Estimation of Carbon Stocks from Mexico's Pantanos de Centla Mangroves

The blue carbon ecosystems of southeastern Mexico are among the largest of any measured globally

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Sabalo estuarine mangrove forest, Pantanos de Centla.

This research project was carried out with support from the Commission for Environmental Cooperation's (CEC's) 2013–2014 project, North America's Blue Carbon: Assessing the Role of Coastal Habitats in the Continent's Carbon Budget.

Important Mexican Mangrove Carbon Stocks

The mangroves of southeastern Mexico's Pantanos de Centla—the largest wetland in Mesoamerica—contain exceptionally large carbon stocks, which are among the largest of any mangrove ecosystem on Earth and among the largest of any tropical ecosystem. Clearing mangroves so that the land or shoreline can serve other uses thus comes at a high cost, because the replacement use may not store nearly as much carbon or in fact may allow stored carbon to be lost through greenhouse gas emissions, and it may also fail to provide other important ecosystem services that are characteristic of mangrove forests.

Research has been conducted to assess carbon stocks in these ecosystems and, in particular, the differences in carbon storage between mangroves along the coastal fringe and estuarine mangroves. The project also examined the carbon stocks of cattle pastures that were established on sites previously occupied by mangrove forests, including the potential emissions that could arise from conversion of mangroves to cattle pastures. Results indicate that mangrove carbon stocks in the Pantanos de Centla are exceedingly high compared to those of the upland forests of Mexico and, moreover, that significant emissions result from the conversion of mangrove forests to cattle pastures.

This research represents the first quantification of carbon stocks in the largest wetland in Mesoamerica. It is also the first time that measurements of carbon stocks and estimates of emissions arising from converting these mangroves to other land uses have been published.

Project Summary

Mangroves are highly productive ecosystems that are ecologically and economically important at local to global scales. Their disproportionate contribution to carbon storage suggests that their conservation and restoration can be a pathway to help mitigate greenhouse gas emissions.

Quantifying carbon emissions that result from mangrove conversion has been difficult, in part because of a lack of broad-scale data on the amount of carbon stored in these ecosystems, particularly belowground, and how other land uses may affect these stocks. Data on the carbon stock losses and greenhouse gas emissions associated with land use is practically non-existent. This is a barrier to the establishment of ecosystem values related to mangrove conservation or restoration activities for either climate change mitigation or adaptation strategies.

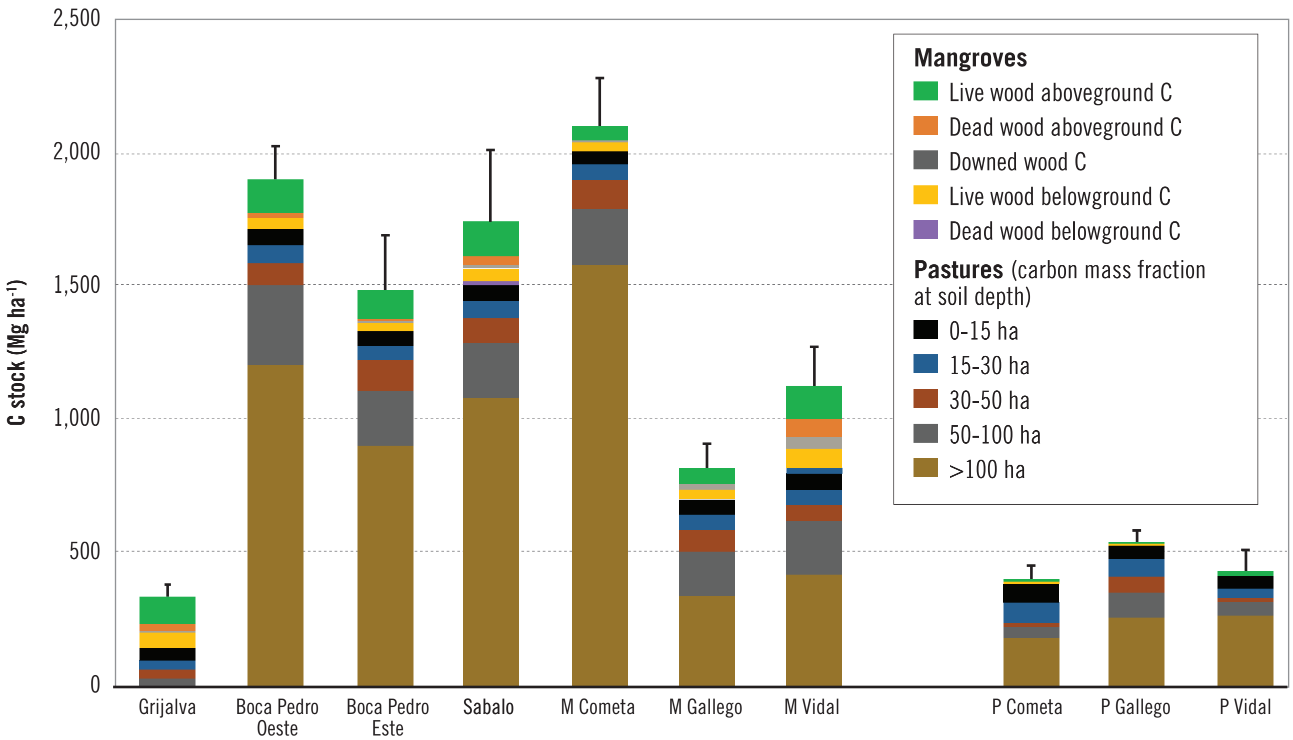
The first objective of this study was to quantify the carbon stocks of oceanic (coastal fringe) and estuarine mangroves in the Pantanos de Centla, Mexico. The second objective was to investigate how mangrove conversion to cattle pasture affects the structure and size of carbon stocks and how this might compare to pasture conversion in upland forests. Specific research questions included: What are the carbon stocks of the mangroves of the Pantanos de Centla? How do they differ between coastal fringe and estuarine mangroves? What are the carbon stocks of cattle pastures that were established on sites previously occupied by mangroves? What potential emissions could arise from conversion of mangrove to cattle pasture? And finally, how do these compare to losses associated with conversion of upland tropical forest to pasture?

The total ecosystem stocks for mangrove sites varied greatly from a minimum of 342 Mg C/ha at the Grijalva site to a maximum of 2,099 Mg C/ha at the Cometa site (Figure 1). The mean ecosystem carbon stock for the mangroves was 1,358 Mg C/ha, compared to 458 Mg C/ha for the cattle pastures. The ecosystem carbon stocks of the mangroves sampled in this study were larger than the global mean reported for all mangroves (approximately 965 Mg C/ha). Similarly to soil pools, the Grijalva site was significantly different from all other sites at the low end, and the Cometa, Boca Pedro Oeste, and Boca Pedro Este sites were significantly different from all other sites at the high end. Soil carbon pools accounted for a mean of 86% of the total ecosystem pool, with a range of 59% to 97%. Soils made up >98% of the total ecosystem carbon stock in the pastures.

The losses in carbon stocks from mangrove conversion to cattle pasture (1,464 Mg CO_2e/ha) were seven times those of emissions from dry forest conversion and three times greater than emissions from Amazon forest to pasture conversion.

