Wetlands Ecol Manage (2020) 28:527–541
https://doi.org/10.1007/s11273-020-09729-w

ORIGINAL PAPER

Mapping sea level rise impacts to identify climate change adaptation opportunities in the Chesapeake and Delaware Bays, USA

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Received: 18 October 2019 / Accepted: 27 April 2020 / Published online: 4 May 2020

Abstract Salt marshes are at risk globally if they cannot keep pace with sea level rise. Along the United States Mid-Atlantic coast, high marsh has already declined, and is particularly vulnerable to future loss due to greater regional rates of relative sea level rise and limited capacity for both vertical accretion and landward migration. To support climate adaptation efforts in the region, we conducted a spatial overlay analysis to (1) assess interior ponding in the high tidal marsh zone caused by waterlogging, and (2) identify restoration opportunities where poor drainage is limiting natural recovery. Surface inundation has increased across over 14,000 ha of high marsh in the region, mostly along the eastern Chesapeake Bay and New Jersey coast. Within this waterlogged area, we identified 239 potential restoration sites (275 ha). Validation data indicate our analysis had relatively high accuracy in identifying potential restoration sites, with a true positive rate of 76% and a true negative rate of 96%. Widespread waterlogging emphasizes the need for climate adaptation efforts to restore and protect high marsh in the face of future change. Our recommended restoration strategy of connecting waterlogged sites to tidal creeks aligns with best practices by enabling drainage of high marsh to halt or even reverse ponding, improve recovery from future flooding events, and ultimately facilitate marsh migration with sea level rise.

Keywords Sea level rise · Marsh migration · Tidal wetlands · Waterlogging · Ponding · Wetland restoration

Introduction

Tidal marshes provide immense ecological and economic value, including protection from storms, nursery grounds for commercially important fisheries, enhancement of ecotourism, sequestration of carbon, and essential habitat for wildlife. Yet they are among the most vulnerable ecosystems to sea level rise. Global mean sea level has risen 0.19 m over the past century (Pachauri and Mayer 2015), and the rate has been accelerating over time (Church and White 2006). Many marshes have not kept pace with sea-level rise over recent decades, and are unlikely to in the future. In a meta-analysis of salt marshes in North America

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11273-020-09729-w) contains supplementary material, which is available to authorized users.

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and Europe, 60% could be lost by 2100 under the most optimistic emissions scenario, and up to 90% could be lost under the most extreme emissions scenario (Crosby et al. 2016).

Platform drowning, wave edge erosion, and interior ponding are the major agents of tidal marsh loss (Mariotti 2016). Marshes can counteract these impacts and maintain themselves through the accumulation of sediment and organic matter (i.e. vertical accretion) and migration inland as saltwater influence reaches upslope (i.e. marsh migration) (Kirwan et al. 2016a, b; Kirwan and Gedan 2019). In the Chesapeake Bay of the United States, a recent analysis of historical maps and aerial photography found that more marsh (101 km^2) has been created due to upland drowning than was lost (94 km^2), primarily to shoreline erosion, since the mid-nineteenth century (Schieder et al. 2018). Such patterns have also been found in other regions of the world, including Italy's Venice lagoon (Rizzetto and Tosi 2011) and Portugal's Tagus estuary (Simas et al. 2001).

However, there are several reasons to doubt that marsh migration can fully compensate eroded marsh over large spatial scales in the future. In regions with relatively higher rates of sea level rise and lower accretion rates, including the U.S. Mid-Atlantic, marshes may be especially vulnerable to decline (Ezer and Corlett 2012; Sallenger et al. 2012). High marshes naturally accrete sediment more slowly than low marshes, putting them at even greater risk of submergence (Gedan et al. 2009). In the Chesapeake Bay, sea level rise has already contributed to the degradation of over 80,000 ha (70%) of tidal marsh (Kearney et al. 2002). Marshes in Dorchester County on Maryland's eastern shore have suffered particularly high losses due to submergence and erosion of the marsh interior (Kearney et al. 2002; Schepers et al. 2017), and are among the most vulnerable to future decline (Titus and Richman 2001). Some computer models predict almost complete loss of tidal marsh in the Chesapeake Bay this century (Glick et al. 2008).

Furthermore, in many coastal regions, human activities have limited the potential for both vertical accretion and landward migration of marshes. Land subsidence from groundwater extraction has lowered marsh elevation, contributing to high rates of submergence; dredging of shipping canals has altered tidal flows, increasing erosion energy and reducing sediment delivery; and urbanization has reduced sediment input and restricted upslope movement (Adam 2002; Kirwan and Megonigal 2013). Even where marsh migration can proceed, drowned uplands do not always convert to a fully functioning tidal marsh ecosystem. On the Atlantic coast of the U.S. *Phragmites australis* frequently invades forest-marsh transition zones and then persists as an extensive monoculture after the forest has died back, degrading habitat for wildlife species of concern (Lerner et al. 2013). In this region, native high marsh vegetation is frequently dominated by low-statured grasses (*Spartina patens* and *Distichlis spicata*), which provide essential habitat for at-risk salt marsh obligate birds, including Saltmarsh Sparrow (*Ammodramus caudacutus*) and Black Rail (*Laterallus jamaicensis*). Both of these species are rapidly declining due to accelerating sea level rise and habitat loss, and are proposed for listing under the Endangered Species Act.

