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Research article

Modeling the Economic Value of Blue Carbon in Delaware Estuary Wetlands: Historic Estimates and Future Projections

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ABSTRACT

Coastal wetlands sequester large amounts of carbon in their soils, effectively removing carbon dioxide from the atmosphere and acting as a carbon sink. In this paper, we estimate the economic value of carbon sequestered by wetlands in the Delaware Estuary. We estimate the value of the current stock of wetlands, the value of the historic loss of wetlands, and under a range of different scenarios the expected future loss. We use historical topographic maps and Land Cover inventories of the Delaware Estuary to measure the acreage of tidal wetlands in nine distinct time periods from 1778 to 2011. Using these data, we estimate an annual rate of wetland loss of 1.03 km^2. Coupling observed land cover change with exogenous factors including sea-level rise, population pressure, and channel dredging, we estimate changes in tidal wetland area under a range of future scenarios for our expected future economic loss estimates.

1. Introduction

The Delaware Estuary, situated in the Mid-Atlantic region of the United States is a working estuary, like many around the world. As of the 2010 census, the counties bordering the Delaware Estuary are home to 6 million people (U.S. Census Bureau, 2010). The Delaware Estuary has been important to regional maritime commerce since the 1800s, is heavily developed in its upper reaches and less developed in its lower reaches, and provides essential habitat to a number of important commercial and recreational species, including horseshoe crabs and the Red Knot (Myers et al., 2010). The Delaware Estuary represents an important example for other working estuaries, where natural ecosystems and human activity collide.

The Delaware estuary is home to over 700 km^2 of coastal wetlands, and like many other wetlands in the United States and around the world, wetland area is declining (Dahl, 1990; Tiner et al., 2011; Tiner Jr, 1985). Human activities including diking (Weishar et al., 2005), conversion to residential and farming land, pollution, and channel dredging have caused Delaware wetland area to decline by 54% since pre-colonial conditions. The Delaware Estuary is not unique in rapidly losing wetlands, and there is a pressing need for better understanding of the value of lost wetlands to improve management decisions.

Coastal wetlands play an important role in regulating atmospheric carbon dioxide, but are under threat from anthropogenic modifications. This work develops and outlines a replicable model that can be applied to value changing coastal marsh ecosystems, the results of which provide important insights for policy makers to improve coastal management decisions. After identifiying the study area, the model takes changes in land cover as an input, estimates net carbon sequestration using local observations, and provides estimates of the economic value of carbon sequestration as the output. We use the Delaware Estuary as an example for how to apply the model.

1.1. Ecosystem services

Coastal wetlands rank among the most highly productive ecosystems on earth, providing critical refuge and nursery habitat for numerous aquatic, terrestrial, and avian species (Clark et al., 1993; Roman et al., 2000). Refuge and nursery habitat are just two

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examples of the ecosystem services provided by coastal wetlands. Ecosystem services are defined as the natural processes and components of ecosystems that provide goods and services that satisfy human needs, either directly or indirectly (De Groot, 1992; Fenichel et al., 2016; Guerry et al., 2015; Tiner, 2003). Other ecosystem services provided by wetlands include water filtration, sediment retention, storm surge buffering, and carbon sequestration (Barbier et al., 2011; Morgan et al., 2009; Pinsky et al., 2013). Carbon stored and sequestered in coastal and marine ecosystems is often termed "Blue Carbon" (McLeod et al., 2011; Nellemann et al., 2009) and is the primary focus of this paper.

Coastal wetlands play an important role in climate change mitigation. Taken together, all blue carbon sinks, including mangroves, seagrasses, and intertidal marshes, sequester carbon at a rate in excess of 100 TgC yr^{-1}, roughly equivalent to carbon sequestration from all terrestrial forests (Hopkinson et al., 2012).

Carbon dioxide fixed in coastal wetland plants via photosynthesis can be stored for thousands of years in anoxic soils as slowly decaying peat (Mitsch and Gosselink, 2015). Wetlands also capture and bury carbon rich detritus, further increasing the rate of carbon storage in soils. Wetlands emit methane (CH_4), a potent greenhouse gas, as a by-product of organic matter decomposition. However, sulphate reducing bacteria in coastal soils hinder the flux of methane, and thus coastal wetland systems emit much lower quantities of CH_4 than their freshwater counterparts (Bartlett and Harriss, 1993; Bridgham et al., 2006; Poffenbarger et al., 2011). Fluxes of the greenhouse gas N_2O, high in terrestrial ecosystems, are also low in coastal wetlands (Smith et al., 1983).

Literature estimates of the value of carbon sequestration in coastal wetlands vary widely. Barbier et al. (2011) estimate a value of \$3420 km^{-2} yr^{-1}, while Costanza et al. (2014) calculate a mean value of \$7550 km^{-2} yr^{-1} (2015\$) from a range of published and unpublished studies. Values from the United Kingdom range from \$6070 to \$20,780 km^{-2} yr^{-1} (Beaumont et al., 2014). All values are converted to 2015\$ using year of publication exchange rates, where necessary, and the consumer price index.