The results showed the effects of land use on soil properties throughout the soil profile and at depths >1 m. At these depths, soils in pastures were higher in bulk density, but lower in carbon concentration, carbon density, and carbon mass. Given the influences of land conversion and land use on soils, comparisons with intact mangroves at similar depths should be made with recognition of differences due to collapse, compaction, and erosion. These changes in soil properties also increase the difficulty of determining losses due to land cover change. Because of these factors, soil loss determinations were based on comparing losses on an equivalent mass of mineral soil in the top 1 m of mangrove soils rather than the total depth

Figure 1. Total ecosystem carbon stocks of mangroves and former mangrove forests converted to cattle pastures in the Pantanos de Centla, Mexico



(1,464 Mg CO_2e/ha). This yielded a much more conservative estimate of carbon loss than an estimate derived by the stock-change approach, which included aboveground pools and soils to 3 m soil depth. Using this approach, the estimated mean emissions from mangrove to pasture conversion were 3,264 Mg CO_2e/ha (Figure 2). Limiting losses to the surface 1 m as reported here may therefore be underestimating losses from deeper horizons.

It is clear that mangrove conversion to other land uses comes at a great cost in terms of large quantities of greenhouse gas emissions as well as losses in other important ecosystem services. The large carbon stocks, high rates of mangrove deforestation, and subsequent high greenhouse gas emissions point to the relevance of including mangroves in nationally appropriate climate change mitigation and adaptation strategies.

Pantanos de Centla Mangroves a High Priority

Land use change such as wetland-to-pasture conversion leads to large ecosystem carbon loss and emissions to the atmosphere. Carbon losses from mangrove conversion to pasture are extremely high compared to other land uses.

Because of the size of their carbon stocks, their high greenhouse gas emissions with land use, their high rates of deforestation, and their provision of many other ecosystem services, the Pantanos de Centla mangroves should be considered a high priority for inclusion in climate change mitigation and adaptation strategies.

Scientists from Oklahoma State University and the *Universidad Juárez Autónoma de Tabasco* have formed a strong collaborative team to conduct important blue carbon research along the southern coast of the Gulf of Mexico (Pantanos de Centla). Tremendous opportunities for research, education, and outreach exist for this important and threatened region.

Given the continental importance of the Pantanos de Centla (as well as the coastlands of Campeche, Tabasco, and Veracruz), the threats to its persistence, and the emissions when these blue carbon ecosystems are converted, additional studies on their ecology, management, and conservation are warranted.

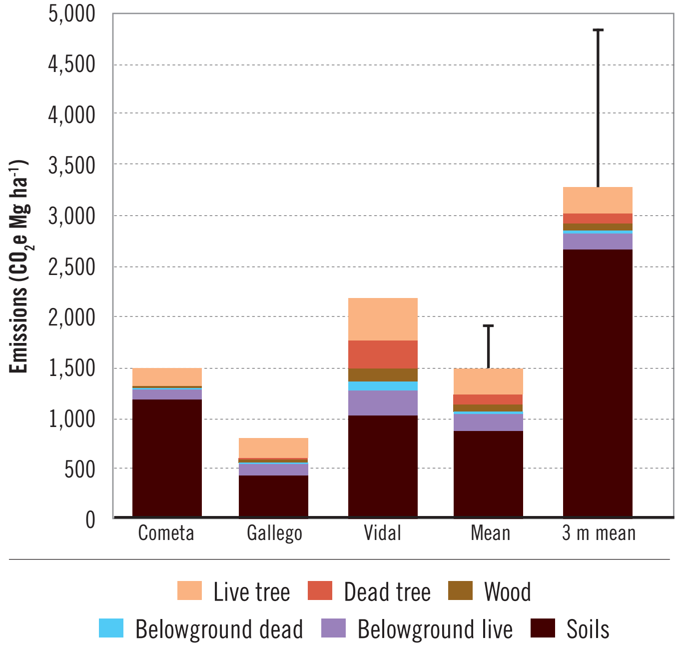
Future research needs include:

- Soil sampling in wetlands that extends below 1 m to see all the effects of land use, land-use change, and forestry (LULUCF)
- Measuring carbon stocks of other blue carbon ecosystems of the Pantanos de Centla, especially salt marshes and floodplain forest
- Quantification of emissions from land use of mangroves and other coastal ecosystems (i.e., salt marshes)
- Rates of carbon sequestration with restoration of degraded mangroves
- Provision of graduate student opportunities for Mexican students interested in blue carbon dynamics

Project Publications

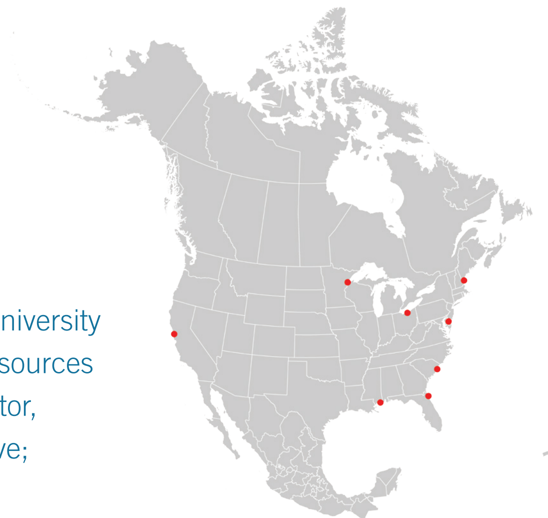
Kauffman J.B., H. Hernández Trejo, M.C. Jesús García, C. Heider, W.M. Contreras. 2015. Carbon stocks of mangroves and losses arising from their conversion to cattle pastures in the Pantanos de Centla, Mexico. *Wetlands Ecology and Management*. August 2015.

Figure 2. Predicted emissions arising from conversion of mangrove forests to pasture: to soil depth 1 m based on biomass equivalence, and to 3 m based on the stock change approach



Quantification of Soil Organic Carbon at Eight National Estuarine Research Reserve System Marshes in the United States

These findings have implications for how marsh-scale carbon budgets are calculated and incorporated into blue carbon policies



Principal investigators:
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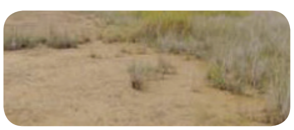
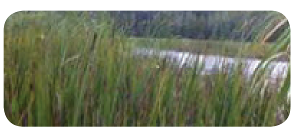
Wells NERR

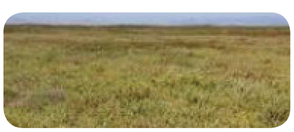
Delaware NERR



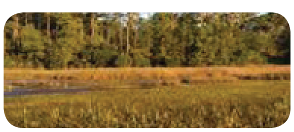
Grand Bay NERR



Lake Superior NERR

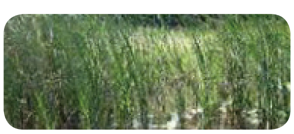


San Francisco Bay NERR



North Inlet-Winyah Bay NERR

GTM NERR



Old Woman Creek NERR

This research project was carried out with support from the Commission for Environmental Cooperation's (CEC's) 2013–2014 project North America's Blue Carbon: Assessing the Role of Coastal Habitats in the Continent's Carbon Budget.

