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The impact of past management practices on tidal marsh resilience to sea level rise in the Delaware Estuary

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ABSTRACT

Defining appropriate management and conservation strategies to maximize tidal marsh resilience to sea level rise requires a clear understanding of the causes of marsh degradation. While sea level rise is a well-known threat to tidal marshes, current and past management practices on marshes can also greatly influence present-day marsh condition, resilience and future persistence. Using point-intercept analysis of maps and imagery, we assessed the past and current landcover and elevation of Delaware Estuary tidal marshes in New Jersey, USA. We estimated the historic extent of tidal marsh impoundment for agriculture and determined current marsh vegetation composition and elevation in areas that were and were not historically impounded. We estimate that more than half of all tidal marsh in the 36,539 ha study area had been historically impounded. A small fraction of this area remains impounded at present (7.6%). While tidal flow has since returned to formerly diked areas, marsh recovery has been incomplete. Overall 21.6% (4048.8 ha) of formerly impounded marsh has not revegetated, becoming open water after impoundment breaches. Marsh loss as a result of impoundment is also responsible for the loss of 2.3 km of adjacent shoreline beaches. Conversely, only 0.5% of marsh that was never impounded has converted to open water since 1931. This difference is likely due to dramatic elevation deficits caused by impoundment. Marsh elevation of current and formerly impounded areas (derived from LiDAR and validated with RTK GPS) is significantly lower than the elevation of marsh areas that were never impounded. Supporting this finding, the frequency of high marsh vegetation (an indicator of higher elevation)in vegetated formerly impounded areas is half that of areas that were never impounded. Marsh edge erosion and creek expansion have added an additional estimated 3836 ha to the amount of tidal marsh loss since 1931. Marsh transgression inland into forest and agricultural areas has resulted in estimated gains in marsh area of 2815 ha, offsetting a considerable proportion of losses. Given our results, we recommend the following management actions to maximize tidal marsh persistence in the Delaware Estuary: (1) Beneficial use of sediment to offset marsh elevation deficits resulting from historic impoundment, (2) Strategic land protection to maximize the potential for inland marsh migration, (3) Tidal flow restoration to remaining impounded areas in combination with the beneficial use of sediment to address elevation deficits. Determining the impacts to tidal marshes from past management practices makes it possible parse the relative contribution of relative sea level rise and site-level management, resulting in more targeted conservation strategies.

1. Introduction

As impacts from climate change-accelerated sea level rise threaten the continued existence of tidal marshes, many of these marshes have also been negatively impacted by current and former management and land use practices (Kennish, 2001; Silliman et al., 2009). Actions such as impoundment and tidal restriction (Roman et al., 1984), ditching (Bourn, 1950), open water marsh management (Wolfe, 1996), sediment removal (Hackney and Cleary, 1987) and hydrological alterations and diversions (Allison and Meselhe, 2010; Elias et al., 2003) can play an important role in determining present marsh condition and in turn, its resilience to sea level rise. Understanding the relative contributions of sea level rise and

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effects of management to tidal marsh losses, condition and resilience can allow for conservation and management strategies that are more targeted and effective.

In particular, identifying current and past management actions that negatively impact tidal marshes and threaten their future persistence (Gedan et al., 2009) can guide management at the site level to reverse these impacts through restoration (Weinstein et al., 2001). Conversely, if the cause of problems in marshes is assigned to sea level rise alone (Kirwan et al., 2010), practitioners may conclude that restoration actions will not correct the root problem (i.e. global carbon emissions) and therefore only represent a stop-gap on the way toward the inevitable outcome of marsh loss.

It is becoming clear that sea level rise alone may not necessarily spell the extinction of tidal marshes in many settings (Kirwan and Megonigal, 2013). Tidal marshes with higher marsh accretion rates and capacity for inland migration offer the potential for long-term persistence, particularly in estuaries with moderate to high tidal ranges (Kirwan et al., 2016). The Delaware Estuary, in concept, should represent a sea level rise-resilient tidal marsh system, with moderate (1.6–1.8 m) tidal range (Galperin and Mellor, 1990), high suspended sediment loads (Cook et al., 2007) and large frontage of undeveloped tidal marsh/upland ecotone (Smith, 2013) to allow for inland transgression (Kirwan et al., 2016). Despite these attributes, large acreages of these marshes have converted to open water and a significant proportion of the remaining marsh is in degraded condition (Kearney et al., 2002).

This paradox is not readily explained, but a consideration of past management of these marshes may offer insight. One important consideration is that large regions of Delaware Estuary tidal marsh were once impounded and drained for agricultural use (Philipp, 2005; Weinstein et al., 2000). Although the majority of these marshes are now not actively managed and are under tidal influence, the legacy of past impoundment may impact present and future resilience to sea level rise.

