estuaries (tidal systems) and small deltas, to 0.6 in large rivers. We also found that trends in mangrove SOC stocks responded to coastal environmental settings regardless of which coastal morphology classification system was used (Figure 3, a and b).

Discussion

We demonstrated how diversity in coastal morphology can contribute to the global synthesis of complex geomorphological, geophysical, and climatic components that explain the ecological features of mangroves. This approach improves our capacity to predict the global contribution of coastal systems, such as mangrove forests, to global C dynamics. Although our estimate of the global mangrove SOC budget was similar to those of previous studies (2.4 Pg C in Rovai *et al.* 2018; 2.6 Pg C in Atwood *et al.* 2017), we found that mangrove SOC stocks varied markedly across different types of coastal environmental settings, increasing from river-dominated to tide/wave-dominated to carbonate coastlines. A single nation may have different types of coastal environmental settings contiguously where mangroves exist, so that using a mean average of mangrove C storage per nation or latitude does not capture the variability associated with coastal morphology. For example, a global estimate recently provided by Atwood *et al.* (2017) used a country-level mean mangrove SOC stock of 283 Mg C ha^{-1} based on values from 48 countries to extrapolate global patterns for the remaining 57 countries that lack data on

mangrove SOC. Our results indicated that for those latter countries, many of which have mostly carbonate coastal settings, the global mean reference value of mangrove SOC stocks suggested by Atwood *et al.* (2017) was about 50% lower than estimates based on coastal morphology (Figure 3, a and b).

Our proposed framework also has the potential to resolve the unexpected patterns observed between carbonate and terrigenous coastal settings that were identified in previous global mangrove SOC budgets (Jardine and Siikamäki 2014). Climate-based models (Jardine and Siikamäki 2014) projected considerably higher SOC density values ($27\text{--}70\text{ mg C cm}^{-3}$) for mangroves located in river-dominated coastlines (eg Louisiana, Amazon, Sundarbans) as compared to much lower ranges reported in the literature ($11\text{--}24\text{ mg C cm}^{-3}$) and in our own field-based dataset ($17\text{--}23\text{ mg C cm}^{-3}$) (WebTable 1). In addition, climate-based models predict lower mangrove SOC density values ($32\text{--}70\text{ mg C cm}^{-3}$) for mangroves in many carbonate coastal settings (eg South Florida, Bahamas, Malaysia, Papua) than published ($21\text{--}126\text{ mg C cm}^{-3}$) and unpublished ($47\text{--}58\text{ mg C cm}^{-3}$) estimates. Our work substantially improves recent global mangrove SOC stock estimates by accounting for within-country variability in C sinks linked to diverse coastal morphology. For extensive coastlines that have a variety of coastal morphologies, such as Brazil (second-largest mangrove area in the world), Australia (fifth), and Mexico (sixth), a framework that incorporates coastal environmental settings substantially improves current SOC stock assessments. At the same time, for equally diverse coastlines for which less data are available, including coastal areas in West Africa and the Indo-West Pacific (IWP) regions, such a framework provides a powerful approach to address global variability in mangrove SOC.

SOC also varied within each of the coastal environmental setting categories (Figure 3, a and b), and was particularly evident within the arctic coastal setting. Although a range of factors may be responsible, we believe that the discrepancies may in fact be due simply to the current scarcity of data for this particular coastal morphology type. In general, however, the high degree of variability observed for each type of coastal environmental setting can be explained by the heterogeneity of environments represented in our dataset. Although the classification system we used to assign categories to sites described the main distinctive types of coastal morphology, variations in these environmental settings (eg river-dominated estuary, tide-dominated delta, etc) accounted for much of the variability within each category. In addition, elevation along microtopographic profiles forms specific ecological zones within each coastal environmental setting (ie fringe, riverine, interior; *sensu* Lugo and Snedaker 1974) also influences soil properties. Despite this variability, our results underscore the role of geophysical controls (eg tides, river discharge) in the spatial diversity of mangrove SOC stocks. Unfortunately, the scarcity of information on ecological zones, as well as the current lack of more detailed mapping of coastal environmental settings that includes

such divisions, limits the ability of coastal scientists to deliver more robust estimates of global mangrove C processes.