Carbon Storage Variability in US Marshes

The National Estuarine Research Reserve System (NERRS) is a network of 28 National Oceanic and Atmospheric Administration (NOAA)-supported protected sites throughout the United States that is dedicated to protecting and restoring coastal ecosystems through integrated research, stewardship, education, and community partnerships. This research examined the spatial variability of carbon storage within and

across the NERRs of Maine, Delaware, South Carolina, Florida, Mississippi, California, Wisconsin, and Ohio and quantified the percent soil organic matter, percent organic carbon content, and variability in sediment carbon density in the upper 20 cm of the soil across a range of marsh types that differ in geomorphic setting, dominant vegetation, and salinity. Results assist in the prediction of carbon stocks in salt marshes experiencing changing environmental conditions and anthropogenic stressors and where access to the more expensive analytical technology and expertise is unavailable or cost-prohibitive.

Project Summary

This research fills critical gaps in understanding spatial variability in soil organic carbon density in the upper 20 cm across a range of sites of the National Estuarine Research Reserves System (NERRS) of Maine, Delaware, South Carolina, Florida, Mississippi, California, Wisconsin, and Ohio. The sites selected for this study represent a gradient from freshwater (WI, OH), to brackish (DE, CA) to high-salinity (ME, SC, FL, MS) marshes that vary in their geomorphic context and dominant vegetative communities. Including these ranges was done on purpose to improve estimates of sediment carbon density throughout the full extent of marsh types and to obtain a better understanding of the potential for loss on ignition methodology to be extrapolated across marsh habitats throughout North America.

Twenty cores, of 7.62 cm diameter by 20 cm length, were collected randomly within the four dominant vegetation types at each of the eight sites. Cores were split and processed for paired samples of percent sediment organic matter through loss on ignition and percent organic carbon content through elemental analysis over homogenized 5 cm depth intervals. Using percent carbon content and dry bulk density measurements, sediment carbon density was calculated and compared across sites, marsh zones, and vegetation types.

Results show that sediment organic matter by loss on ignition and sediment organic carbon content (%) are highly correlated, that the global relationship differs from that of other published studies (e.g., Craft et al. 1991; Callaway et al. 2012) (Figure 1), and that individual sites contribute significantly to variation in this global relationship. Across broad spatial scales, a single curve adequately captures the vast majority of the variability in sediment organic carbon explained by loss on ignition (LOI). Study results show that at finer scales in some regions, however, variability in sediment properties may dictate the use of site-specific calibration curves.

Results of a breakpoint analysis revealed a shift in the relationship between organic carbon content and bulk density at an organic carbon content of 2.04%. Above this value, the relationship was highly significant and had a slope very similar to those observed in previous studies. Below this value, the relationship was not statistically significant. Interestingly, the samples with organic carbon content below 2.04% were almost exclusively from the southeastern United States (South Carolina, Florida, and Mississippi) and were largely confined to the mid-marsh halophyte and/or short-form *Spartina alterniflora* vegetation zone (data not shown).

Mean sediment organic carbon density in the upper 20 cm ranged from 0.001 to 0.061 g C cm^{-3}, with a grand mean of 0.030 ± 0.011 g C cm^{-3}, and differed significantly by site (Figure 2). Sediments from Maine and California contained significantly more organic carbon per cubic centimeter than the other sites sampled. Mean sediment organic carbon density also differed significantly between high and low marsh zones in South Carolina, Mississippi, and Florida, although the pattern of this difference was not uniform. In Mississippi, the low marsh zone had significantly greater organic carbon density than the high marsh zone, whereas in South Carolina and California, the opposite pattern was observed. Finally, mean sediment organic carbon density differed significantly with vegetation at half the sites sampled (Maine, Mississippi, California, and South Carolina, data not shown). These results reveal considerable spatial variation in sediment organic carbon density in the upper 20 cm at the marsh scale. Superficially, these differences can be observed in the photo collage in Figure 3.

Figure 1. Sediment organic carbon content (%) versus organic matter content by LOI (%)

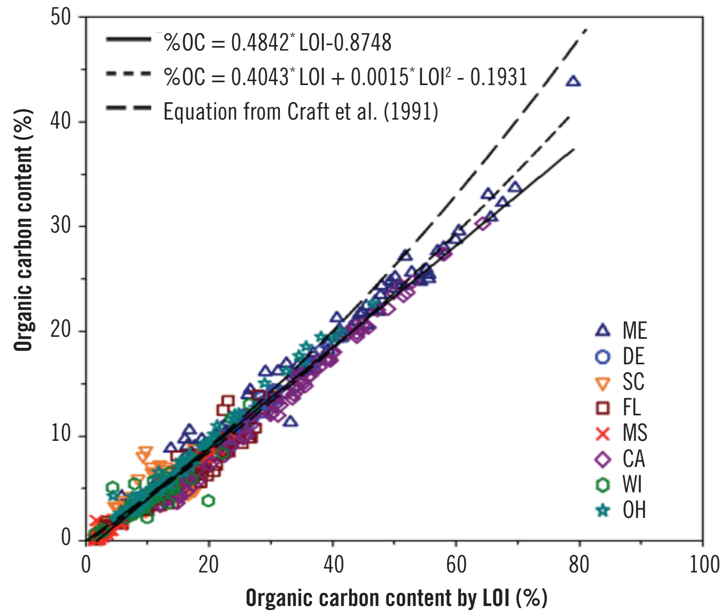
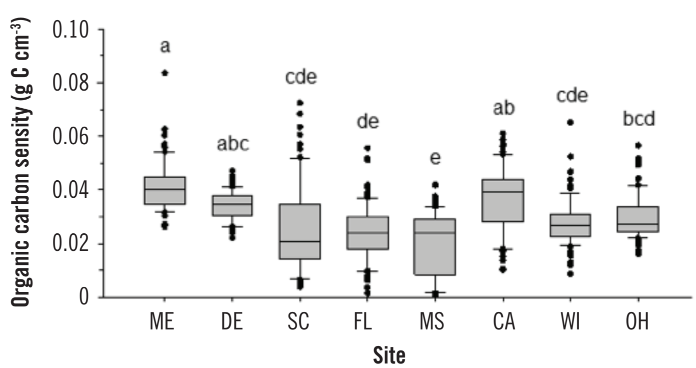
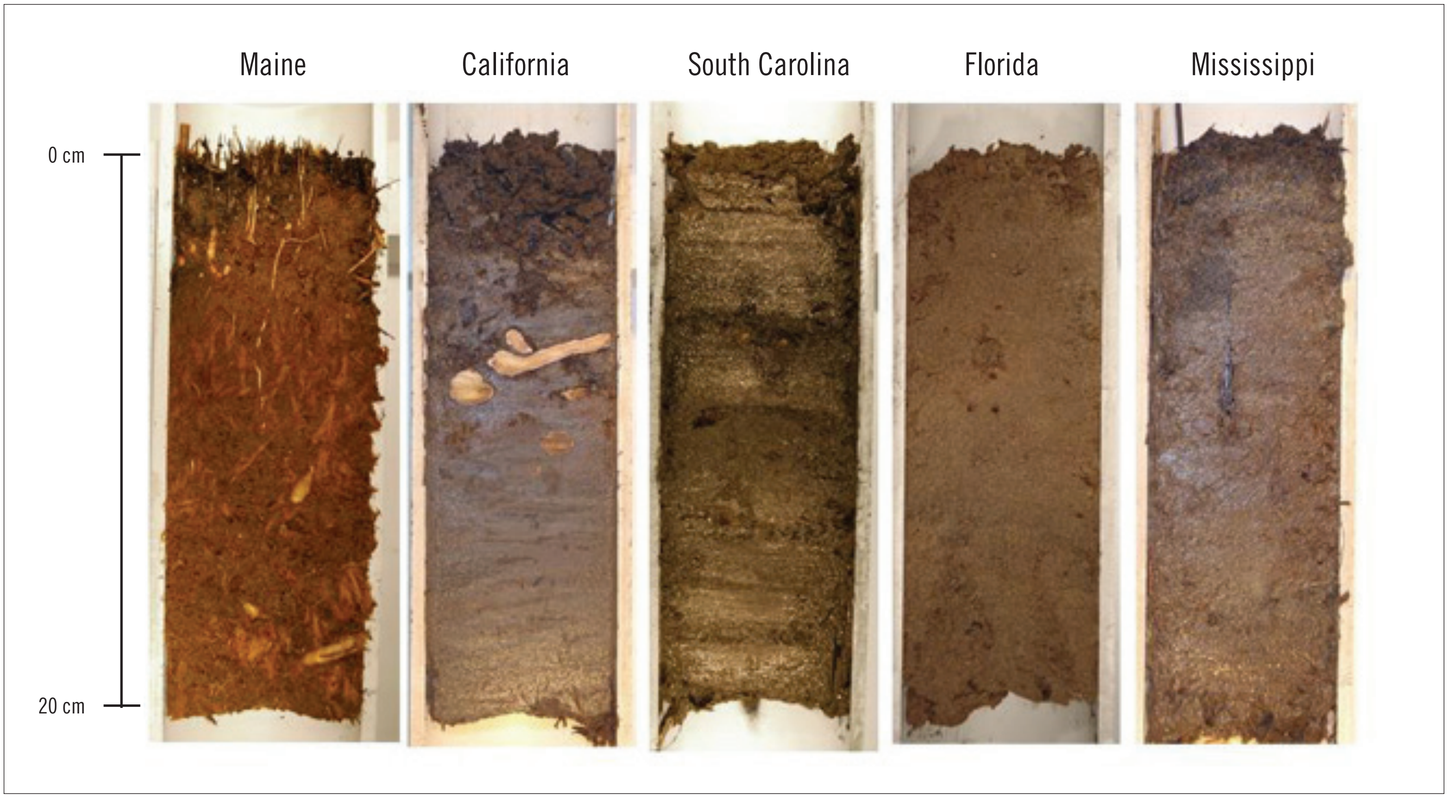