The practice of impounding and farming tidal marshes achieved large scale application in only a few places in North America (Nesbit, 1885), although large acreages of impounded tidal marsh are still extant northern Europe (Allen, 2000). In eastern North America, these places were the Delaware Bay (Nesbit, 1885), the Carolinas (Tompkins, 1987) and Canada Maritimes (Butzer, 2002; van Proosdij et al., 2013). The geographic, cultural and tidal context of these regions made landscape-scale impoundment of marshes for agricultural production both feasible and cost effective.

Impounded Delaware Estuary tidal marshes were used to grow field crops and "salt hay", which included a mix of high marsh plant species that were used for fodder and other purposes (Sebold, 1992). At least 6000 ha of marshes were impounded Salem County, New Jersey alone by the mid-1800s (Cook, 1870). This is in addition to comparable areas in the two other New Jersey counties bordering the bay (Cumberland, and Cape May) as well as along Delaware's coastline (Phillip, 1995; Sebold, 1992). To date, no comprehensive mapping of historically impounded marshes has been made.

While much of Canada Maritimes' "dykelands" are still intact, with 32,350 ha of impounded tidal marsh managed by provincial governments (van Proosdij et al., 2013), impoundment management was always a private enterprise in the Delaware Bay (New Jersey Legislature, 1911). As a result, under-engineered dikes, ditches and sluices needed constant maintenance and required close cooperation among adjacent landowners (Sebold, 1992; Vorst, 1977). When economic conditions changed beginning with the Great Depression and continuing through World War II, resources were too scarce to invest in impoundment maintenance and dikes began to lapse (Sebold, 1992; Stutz, 1992). Beyond the Depression, the practice became less economically viable over time. This coincided with the era of wetland conservation that saw state and federal governments, along with non-profits take over ownership of tidal marshes. With the exception of one large multi-site project that incorporated explicit restoration goals and actions (Teal and Weishar, 2005), these new conservation lands reverted to tidal flow in ad-hoc coastal realignment (Esteves, 2013) as dikes were allowed to lapse.

When tidal marshes are impounded, tidal flow is prevented from entering the marsh and drainage systems within the impoundment further dry the marsh to allow for farming activity. This change in hydrology exposes the marsh soils to air and the underlying peat soils begin to break down resulting in a loss of surface elevation (Portnoy, 1999; Roman et al., 1984; Warren, 1911; Weinstein et al., 2000; Weinstein and Weishar, 2002). Compaction from equipment, vegetation removal and tidal and sediment deprivation all contribute to further decrease elevation and work against the process of marsh vertical accretion in response to sea level rise (Bryant and Chabreck, 1998; Warren and Niering, 1993).

Impounded marshes behind dikes frequently fall to surface elevations that are too low to support natural marsh vegetation once dikes are removed (Weinstein and Weishar, 2002). Some marshes of the Delaware Bay have lost from 60 cm to 1.2 m of elevation after impoundment (Warren, 1911; Weinstein et al., 2000). Elevation loss likely varies as a result of landscape context and period during which the areas was impounded. The dramatic effects on elevation resulting from impoundment coupled with the large acreage of the Bay's marshes that were under this form of management suggests that the majority of the Delaware Bay's marshes may be, in many cases, significantly lower elevations than marshes that were never impounded. In some cases dike breaches have led to considerable subsequent losses in marsh area as a result of these elevation deficits (Weinstein et al., 2000).

To improve upon the management and restoration of Delaware estuary tidal marshes, we test the hypothesis that past impoundment explains present-day variation in tidal marsh elevation and vegetation composition. We do this by first determining a baseline historical extent of tidal marsh impoundment and second, examining whether these past practices have impacted present day marsh vegetation composition and elevation. Furthermore we estimate net change in tidal marsh area since 1931 by quantifying marsh conversion to open water and increases in area via marsh migration into upland. Our goal is to develop a revised tidal marsh conservation management model that incorporates both a perspective on climate change-induced causes of tidal marsh degradation and loss as well as those caused by past management practices (Almeida et al., 2014) which manifest themselves in present day marsh degradation and vulnerability to sea level rise.

2. Methods

2.1. Study area

We defined our study area as the New Jersey Delaware Bay tidal marsh extent in 1931 (Fig. 2). To delineate this area, we used National Wetlands Inventory (NWI) map areas (Wilen and Bates, 1995) classified as "Estuarine and Marine Wetland" as a starting point. We then digitized and added areas omitted by NWI that had been lost between 1931 and the creation/updating of NWI maps in the 1990s and 2000s. These area were either (1) interior marsh that had converted to mud/open water or (2) bay-fringing marsh lost to edge erosion (Phillips, 1986). To arrive at a total estimate of marsh edge erosion, we also mapped areas that had eroded since NWI mapping and present using 2015 imagery (NJ Office of Information Technology, Office of Geographic Information Systems Orthoimagery 2015).