Conclusions

Our results show how the incorporation of coastal environmental settings into SOC assessments can improve our capacity to map the spatial variability of mangrove SOC stock estimates at a global scale. The trends in mangrove SOC stocks among different coastline types using a spatially explicit estimate of coastal morphology (Dürr *et al.* 2011) were consistent with a refined (ie site-specific) coastal environmental settings classification approach (Thom 1982). In both classification systems, higher SOC stocks were found in carbonate and arctic coastal settings and lower SOC stocks were detected in terrigenous coastal settings; these results were consistent with estimates reported in the literature. In this respect, our findings highlight the role of carbonate settings as global blue carbon hotspots, particularly in the Neotropics, where 57% of global tropical carbonate coastlines are located (Dürr *et al.* 2011). Finally, we have provided a global mangrove area estimate occupying distinct coastal environmental settings. Incorporating coastal morphology into C stock assessments will improve the accuracy of global estimates of mangrove C dynamics. We encourage members of the scientific community who specialize in the global ecology of mangroves to more frequently incorporate coastal environmental settings and new inventories of coastal morphology in their evaluations of C stocks, which we believe will result in more robust local and regional estimates of SOC that can be extrapolated to a global scale.

Acknowledgements

Funding for this work was provided by the US National Science Foundation (NSF) Coastal SEES program (EAR-1427389), Frontiers of Earth Surface Dynamics [OCE-1135427], and the Louisiana Sea Grant College Program. ASR thanks CAPES/CNPq Science without Borders (PDSE/CsF) for an international fellowship (grant number BEX1930/13-3).

References

- Adame MF, Kauffman JB, Medina I, *et al.* 2013. Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. *PLoS ONE* **8**: e56569.
- Atwood TB, Connolly RM, Almahasheer H, *et al.* 2017. Global patterns in mangrove soil carbon stocks and losses. *Nat Clim Change* **7**: 523–28.
- Bouillon S, Borges AV, Castañeda-Moya E, *et al.* 2008. Mangrove production and carbon sinks: a revision of global budget estimates. *Global Biogeochem Cy* **22**: GB2013.
- Boyd R, Dalrymple R, and Zaitlin BA. 1992. Classification of clastic coastal depositional

- environments. *Sediment Geol* **80**: 139–50.
- Chmura GL, Anisfeld SC, Cahoon DR, and Lynch JC. 2003. Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochem Cy* **17**: 1111.
- Day JW, Christian RR, Boesch DM, *et al.* 2008. Consequences of climate change on the ecogeomorphology of coastal wetlands. *Estuar Coast* **31**: 477–91.
- Donato DC, Kauffman JB, Murdiyarso D, *et al.* 2011. Mangroves among the most carbon-rich forests in the tropics. *Nat Geosci* **4**: 293–97.
- Dürr HH, Laruelle GG, van Kempen CM, *et al.* 2011. Worldwide typology of nearshore coastal systems: defining the estuarine filter of river inputs to the oceans. *Estuar Coast* **34**: 441–58.
- Ewel KC, Twilley RR, and Ong JE. 1998. Different kinds of mangrove forests provide different goods and services. *Global Ecol Biogeogr* **7**: 83–94.
- Friess DA and Webb EL. 2014. Variability in mangrove change estimates and implications for the assessment of ecosystem service provision. *Global Ecol Biogeogr* **23**: 715–25.
- Hamilton SE and Casey D. 2016. Creation of a high spatio-temporal resolution global database of continuous mangrove forest cover for the 21st century (CGMFC-21). *Global Ecol Biogeogr* **25**: 729–38.
- Harrison JA, Seitzinger SP, Bouwman AF, *et al.* 2005. Dissolved inorganic phosphorus export to the coastal zone: results from a spatially explicit, global model. *Global Biogeochem Cy* **19**: GB4S03.
- Holdridge LR. 1967. Life zone ecology. San Jose, Costa Rica: Tropical Science Center.
- Houghton RA. 2007. Balancing the global carbon budget. *Annu Rev Earth Pl Sc* **35**: 313–47.
- Jardine SL and Siikamäki JV. 2014. A global predictive model of carbon in mangrove soils. *Environ Res Lett* **9**: 104013.
- Le Quéré C, Andrew RM, Canadell JG, *et al.* 2016. Global carbon budget 2016. *Earth Syst Sci Data* **8**: 605–49.
- Lugo AE and Snedaker SC. 1974. The ecology of mangroves. *Annu Rev Ecol Syst* **5**: 39–64.
- McKee KL, Cahoon DR, and Feller IC. 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. *Global Ecol Biogeogr* **16**: 545–56.
- Post WM, Emanuel WR, Zinke PJ, and Stangenberger AG. 1982. Soil carbon pools and world life zones. *Nature* **298**: 156–59.
- Rovai AS, Twilley RR, Castañeda-Moya E, *et al.* 2018. Global controls on carbon storage in mangrove soils. *Nat Clim Change* **8**: 534–38.
- Thom BG. 1982. Mangrove ecology – a geomorphological perspective. In: Clough BF (Ed). *Mangrove ecosystems in Australia: structure, function and management*. Canberra, Australia: Australian National University Press.