Figure 2. Distribution of organic carbon density within and across eight marsh sites of the NERRs



Note: Median values denoted by horizontal line, boxes contain the 25th and 75th quartiles, whiskers denote the 10th and 90th percentiles, and outliers are denoted by points. Sites with the same letter are not significantly different from one another ($p > 0.05$). State abbreviations indicate site location.

Figure 3. Cores from five sampled NERR site marshes



Differences in sediment organic carbon density among different vegetation communities could not be explained by the standing biomass of those plant communities, however, as there were not significant relationships between any measures of sediment organic carbon density and total aboveground biomass, either within or among sites. Combined, these findings have implications for calculations of marsh-scale carbon budgets.

This study greatly increases the number of sites across the United States for which sediment carbon density measurements exist and improves our understanding of methodologies that use loss on ignition as a proxy for sediment organic carbon. The results suggest that region-specific calibration curves that relate sediment organic matter to sediment carbon content are needed in some regions and that significant differences exist in sediment organic carbon density in the upper 20 cm by site, zone, and vegetation type. Importantly, the significant differences in sediment carbon density within and across marshes have implications for how marsh-scale carbon budgets are calculated and incorporated into blue carbon policies.

Expanding Blue Carbon Work in North American Wetlands

Future work should further expand the number of locations with sediment carbon density measurements and explore the degree to which additional regional calibration curves are needed. Additional studies should also explore changes in sediment carbon density with depth by collecting longer cores to improve calculations of carbon budgets at the marsh scale. The 28 reserves of the National Estuarine Research Reserve System are excellent potential partners to expand blue carbon work in protected wetlands of the United States that encompass a range of marsh types, management regimes, and natural and anthropogenic stressors.

Changes in sediment carbon density with depth (>20 cm) could also be explored by collecting longer cores to improve calculations of carbon budgets at the marsh scale. This additional research on spatial variability in carbon density measurements could then be linked to high-resolution habitat maps of marshes.

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Quantification of Seagrass Carbon Stocks in the Gulf of Mexico from Tip of Florida to Veracruz, Mexico

This study demonstrated that Gulf of Mexico blue carbon stocks are substantial, especially at restored sites

Principal investigators:
Dr. Anitra Thorhaug (President, Greater Caribbean Energy and Environment Foundation), **Dr. Helen Poulos** (Postdoctoral Teaching Fellow, Wesleyan University) and **Jorge López-Portillo Guzmán** (Inecol, Xalapa, Mexico)

Core sample from restored seagress bed with evident changes in colour from top to bottom, a transition from fine to coarse sediments, smell of anaerobic decomposition.

This research project was carried out with support from the Commission for Environmental Cooperation's (CEC's) 2013–2014 project North America's Blue Carbon: Assessing the Role of Coastal Habitats in the Continent's Carbon Budget.

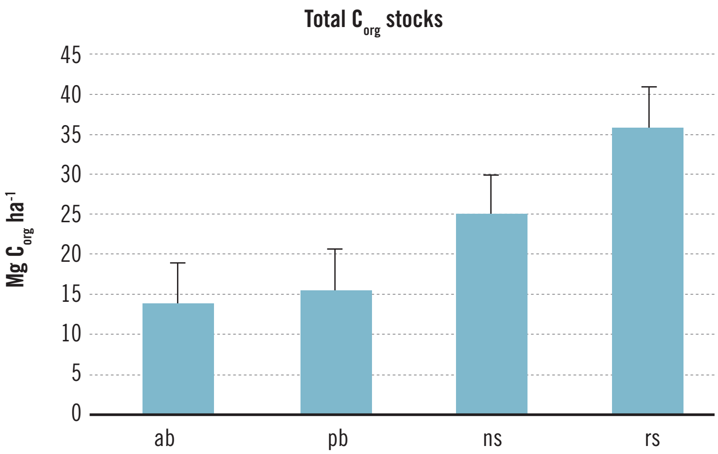
Gulf of Mexico Organic Seagrass Carbon Loss and Gains

This study compared the carbon stocks (organic matter, organic carbon content, and carbon density) of i) natural and ii) restored seagrass beds over a range of geographical locations and restoration ages in the upper 20 cm of sediments. Additional coring in iii) polluted barren sites that once had seagrass, but were never restored and iv) sites that were always barren enabled quantification of total and yearly carbon losses from pollution and of organic carbon gains from seagrass restoration in the Gulf of Mexico. The results represent the first comprehensive set of measured values for loss of organic seagrass carbon from pollution in the Gulf of Mexico and of carbon gains through seagrass restoration. Results are significant because they cover an important regional sea basin: that of the Greater Caribbean Sea.

