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Carbon export from fringing saltmarsh shoreline erosion overwhelms carbon storage across a critical width threshold

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ABSTRACT

Saltmarshes are carbon storage hotspots and help to offset anthropogenic carbon emissions; however, marshes are threatened by sea-level rise, erosion, and human development. Recent efforts to constrain the saltmarsh carbon cycle have focused on the processes of carbon burial and sequestration with respect to sea-level rise and global warming. Simultaneously, many marshes that fringe the margins of estuaries and barrier islands are eroding, which releases old carbon from the saltmarsh and transports it into the estuary, and that process should be included in marsh carbon budgets. Additionally, if marshes cannot transgress the upland at a rate that balances shoreline retreat, then the marsh will narrow, thus reducing the area available for carbon storage. Here, we present the development of a box model that incorporates both carbon storage and carbon export via shoreline erosion to estimate the annual carbon budget of saltmarsh sediments. We test the model using field data collected at a fringing marsh within the Rachel Carson National Estuarine Research Reserve in North Carolina. The shoreline erosion rates along the fringing marsh are variable and the model output shows that the stretch of marsh that is retreating 0.76 m yr^{-1} switched to a carbon source in 1930, while another portion of the marsh that is retreating more slowly (0.65 m yr^{-1}) will switch to a source in 2021. The model indicates that the carbon budget of a saltmarsh is highly sensitive to the rate of shoreline retreat and that rapidly-eroding marshes may already be net sources of carbon. These results underscore the importance of conserving existing marshes, mitigating shoreline erosion, and considering shoreline erosion in the design of saltmarsh restoration projects.

1. Introduction

Blue carbon habitats, such as saltmarshes, mangroves, and seagrass beds, have a tremendous capacity to capture and store carbon dioxide from the atmosphere (Murray et al., 2011). These coastal habitats occupy an order-of-magnitude lower percentage of total global habitat area than terrestrial environments, but have greater carbon burial rates (Chmura et al., 2003; Duarte et al., 2005; Houghton, 2007). Saltmarshes have the highest carbon burial rate per unit area of all blue carbon habitats with a mean of 244.7 ± 26.1 g C m^{-2} yr^{-1} (Ouyang and Lee, 2014), which is greater than long-term burial rates from temperate, tropical, and boreal forests, which range from 0.7 to 13.1 g C m^{-2} yr^{-1} (Schlesinger, 1997; Zehetner, 2010). Saltmarshes occur globally in a variety of settings including fringing the margins of estuaries (fringing marsh), perched on top of relict tidal delta sand bodies (marsh islands), or in river deltas (Berelson and Heron, 1985; Roberts, 1997; Roman et al., 2000). Carbon storage in saltmarshes can be used to offset CO_2 emissions from greenhouse gases, provided that marsh accretion keeps pace with sea-level rise. Accelerating sea-level rise will create more accommodation space for marsh growth and could potentially increase carbon sequestration with time (Crooks et al., 2011; McLeod et al., 2011). However, if the rate of relative sea-level rise is too high, or if there is not ample sediment supply, then the marsh may retreat landward or drown (Morris et al., 2002; Kirwan et al., 2010; Mariotti and Carr, 2014). Conservation and restoration of marshes is a management priority given their importance as carbon sequestration sites as well as the variety of additional ecosystem services they provide, such as buffering

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storm-wave energy, providing nursery habitat for juvenile fish, and nutrient cycling (Peterson and Turner, 1994; Gedan et al., 2009; Barbier et al., 2011; Moller et al., 2014).

1.1. Saltmarsh carbon storage

Carbon is buried in the saltmarsh over annual to decadal time scales within living aboveground and belowground biomass and the trapping of allogenic carbon from the water column (Leonard and Luther, 1995). Sources of biogenic carbon in a saltmarsh include: grasses (e.g. *Spartina alterniflora*, *Juncus roemerianus*), benthic algae, and bacteria (Ember et al., 1987). Terrestrial carbon sourced from runoff during high rainfall events as well as phytoplankton and microphytobenthos in the estuary are potential allogenic sources of carbon to saltmarshes (Ember et al., 1987; Middelburg et al., 1997; Gebrehiwet et al., 2008). The inventory of buried organic sediment increases through time as marshes accrete vertically with rising sea level and some portion of the buried carbon is sequestered over millennia in marsh strata after microbial degradation (McLeod et al., 2011; Chmura, 2013). Therefore, carbon burial refers to the buildup of carbon across the marsh surface to some shallow depth; whereas carbon sequestration is the fraction of this carbon that remains stored at greater depths in marsh strata. We define carbon storage as the combination of both burial and sequestration, thus storage represents the time-averaged accumulation of carbon, measured from the marsh surface to the base of the marsh unit and extrapolated across an area of the marsh.