- Twilley RR, Castañeda-Moya E, Rivera-Monroy VH, and Rovai AS. 2017. Productivity and carbon dynamics in mangrove wetlands. In: Rivera-Monroy VH, Lee SY, Kristensen E, and Twilley RR (Eds). *Mangrove ecosystems: a global biogeographic perspective*. Cham, Switzerland: Springer International Publishing.
- Twilley RR, Chen R, and Hargis T. 1992. Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. *Water Air Soil Poll* **64**: 265–88.
- Woodroffe C. 1992. Mangrove sediments and geomorphology. In: Robertson AI and Alongi DM (Eds). *Coastal and estuarine studies – tropical mangrove ecosystems*. Washington, DC: American Geophysical Union.
- Woodroffe, C.D., 2002. *Coasts: form, process and evolution*, Cambridge University Press. Cambridge, United Kingdom. 623 pp.

Supporting Information

Additional, web-only material may be found in the online version of this article at

Figure captions

Figure 1. Coastal ecogeomorphology conceptual framework showing how bidirectional fluxes between abiotic and biotic components control nutrient stoichiometry and carbon (C) storage in mangroves. Distinct coastal environmental settings (eg deltas, estuaries, lagoons, carbonate) are formed by the relative contribution of geophysical variables (eg river discharge, tidal amplitude, wave energy). Along with regional climatic drivers, these geophysical forcings constrain C partitioning among ecosystem compartments (soil, above- and belowground biomass). PET: potential evapotranspiration; C:N:P: carbon-to-nitrogen-to-phosphorus ratio; SOC: soil organic carbon; AGB: aboveground biomass. Diagrams of the coastal environmental settings adapted from Boyd *et al.* (1992) and Dürr *et al.* (2011).

Figure 2. Global mangrove area divided into distinct coastal environmental settings (a–c). Hashed and solid patterns in the bar chart show values for the Atlantic East Pacific and Indo-West Pacific regions, respectively. Open blue circles mark the sites from which mangrove SOC density (mg cm^{-3}) estimates were obtained.

Figure 3. SOC density (mg cm^{-3}) grouped by coastal environmental settings according to classification systems by (a) Dürr *et al.* (2011) and (b) Thom (1982). SOC increases from deltaic to carbonate settings regardless of the classification system used. Centered bars/lines and bands display the mean and 95% confidence interval, respectively, whereas organic shapes and open circles show data density and spread, respectively. Dürr *et al.* (2011) classification system: I: deltas (large rivers); II: small deltas; III: tidal systems; IV:

lagoons; V: carbonate; VI: arheic. Thom (1982) classification system: DT: deltas; BR: bedrock; ET: estuaries; LG: lagoons; CP: composites; CT: carbonate.

Figure 4. Global mangrove SOC stocks distributed along distinct types of coastal environmental settings in the Atlantic East Pacific (hashed pattern) and Indo-West Pacific (solid color) regions. I: deltas (large rivers); II: small deltas; III: tidal systems; IV: lagoons; V: carbonate; VI: arheic.

COASTAL PROCESSES

ECOLOGICAL PROCESSES

CARBON ALLOCATION

Coastal environmental settings (Dürr et al. 2011)

Coastal environmental settings (Thom 1982)