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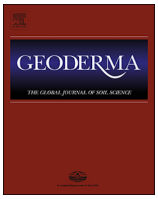

The importance of geomorphic context for estimating the carbon stock of salt marshes

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ABSTRACT

We measured total carbon stocks of three marshes: Two formed in association with a developing spit along the Gulf of St. Lawrence coast of New Brunswick, Canada, and another with a lagoon on the coast of Maine, USA. Overall, 46 cores and 157 depth recordings were collected to determine depth of the marsh deposits. Total marsh soil volume was estimated by interpolation. In all marshes soil depth varied in a predictable pattern based upon marsh developmental history. In spit marshes deposit age and thickness increased towards the oldest portion of the spit. In the lagoonal marsh, soil depth was greatest in the center and declined towards both the upland and seaward margins. This same pattern held on axes perpendicular to the primary, age axis of the spit marshes. In each marsh C density did not significantly vary with depth so that marsh depth was an acceptable estimator of C stock, and therefore driven by the geomorphic context of the marshes we studied. There were major differences in C stock estimates produced using GIS interpolation, average C contained in all marsh cores, or cores along a single transect. Our study demonstrates that assuming a soil depth of just 0.5 or 1 m can substantially under- or overestimate marsh carbon stocks and the value of that stock on a carbon market.

1. Introduction

Salt marshes occur in an elevation range bracketing mean high water and support vegetation adapted to the stresses caused by daily inundation of salt water (e.g., Silvestri et al., 2005). They accrete vertically and expand laterally over time due to the accumulation of plant material and input of sediments from the tidal waters as sea level rises (e.g. FitzGerald et al., 2008). Provided sufficient supplies of sediment are present in tidal waters and/or the organic matter accumulation is high enough, salt marshes will accrete roughly in equilibrium with sea level rise and have done so for millennia (e.g. Kelley et al., 1995). In the process, they build up stocks of organic-rich soil, recognized as blue carbon (Mcleod et al., 2011).

On an areal basis, salt marshes are the world's most efficient soil carbon (C) sinks (Mcleod et al., 2011). Belowground plant productivity is high while anoxic soil conditions can inhibit organic matter decomposition (Hackney, 1987; Kristensen et al., 1995). Furthermore, while freshwater wetlands are net methane sources, saline tidal marshes tend to have very low methane emissions and will act as net methane sinks at times (Poffenbarger et al., 2011).

Disturbance of these ecosystems can liberate large quantities of this stored C as carbon dioxide (CO_2) (e.g. Drexler et al., 2009; Hatala et al., 2012; Pendleton et al., 2012). More than 25% of the estimated global area of salt marshes has been lost since the early 1800s, and losses continue (Adam, 2002; Lotze et al., 2006). As a result, there is a growing recognition of the need for salt marsh conservation and restoration considering the role it can play in mitigation of climate change (Ullman et al., 2013). Soil depth and soil organic C (OC) density (grams of OC per unit volume of soil) are key characteristics that determine both the value of the soil OC and the magnitude of possible CO_2 emissions when disturbed (Lovelock et al., 2017). In consequence, methodologies have been published for estimation of marsh-wide C stock (e.g. Fourqurean et al., 2014).

Estimates of marsh-wide carbon stock are critical if the stocks are to be valued on carbon markets. Yet, to our knowledge, no studies have been published that quantify the total C stock of single salt marshes deposits over their full depth and volume. There are regional and global estimates based on C densities, but these estimates are limited to the upper 50 cm to 1 m of marsh soil (e.g., Chmura et al., 2003; Duarte et al., 2013). This is necessary to allow comparison among sites with

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different depths and because few studies have analyzed carbon density of marsh soil below 50 cm depth.

Duarte et al. (2013) estimate that, globally, salt marshes store an average of 162 Mg C ha^{-1}, limited to the upper 1 m of soil. The default emission factor used to estimate C loss from salt marsh disturbance produced by the IPCC likewise only considers the top 1 m of marsh soil (Kennedy et al., 2014).

There has been more extensive documentation of C stocks in mangroves (e.g. Donato et al., 2011; Kauffman et al., 2011, 2014, 2016; Adame et al., 2013; Alongi et al., 2016) than salt marshes. Like salt marshes, however, few of these studies have quantified C stock below 1 m although it is acknowledged that significant stocks of C can occur below this depth. Further, while it has been assumed by some that the C stock in the surface 1 m of marsh soil is the most vulnerable to loss due to disturbance (Pendleton et al., 2012), in some drained areas subsidence of marsh peat due to C loss has exceeded 1 m (e.g. Deverel and Leighton, 2010) suggesting that C stocks below 1 m depth can be affected by land use change. Thus, there is a need for comprehensive C inventories which include the full depth range of individual salt marshes to help improve estimates of global C stocks and improve predictions of C losses due to land use changes and disturbance.

The paucity of marsh-wide C stock estimates also means that variation in C stocks with environmental or geomorphic characteristics has not been well established. Differences in organic matter accumulation and decomposition could affect the overall C stock between and within marshes. For example, the production of *Spartina alterniflora* increases in warmer climates (Kirwan et al., 2009), yet decomposition also increases with temperature (Davidson and Janssens, 2006; Kirwan and Blum, 2011). Kirwan et al. (2014) suggest that, despite increased decomposition with temperature, the increased productivity of marsh vegetation may lead to increases in organic matter accumulation. Thus, while the degree to which temperature-controlled decomposition, latitudinal variation in productivity, and effects of geomorphic context has not been well established, current work suggests that accounting for such variables is vital to accurate C stock estimates. For example, over time the amount of stored C should increase, but differences in C accumulation rates, dominant sediment grain size and vegetation assemblage with shifts in local environmental conditions may affect long term stock. Differences in marsh antecedent topography will dictate marsh depth. Also unknown is how months of freezing will affect the C stock of high latitude salt marshes relative to lower latitude sites.