1.2. Saltmarsh carbon export

Previous work on the saltmarsh carbon cycle focused on marsh accretion and associated carbon burial and sequestration (e.g. Mudd et al., 2009; Kirwan and Mudd, 2012; Morris et al., 2012). Saltmarshes are being lost globally at alarming rates (Duarte et al., 2008; Duarte, 2009; Nelleman et al., 2009); therefore, carbon export needs to be assessed and included in order to create more accurate saltmarsh carbon budgets. Marsh loss is occurring rapidly in locations such as Louisiana and Chesapeake Bay, where the rates of loss are 43 km^2 per year and 270 m^2 per year, respectively (Wray et al., 1995; Couvillion et al., 2011). Around 25% of the global area originally covered by saltmarshes has been lost, and current loss rates in North America are around 1–2% per year (Bridgham et al., 2006). These losses are occurring in response to a variety of natural and anthropogenic forces, such as climate change (i.e. marsh drowning and erosion in response to accelerated sea-level rise; De Laune et al., 1990; Nicholls et al., 1999; Allen, 2000), human disturbances (e.g. modifications to river systems, deforestation and agricultural reclamation; Day et al., 2000; Pendleton et al., 2012; Ganju et al., 2013; Kirwan and Megonigal, 2013), and wave-induced shoreline erosion (FitzGerald, 2008; Mariotti and Fagherazzi, 2013; Leonardi and Fagherazzi, 2014; McLoughlin et al., 2015). Global estimates of carbon released by saltmarsh land-use change are large, ranging from 0.02 to 0.24 Pg CO_2 yr^{-1} (Pendleton et al., 2012), and these estimates are conservative because they do not include direct measures of erosion, which can release sequestered carbon rapidly on event time scales (Coverdale et al., 2014).

Shoreline erosion is suggested to be the principle natural mechanism for current global saltmarsh loss (Schwimmer, 2001; van de Koppel et al., 2005; Gedan et al., 2009; Mariotti and Fagherazzi, 2010; Marani et al., 2011), and erosion is progressing at alarming rates in response to relative sea-level rise, human activities (e.g. boat wakes), and currents and waves (Schwimmer, 2001; van der Wal and Pye, 2004; Mariotti and Fagherazzi, 2010). In some locations, rates of shoreline erosion are an order of magnitude greater than platform accretion rates (Mattheus et al., 2010). This suggests that carbon export via shoreline erosion could eventually outpace carbon storage, especially if the depth of erosion is equal to or greater than the thickness of the marsh. Even healthy marshes that are keeping up with sea-level rise and transgressing landward may narrow due to rapid shoreline erosion (Reed, 1995; Temmerman et al., 2004), which will reduce the area of the marsh available for carbon storage. A transition in saltmarsh function from a net carbon sink to a source is particularly likely at eroding fringing marshes that are narrowing because upland transgression is impeded by steep topography (Rodriguez et al., 2013) and/or anthropogenic barriers, such as sea walls (Doody, 2004; Pontee, 2013). If a marsh can neither maintain its elevation with respect to sea level, nor migrate landward, it will eventually submerge or lose area, which could result in the export of carbon that has been sequestered in marsh strata and loss of the carbon storage capacity across the marsh platform.

The efficacy of a saltmarsh as a carbon storage site depends, in part, on the relative contributions of carbon storage across the saltmarsh platform and erosion at the shoreline. In order to assess how geomorphic change impacts the saltmarsh carbon budget, we developed a box model that estimates the net import or export of carbon to the marsh by comparing carbon storage to shoreline erosion. We then apply this model to an eroding fringing saltmarsh in North Carolina to determine its carbon budget and whether it functions as a carbon sink.

2. Methods

2.1. Saltmarsh carbon box model

Our model includes both annual estimates of carbon export via shoreline erosion and carbon storage (Fig. 1). Because the amount of carbon stored per year is scaled to the area of the marsh, in this model, carbon storage decreases as the marsh decreases in width. This is an important component of the model because not only does erosion result in carbon export, but it also limits carbon storage by reducing marsh area. The net annual carbon budget of the saltmarsh, which is the output of this model, can be used to identify the timing and width when carbon export outpaces storage and the marsh transitions to a carbon source (Fig. 2). Sea-level rise and temperature remain constant in our model simulations in order to isolate the impacts of shoreline erosion on the carbon budget; however, it has been shown that global warming and sea-level rise will likely alter carbon storage and export rates (McLeod et al., 2011; Kirwan and Mudd, 2012).

2.2. Parameters and assumptions

This model examines the net annual carbon budget of a saltmarsh (C_n) by differencing carbon storage (C_s; g yr^{-1}) and carbon export (C_e; g yr^{-1}), where positive C_n values indicate net carbon storage and negative C_n values indicate net carbon export (Fig. 1).

$$C_n = C_s - C_e \tag{1}$$

C_s is a function of the marsh area (M_a; m^2) and the carbon accumulation rate (C_{ar}; g m^{-2} yr^{-1}) and can be expressed using the equation:

$$C_s = M_a \times C_{ar} \tag{2}$$

M_a is calculated for each time step (dt; yr) by summing the initial marsh area (M_o; m^2), the change in marsh area at the shoreline, and the change in marsh area at the upland boundary.