Project Summary

This project measured sequestered organic carbon around the Gulf of Mexico at nine former restoration sites in one of the richest carbon regions of North America, containing 45% of the North American carbon budget (Hofmann et al. 2011, Herrmann et al. 2015). Field measurements of seagrass blue carbon components show high amounts of sequestered carbon for both naturally occurring and restored seagrasses around the Gulf of Mexico (GOM) from the far southeastern tip of Florida through Veracruz, Mexico. Samples were extracted from quadruplicate 7.5 × 20 cm cores down a 30 m line in barren, barren-polluted, and restored versus natural seagrass sites (within 650 m of the restored meadow).

Figure 1. Total organic carbon stocks based on 20 cm cores in Gulf of Mexico seagrass beds



Note: Carbon stocks of always-barren (ab), polluted-barren (pb), natural seagrass (ns), and restored seagrass (rs) sites plotted as means +SE.

Samples were continually kept cold throughout processing to retard microbiological degradation. Core sections were processed and analyzed for organic carbon (C_{org}), $CaCO_3$ (an important component of the seagrass bed habitat and a source of inorganic carbon from shell material), C:N ratio, and sediment texture and were statistically compared. First-time global results using fine-scale, site-level estimates of loss from site-level carbon stocks in the 20 cm cores and the sites' pollution dates indicate that seagrass bed destruction and death of *Thalassia testudinum* and *Halodule wrightii* release an average of 1.13 Mg Corg ha^{-1} y^{-1} of carbon. These carbon losses immediately begin to reverse following seagrass restoration and, for both major species, *Thalassia testudinum* and *Halodule wrightii*, restoration generates an average gain in organic carbon of 6.4 Mg C_{org} ha^{-1} y^{-1}, averaged across all restoration ages using site-specific estimates of loss per year, estimated as the difference between restored and natural seagrass bed C_{org} divided by the number of years since restoration.

The average C_{org} sequestration in Texas across restored sites after 15 years was lower than the annual sedimentation for the restored sites at the tip of south Florida, which had accumulated carbon for 35 to 42 years post-restoration.

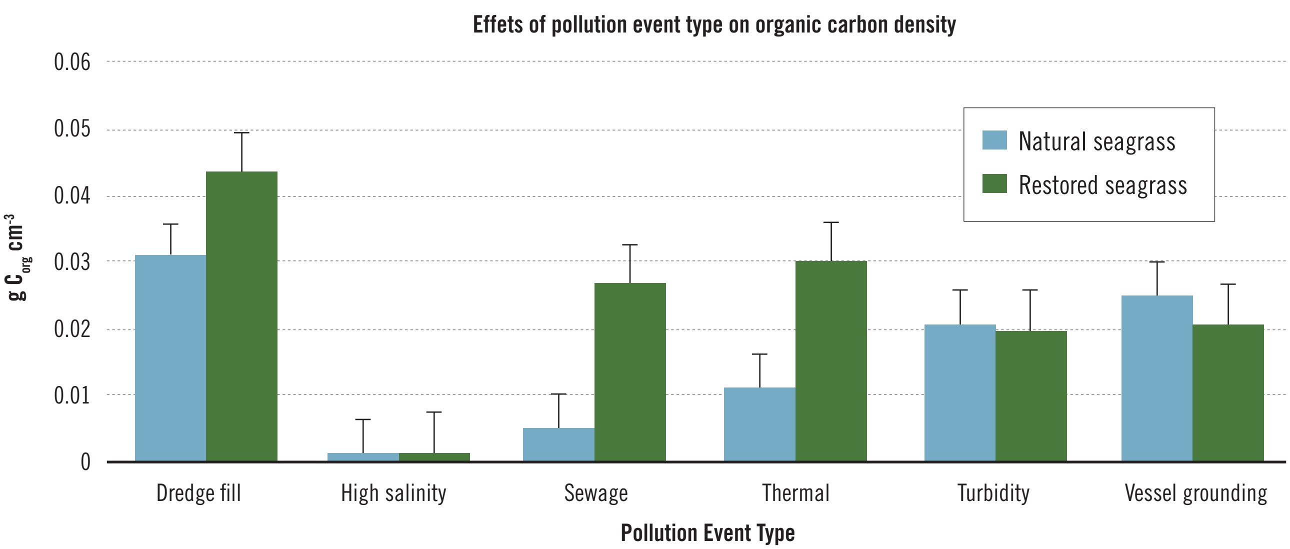
The standing stock of carbon from the tip of southeastern Florida to the Rio Grande border, using various state and federal extent measurements, was approximated as 24.3 Tg Corg. The estimated standing stock in the Mexican states to the southern end of Veracruz is 1,765 Mg Corg, based on limited seagrass distribution data, which is far less, for example, than in the adjacent Texas estuaries (1.765 Gg versus 24,300 Gg). The loss from the tip of southeastern Florida to the Rio Grande border was approximated (also using federal and state approximations and measurements of extent of loss) as 17.9 Tg Corg. Project results showed that about 33% of the carbon originally along the US Gulf of Mexico in the seagrass meadows is estimated to have been eliminated by human activities in the last 75 years.

Measured Values for Natural, Polluted, Restored, and Barren Sites

The mean total organic carbon stocks were 36.8 Mg C_{org} ha^{-1} for restored seagrass beds and 24.9 Mg C_{org} ha^{-1} for natural beds for a 20 cm core length (by summing values for each core across the depth profile). Percent organic carbon increased in restored sites with increasing age since restoration (Figure 1). Seagrass pollution events resulted in an average loss of 20.0 Mg C_{org} ha^{-1}, which was estimated by subtracting the natural seagrass carbon sequestration at each site from the difference between carbon sequestration in always-barren sites and in polluted-barren sites (yearly values were divided by the number of years since the pollution event). Restoration accounted for an average gain of 20.3 Mg ha^{-1} of organic carbon (6.43 Mg C_{org} $ha^{-1}y^{-1}$), which was estimated as the difference between restored seagrass C_{org} and polluted barren C_{org} at each site (yearly values divided by age of restoration).

Sewage spills, dredge and fill operations, and thermal pollution led to significantly higher organic carbon density in restored sites relative to natural seagrass beds (Figure 2).

Figure 2. Effects of pollution event type on organic carbon density in sampled seagrass beds



Note: Mean (+SE) organic carbon density for natural vs. restored seagrass beds among pollution and disturbance event types in the Gulf of Mexico. Values are reported averaged for all sample depths.

Based on these experimental findings of loss, the carbon loss from seagrass death in the US portion of the Gulf of Mexico was estimated to have been approximately 16.6 Tg C_{org} (based on average carbon adapted loss in seagrass) in the period since World War II. There was a loss of 8.3 Tg C_{org} in Florida, 8.1 Tg C_{org} in Texas, 0.05 Tg C_{org} in Louisiana, 0.02 Tg C_{org} in Mississippi, and 0.02 Tg C_{org} in Alabama. Proportionally (to their original standing stock), greater losses occurred in locations like Louisiana and Alabama (with much shorter coastlines) because these states have experienced massive seagrass destruction over the past two decades, even while environmental policies were in place.