Here we provide estimates of the total C stock over the full soil profile for three marshes along the northeastern coast of North America. Cores were collected at high spatial resolution and along multiple transects to link the results to local geomorphic conditions. Our results are used to assess current default estimation values and the valuation of marsh-wide C stocks on the C market. In our analyses we search for factors that can be used to improve estimates of marsh-wide C stocks, such as geomorphic context within and among marshes and variation of C density with depth (i.e., age).

2. Study areas

Our study sites include two marshes on the Gulf of St. Lawrence coast of New Brunswick, Canada and one on the southern coast of Maine, USA (Fig. 1; Table 1). The marshes all have similar vegetation and distribution of species with elevation and distance from the seaward edge of the marsh. The marsh fringe, a transition between upland vegetation and the marsh contains a combination of *Spartina pectinata*, *Juncus gerardii*, and *Juncus balticus*, with smaller amounts of *Typha* and *Bolboschoenus maritimus*. *Phragmites australis* was found in the marsh fringe only at Wells. The high marsh vegetation, which covered most of the marsh area contained primarily *Spartina patens* with lesser amounts of *Distichlis spicata*, *J. gerardii*, *Limonium*, *Plantago maritima*, *Aster subulatus*, *Solidago sempervirens*, *Atriplex patula*, *Suaeda maritima*, *Puccinellia paupercula*, *Triglochin maritima*, and *Salicornia depressa* distributed in patches around the marsh. *Distichlis spicata* was present only at Wells. At Carron Point and Grants Beach *J. gerardii* was more common than at Wells, covering a greater area than *S. patens*. The low marsh area, vegetated by *Spartina alterniflora*, tended to cover a small spatial area at our study sites - usually a narrow band at the seaward edge of the marsh or along the margins of tidal channels. The marshes all had erosional seaward margins.

The marshes were categorized according to the scheme Kelley et al. (1995) derived for salt marshes along the Maine coastline. All marshes in our study primarily fall under the back-barrier classification. We further subdivide the back-barrier systems into interior marsh, which refers to the marshes built out from the mainland edge opposite of the barrier spit, typically separated by a river, inlet, or lagoon waters, and spit marsh, which refers to marsh built immediately behind the sand spit.

The Wells marsh is built in a lagoon and comprises both interior and spit marsh sections bisected by the dredged interior channel (Webhannet River) that empties into the ocean though a channel in the spit (Fig. 2). The most extensive portion of the marsh has built out from the mainland in the western side of the Webhannet River, with a smaller portion built behind the southeastern barrier spit (Fig. 2). The mean tidal range is ~2.7 m (NOAA 2016). The marsh surface contains numerous pools and many tidal creeks extend deep into the marsh. Much of the seaward edge of the marsh is eroding and slumping, typically appearing as 1–2 m high (during low tide) erosional cliff faces. The Wells system has been previously radiocarbon dated, and marsh formation between 3102 and 3243 cal BC (calibration using Oxcal with Intcal 2013 curve – Bronk Ramsey, 2017; Reimer et al., 2013) for some areas of the marsh (Kelley et al., 1995). Soils at Wells classify largely as sulfaquent, though 5 of 17 collected cores at the site classify as sulfihemist.

Grants Beach is a spit marsh (Fig. 2) built almost entirely behind a compound sand spit, though the southeastern section of the marsh grades into a fluvial minor marsh of a nearby stream (the southeastern section is not analyzed in this study). The tidal range is ~1.2 m (FOC, 2016). The eastern end of the marsh has erosional seaward cliff edges with small, ~ > 0.5–1.0 m deep ponds while the western end is divided into several sections by recurved sand spits, topped by dunes, which run perpendicular to the main barrier. Steep dunes border the marsh interior. No dating is available or performed for this marsh, however based upon aerial photographs dating to the late 1950's, much of the western half of the spit and accompanying marsh has developed over the last 50–60 years. Soils at Grants Beach classify as sulfaquent.

Carron Point is a back-barrier marsh (Fig. 2) similar in configuration to Grants Beach but without fluvial influence. The tidal range is ~2.2 m (FOC, 2016). The western section of the marsh has several long recurved relict sand ridges covered by marsh fringe vegetation with high marsh vegetation in the low areas between the ridges. Few tidal creeks are present in this section. The western section is dominated by *J. gerardii* and *J. balticus* except in the lowest areas between the sand ridges, where there is a mix of *S. patens* with *J. gerardii*. The eastern end of the marsh does not have ridges and is characterized by patchy marsh vegetation and many tidal creeks. The seaward edge is eroding, and soil is slumping along the entire southern edge of the marsh, creating exposed cliff faces. No dating was available or performed for this marsh. Soils at Carron Point classify as sulfaquent, however 2 of 10 collected cores at the site classified as sulfihemist.

3. Methods

3.1. Soil sampling

The sampling design is a modification of methods used in similar C density studies of mangroves (Donato et al., 2011; Kauffman and Donato, 2012). Cores were collected along transects from the upland to the seaward edge of the marshes with intervals adjusted to