1.2. Wetland modification

The boundaries of coastal wetlands change both vertically and horizontally. Marshes can accrete vertically in sediment rich estuaries, but fail to keep pace with sea level rise in sediment poor estuaries or when belowground biomass productivity is insufficient to increase soil volume (Lentz et al., 2016; Weston, 2014). Tides and wave action influence the seaward boundary of marshes (Mariotti and Fagherazzi, 2010), whereas surface hydrology and plant interactions determine the landward boundary with uplands. Human modifications, such as draining and filling, diking and impoundment for water control, and land reclamation, all affect sediment dynamics and alter accretion and erosion rates (Kennish, 2001). Furthermore, wetlands and their surrounding areas are increasingly vulnerable to the effects of climate change, including sea level rise and temperature effects, causing ecosystem services to decline (Osland et al., 2016).

1.3. Carbon sequestration rates

Sequestration rates in North American salt marshes vary widely, ranging from 18 gC m^{-2} yr^{-1} to 1713 gC m^{-2} yr^{-1} with a mean of 214.6 gC m^{-2} yr^{-1} over 85 sites (Chmura et al., 2003). Mean values from the United Kingdom are typically lower, around 120–150 gC m^{-2} yr^{-1} (Beaumont et al., 2014). Carbon sequestration rates vary widely, even at nearby sites, and among different methods of measurement. Thus, there is inherent uncertainty in estimating sequestration rates accurately from a collection of point estimates.

In addition to removing carbon from the atmosphere, wetlands also perform the important function of storing carbon in their soils for periods of hundreds to thousands of years if undisturbed (Artigas et al., 2015; O'Reilly et al., 2014). However, the fate of carbon sequestered in wetlands is difficult to trace once wetlands become degraded or eroded (Bauer et al., 2013; Crooks et al., 2011; Deverel and Leighton, 2010). There are three possible pathways by which marsh carbon can move after disturbance; microbial remineralization and release as CO_2, consumption by detritivores, and physical transport to other locations, such as other parts of the marsh, deep water, or other estuarine habitats (Macreadie et al., 2013). Pendleton et al. (2012) speculate between 25% and 100% of carbon in surface sediments (<1 m deep) and wetland biomass may be reemitted to the atmosphere, mainly as CO_2. Landscape-scale studies show losses of soil carbon of up to 96% (Sigua et al., 2009) with similar results in the agricultural literature (Kirkels et al., 2014). Conversely, Lane et al. (2016) found that less than 10% of available carbon was actually mineralized, post-disturbance, while Macreadie et al. (2013) found disturbed marshes showed ~30% lower soil organic carbon, though the fate of the lost carbon is unclear. In short, the results are highly variable.

1.4. The social cost of carbon

The social cost of carbon (SCC) refers to the estimated economic damages (in present value terms) of the release of an additional metric ton of CO_2 (or CO_2 equivalent) into the atmosphere. Analogously, SCC represents the avoided damages from removing a metric ton of CO_2 (or CO_2 equivalent) from the atmosphere. We can use the SCC to estimate the economic value of carbon sequestration when sequestration rates are known. SCC values are estimated using integrated economic damage assessment frameworks, or Integrated Assessment Models (IAMs), that employ coupled climatic and economic models. The latter involve the prediction of the potential damages associated with given atmospheric levels of CO_2 to estimate future costs (Hope, 2011; Nordhaus, 2014; Tol, 2009; Waldhoff et al., 2014). Uncertainty regarding the damage function's parameters, including the discount rate, and the resulting estimates of future economic losses affect SCC values greatly, which range from \$6 to upwards of \$125/tCO_2 (van den Bergh and Botzen, 2014).

2. Material and methods

We begin with a discussion of our study site, the Delaware Estuary, and then outline our model for valuing changes in carbon sequestration under uncertain land cover scenarios.

2.1. Study site: the Delaware Estuary

2.1.1. Morphology and plant distribution in the Delaware Estuary

The Delaware Estuary is a funnel-shaped estuary that extends from the mouth of the Delaware Bay at Cape Henlopen, Delaware to the "head of tide" at Trenton, New Jersey. The Delaware Estuary can be divided into the Upper Estuary (oligohaline), the Lower Estuary (mesohaline), and the Delaware Bay (polyhaline) (DRBC, 2004). The Upper and Lower Estuaries around Philadelphia, PA and Wilmington, DE are highly developed, while farming and wetland dominate land cover in the Delaware Bay (Fig. 1).

Delaware Bay wetlands are dominated by salt marsh and characterized by extensive stands of smooth cordgrass (*Spartina alterniflora*) in the low marsh and salt hay (*Spartina patens*) and spike grass (*Distichlis spicata*) in the high marsh (Philipp, 2005). The common reed (*Phragmites australis*), an invasive species, is present