Importance of Seagrass Restoration for Climate Change Mitigation

Results suggest that seagrass restoration is an important climate change mitigation strategy that can compensate for the large-scale seagrass organic carbon fluxes that have occurred in response to pollution across the Gulf of Mexico. This study demonstrated that Gulf of Mexico blue carbon stocks are substantial, especially at restored sites. Although seagrass-sequestered carbon has been carelessly lost over the last century in all regions of the Gulf of Mexico and elsewhere, this trend is reversible.

Research Priorities for Measuring Organic Seagrass Carbon

In the future, longer cores (1 m) could be taken to improve calculations of carbon budgets at the seagrass meadow scale. Additional future seagrass carbon measurements could be taken on the Canadian West Coast and the west coasts of California and Oregon. In addition, a variety of sites for Mexico's West Coast estuarine seagrass carbon (from the Sea of Cortez to the Guatemalan border) could be sampled, as well as several major estuaries from the northern Yucatan Peninsula. Further blue carbon research in the northern and northeastern Gulf of Mexico is also needed.

Additional research could assess the contribution of various seagrass, plankton, and mangrove organic carbon components to carbon and inorganic carbon sequestration in various areas in the western and eastern Gulf of Mexico and the East Atlantic and West Pacific coasts. The components of seagrass sequestration need better definition and regional comparison in the Gulf of Mexico, especially given that the region likely has considerable spatiotemporal variability in carbon stocks and flux. Lastly, efforts should focus on determination of stable areas for restoring seagrass that are likely to create the desired sustainable long-term results.

Additional Mexican collaborations to measure carbon in the southwestern and western Gulf of Mexico are also warranted. These collaborations would benefit from restoration technology transfer and restoration trials, especially in highly impacted estuaries with measurements of sequestered carbon and recolonized fisheries.

Analysis of seagrass blue carbon cycle components and comparisons of seagrass and mangrove blue carbon across the Gulf of Mexico and, more broadly, North America would help to advance blue carbon science and policy. Seagrass restoration is a cost-effective carbon sequestration tool for which industry, foundations, and government are potential partners.

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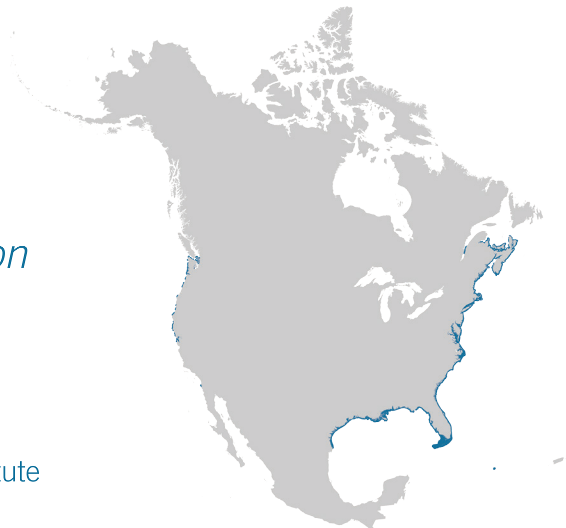
Response of Soil Carbon Accumulation Rates in Marshes to Sea-Level Rise

Marshes may sequester carbon at even faster rates in the future, which makes protection and restoration efforts for them more important

Principal investigator:
Dr. Matthew Kirwan (Assistant Professor, Virginia Institute of Marine Science)



This research project was carried out with support from the Commission for Environmental Cooperation's (CEC's) 2013–2014 project North America's Blue Carbon: Assessing the Role of Coastal Habitats in the Continent's Carbon Budget.

Meta-Analysis of Carbon Accumulation and Historical Rates of Sea-Level Rise

Marshes are already recognized as a critical ecosystem for carbon sequestration. However, carbon sequestration in marshes is dominated by a number of local factors, such as nutrients and climate, making it difficult to isolate the impact of sea-level rise on carbon sequestration across a broad geographic range.

Project Summary

For this project, a meta-analysis was conducted to relate literature-derived North American carbon accumulation rates in 112 marshes to historical rates of sea-level rise on the Atlantic and Pacific coasts of Canada and the United States. The project tested the hypothesis that carbon accumulation rates in marshes should increase in response to sea-level rise, thereby strengthening the role of these blue carbon ecosystems in regulating global climate. To test this hypothesis, data were compiled, consisting of 88 estimates of marsh accumulation in the United States and Canada that are subject to spatially varying rates of historic relative sea-level rise, ranging from approximately 2-10 mm yr^{-1}.

The database of soil carbon accumulation rates included 40 sites from Canada's Atlantic Coast, 24 sites from the US Atlantic Coast, 17 sites from the US Gulf Coast, and 7 sites from the US Pacific Coast. Rates of carbon accumulation were found to vary from 21 to 928 g m^{-2} yr^{-1}. Long-term rates of relative sea-level rise at the sites varied from 2.00-9.65 mm yr-1. Most North

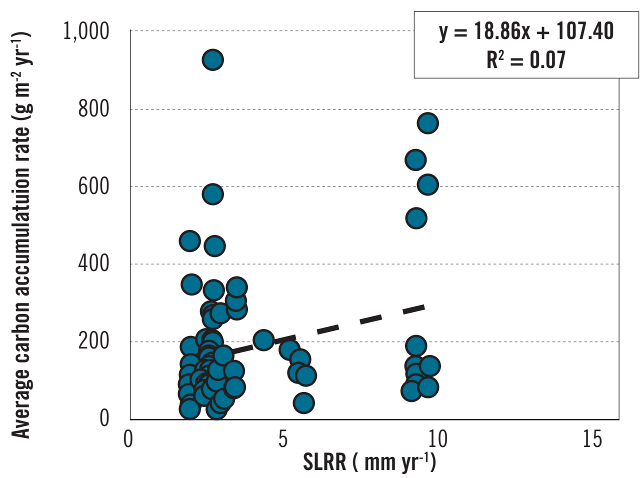
American marshes in the database have experienced historical rates of sea-level rise between 2 and 4 mm yr^{-1}. However, sites near the Mississippi River Delta are rapidly subsiding, so that many Gulf Coast marshes have experienced relative rates of sea-level rise of 9-10 mm yr^{-1}. Therefore, there is a strong geographic influence on relative rates of sea-level rise.

Simple analysis of the entire dataset suggests that soil carbon accumulation rates in these marshes have not been significantly correlated with spatial variations in relative sea-level rise (Figure 1). Although linear regression indicates a slightly positive trend, the relationship is highly variable (R^2= 0.07) and statistically insignificant (p>0.1). The full range of carbon accumulation rates (21-928 g m^{-2} yr^{-1}) occurred over a narrow range of relative rates of sea-level rise (2.75-2.82 mm yr^{-1}). Variability within a single geographic region was also high. For example, carbon accumulation rates ranged from 71 to 763 g m^{-2} yr for 12 estimates in the Mississippi Delta region of Louisiana, all of which are subject to rapid relative rates of sea-level rise (9.24-9.65 mm yr^{-1}). These results indicate that factors other than sea-level rise have a primary influence on soil carbon accumulation rates in marshes.

Flooding frequency and its effect on vegetation type have previously been observed to influence rates of soil carbon accumulation within individual marshes. For example, carbon accumulation rates in frequently flooded, low-elevation portions of a marsh are typically higher than in infrequently flooded, high-elevation portions (Ouyang and Lee 2014). Such patterns can be attributed directly to the influence of flooding on root production, because organic matter decomposition is not strongly sensitive to flooding (Blum 1993; Kirwan et al. 2013). Although the analysis presented above indicates that variability between marshes is high, differences in flooding frequency inferred from vegetation type may explain some of this variation.

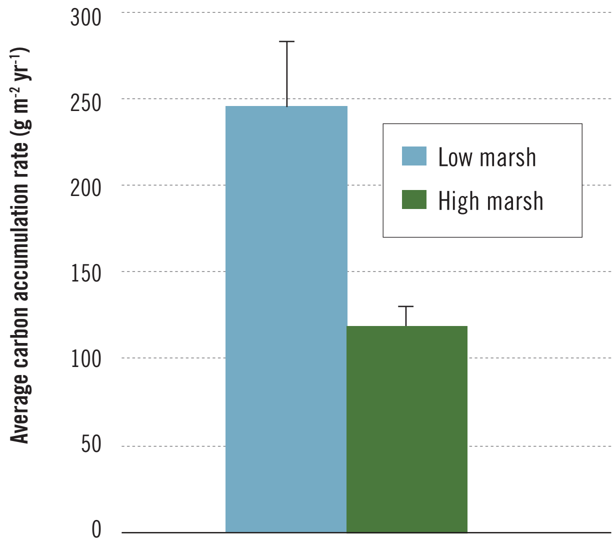
Restricting the analysis to subsets of data based on vegetation type did not lead to a significant relationship between soil carbon accumulation rate and rate of sea-level rise (Figure 2). As observed in Figure 1, the range of carbon accumulation rates within a single vegetation type (e.g., *S. patens*) was as high for a given rate of sea-level rise (approximately 3 mm/yr) as the range observed over the entire gradient of rates of sea-level rise. These results indicate that the high variability in carbon accumulation is related to more subtle measures of flooding duration than can be determined by vegetation type, or is a reflection of processes unrelated to flooding and sea-level rise (e.g., nutrients, climate).

Figure 1. North American carbon accumulation rates in marshes subject to a range of historical relative rates of sea-level rise (SLRR)



Source: Carbon accumulation rates from Ouyang and Lee, 2014. Relative rates of sea-level rise from NOAA and PSMSL.

Figure 2. Average carbon accumulation rates for frequently flooded "low marsh" versus infrequently flooded "high marsh," where the type of marsh was determined by the dominant vegetation (low marsh= *Spartina alterniflora* or *S. foliosa*, high marsh= *S. patens*)



Note: Error bars represent standard error.

Sea-Level Rise Enhances Carbon Accumulation

This was the first attempt to relate historical wetland carbon sequestration rates to sea-level rise. The meta-analysis indicates that factors other than sea-level rise dominate soil carbon burial rates in North American marshes. However, apparent trends relating flooding frequency to soil carbon burial suggest that accelerating rates of sea-level rise will tend to enhance the importance of blue carbon in marsh ecosystems.

This work implies that marshes will sequester carbon at even faster rates in the future, which makes their protection and restoration efforts more important. The most extensive data on marsh carbon sequestration have been obtained along the Atlantic coast of Canada and the United States. In contrast, there are limited data from regions with relatively high rates of sea-level rise, such as the Gulf of Mexico. Therefore, future efforts should focus on collecting carbon sequestration rates from marshes in regions of rapid sea-level rise along the Gulf of Mexico.

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Map of North American marshes with published carbon accumulation rates

Source: Google Earth © image with carbon accumulation locations from Ouyang and Lee, 2014.

Blue Carbon in Northern Marshes: Assessing Processes, Stocks and Rates in Undisturbed, Drained, and Restored Marshes

These efforts will help prioritize conservation initiatives to protect and maximize carbon stocks today and in the future

Principal investigators:
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This research project was carried out with support from the Commission for Environmental Cooperation's (CEC's) 2013–2014 project, North America's Blue Carbon: Assessing the Role of Coastal Habitats in the Continent's Carbon Budget.

Carbon Fate of Northern Salt Marshes

This project provided new data on regional carbon stocks in northeastern North American salt marshes, expanding the past geographical coverage of North America to 48°N.

Project Summary

This research is based upon intensive field research in marshes of northeastern North America on the St. Lawrence River Estuary, Gulf of St. Lawrence, and Gulf of Maine during the summer of 2014. Based upon collection of more than 3,000 samples, this work provides new data on the variability of depth and carbon density of salt marsh peat—thus evaluating carbon stocks, assessing predictors of stocks and rates, and illustrating a new technique for measurement of rates. This study also provides the first data on loss of carbon with agricultural drainage in a cold-climate (with freezing winters) salt marsh.

Peat depth was mapped in marshes at Point Carron, Kouchibouguac National Park, and Grants Beach on the New Brunswick coast of the Gulf of St. Lawrence and at the US National Estuarine Research Reserve at Wells, Maine, on the Gulf of Maine. Two marshes were associated with migrating spits (Point Carron and Grants Beach) and two (Kouchibouguac and Wells) with enclosed lagoons. All demonstrate patterns that could be applied in the same geomorphic context elsewhere. Point Carron and Grants Beach had peat depths decreasing towards the end of the spit, where marsh age can be assumed to be younger. The two lagoonal marshes had deeper peats, with the greatest thickness approximately 500 m inland from the lagoon edge. This pattern may be applicable to other lagoonal marshes, but merits additional investigation. Despite variability in carbon density, peat depth was found to be a significant predictor of carbon stocks in each marsh. When data from all marshes are combined, regression analysis shows that peat depth is a significant predictor of carbon stocks (R^2=0.81, p<0.001) A "sensitivity" or optimization analysis assessed which five locations in each marsh would provide the value closest to the marsh-wide carbon stock calculated from the set of all possible samples within each marsh (e.g., 126 to 11,628). This analysis shows that sampling from the oldest and youngest ends of the spit marshes is the best sampling strategy. A single transect may be sufficient in a lagoonal marsh, but additional investigation is warranted to determine the best location of the transect. Overall, results suggest that reasonable estimates of carbon stocks can be made without intensive analysis of cores. Carbon density in the surface 5 cm does not significantly vary with vegetation zone or tidal amplitude. However, regression models show that carbon density in the surface 5 cm does have a significant relationship to the two climate variables tested, annual average temperature and number of degree days >5°C (a measure of growing season).

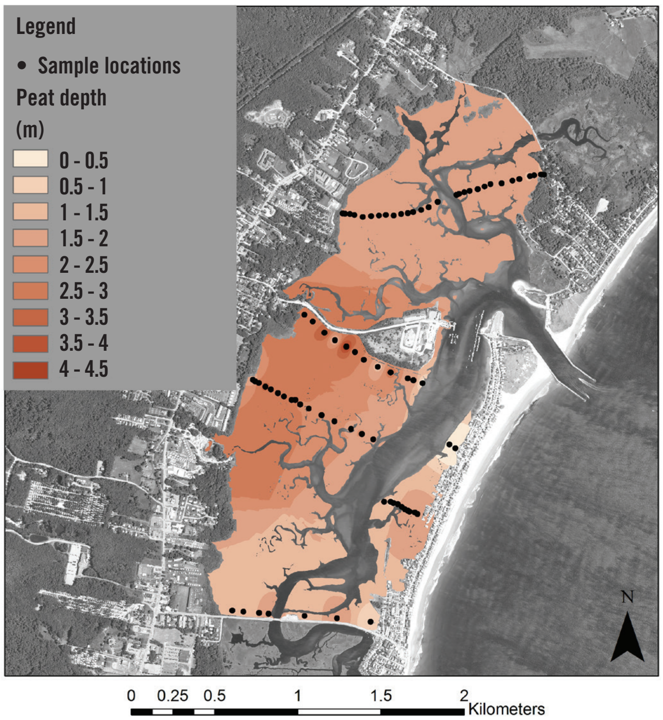
Rates of peat accumulation, determined through profiles of anthropogenic lead, varied within the marshes. Multiple regression analysis with the parameters surface elevation, distance to upland, and distance to creek or marsh edge, along with the nominal variables of vegetation zone and marsh, did not reveal any as significant predictors of peat accumulation rates.

When the predictive value of the above geomorphic parameters is assessed for rates of carbon accumulation in the combined data from the four marshes, only surface elevation is a significant predictor (R^2=0.31, p<0.026). For three of the four marshes, the relationship of geomorphic parameters and carbon accumulation rates is stronger when the geomorphic parameters are applied individually to each marsh (indicating important differences among marshes). Surface elevation has significant predictive power at Grants Beach. At Kouchibouguac and Wells, surface elevation, distance to upland, and distance to creek together are significant predictors.

Marker horizons and surface elevation tables (SETs) are widely used in marshes around the world to measure elevation change. At Wells, measured peat accumulation rates using the SETs (50-92 g C m-2yr-1) were comparable to the rates determined with lead-210 analysis. Analyses of carbon in peat above and below marker horizons demonstrate that the combination of this measurement along with SET and marker horizon depth is a convenient and inexpensive technique for assessing carbon accumulation rates.

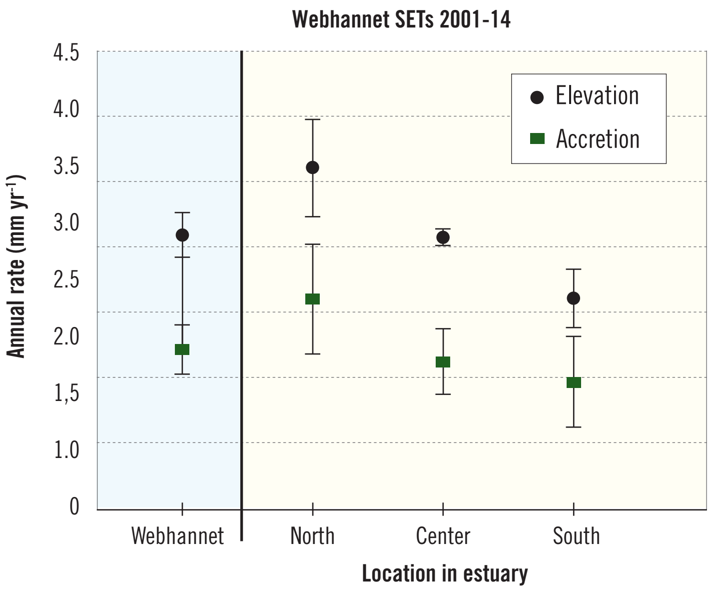
At the southernmost site, Webhannet Marsh in Wells, Maine, SET results suggest that rising sea level is enhancing accumulation of carbon over time, which modeling indicates will continue with present rates of sea-level rise, but that higher rates of sea-level rise

Figure 1. Isopach of peat at the Webhannet salt marsh, Wells National Estuarine Research Reserve, Maine, USA



Note: Black dots represent core or probe locations.

Figure 2. Changes in marsh elevation and surface sediment accretion at Webhannet marsh (Wells)



will threaten carbon stocks. At this site, accretion and subsurface elevation growth of peat was estimated using SET and marker horizons. Sediment accretion (sediments deposited above the marker horizons) averaged 2.2 mm yr-1 over the past 13 years. The actual marsh elevation increased by an average of 3.1 mm yr^{-1}, indicating that peat accumulated at a rate of about 0.9 mm yr^{-1} below the marker horizons (Figure 2). Additional data on carbon density provide an estimate of annual rates of carbon storage for the marsh.

Loss of carbon with agricultural drainage of tidal wetlands has been reported for California, Australia, and Italy, but until this study, no measurements had been made for drained marshes of Atlantic Canada, which presents a different climate regime and where "reclamation" for agriculture has been extensive. Carbon stocks of drained and flooded marshes of the St. Lawrence River Estuary were compared to determine losses, which ranged from 8.6 to 18.5 kg m^{-2}, or 18% to 39% of the original carbon stock. These results indicated that a previously developed model overestimated losses, but will require additional historical research to complete its calibration. More importantly, this rate of loss is greater than the rate of carbon gain at the Wells marsh, highlighting that restoration of drained marshes on the St. Lawrence should be a conservation priority.

Measurements of peat depth (Figure 1) revealed considerable variability in peat depth within a marsh and among marshes. However, the Intergovernmental Panel on Climate Change (IPCC) guidelines for estimation of greenhouse gas emissions from coastal wetlands (Kennedy et al. 2014) provides a default value of 1 m depth for coastal wetland soils and a carbon density of 0.034 and 0.02 g cm-3 for organic and mineral soils, respectively. (Marsh area multiplied by soil, or peat, depth will provide peat volume. Multiplication of this volume by carbon density will provide the stock.) Similar guidelines are incorporated into protocols for assessing carbon stocks for carbon markets. These preliminary results in northern marshes already provide strong evidence that calculations of carbon storage assuming a 1 m depth results in overestimates of carbon stocks in some marshes, such as Grant's Beach, and underestimates in others, such as Wells. Hence, consideration of marsh carbon stocks based simply upon area could be misleading, and prioritization of wetlands for protection or management based upon carbon stocks will require site-specific measures.

Assessing the Role of Tidal Wetlands in Global Carbon Budgets

The role of tidal wetlands in global carbon budgets cannot be adequately assessed until more information is available on tidal wetland carbon stocks and their history. It is not yet clear which variables are most important in determining variability of carbon stocks among marshes: geomorphic context, age, or climate contribute to variability in carbon stocks, but more geomorphic contexts need to be considered (such as fluvial marshes) and marshes at an even greater range of latitudes (both further north and south) should be examined. SETs and marker horizons, deployed in many tidal marshes and mangroves around North America, and these could be used for continent-wide comparisons of present-day carbon accumulation rates.

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