Another issue in low-lying coastal regions is trapped standing water in upland-marsh transition zones derived from storm tides or from the discharge of fresh groundwater, which fails to drain due to isolation from the tidal creek network, resulting in waterlogging and interior erosion of newly transitioned marsh (Fig. 1; Brinson et al. 1995; Blum et al. 2002; Lerner et al. 2013). There has been a significant increase in the rate of surface flooding in marshes in the Mid-Atlantic region (i.e. Maryland, Virginia, and New Jersey) over the past century (Erwin et al. 2006; Schepers et al. 2017). This phenomenon deserves attention from conservation practitioners due to its potential to cause the erosion and loss of high marsh vegetation long before sea level rise introduces daily tidal influence and consequent conversion to low marsh. Such sites have the elevation capital to drain, but fail to do so because shallow basin topography develops due to factors such as elevated regions in the mid-marsh zone or ground surface collapse from reduced plant productivity or death (Blum et al. 2002; Day et al. 2011). Cases of interior erosion are especially concerning as they can lead to permanent marsh loss even where accretion rates are otherwise sufficient to keep pace with sea level rise (Mariotti 2016).

In light of their ecological importance and vulnerability to sea level rise, there is a compelling need to develop strategies to increase tidal marsh resilience and reduce rates of loss in the U.S. Mid-Atlantic region. While other studies have documented the

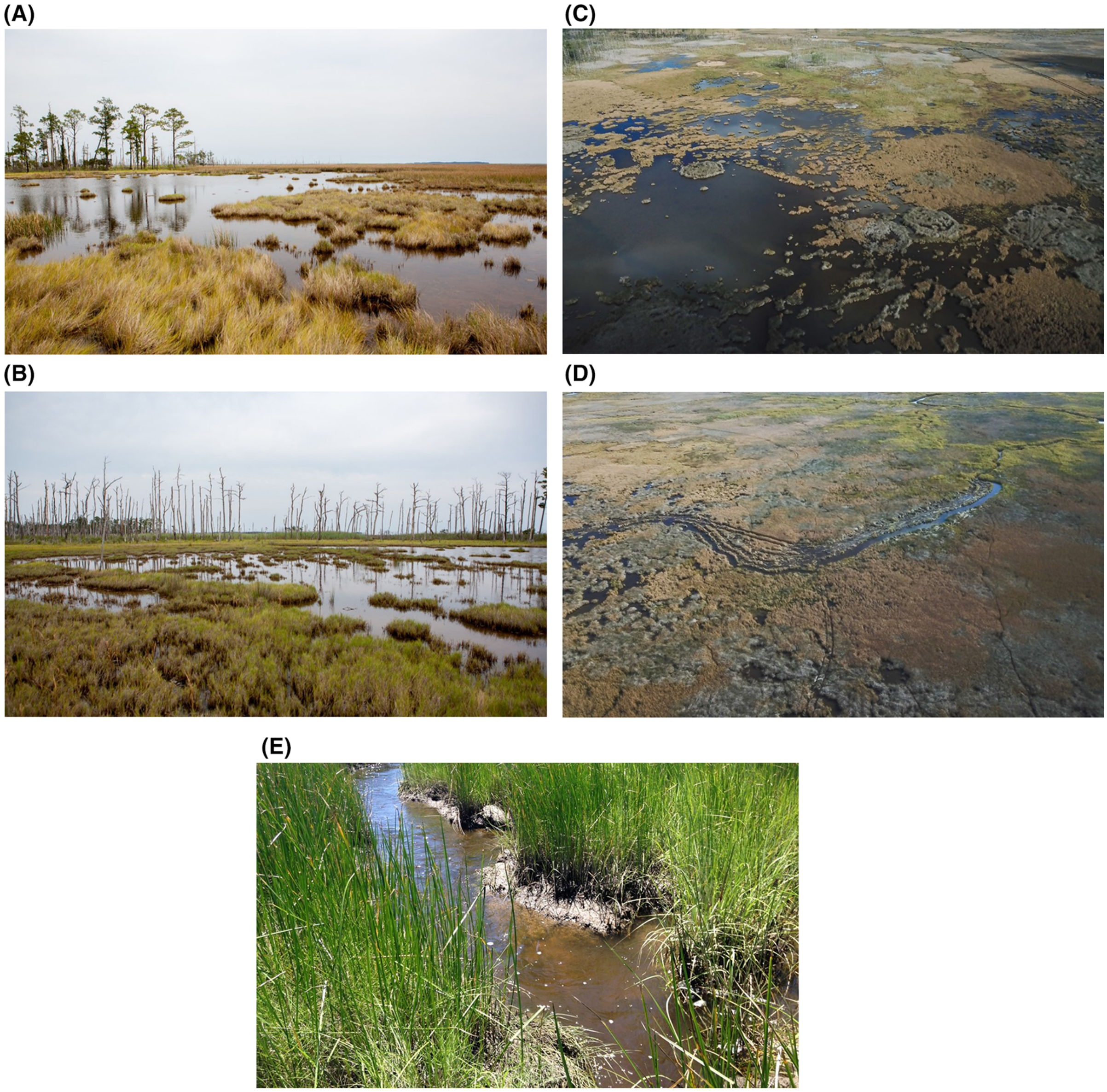

Fig. 1 Waterlogged soils at the upland-marsh transition boundary (**a**–**c**) and the ditch constructed to drain these soils (**d**, **e**) at Farm Creek Marsh, MD. Conditions are shown from on the ground (**a**, **b**, **e**) and aerial photographs (**c**, **d**). Photo credits: **a**, **b** Camilla Cerea/Audubon, **c**, **d** Maryland Department of Natural Resources, **e** David Curson

impacts of sea level rise in this region, here we aim to identify where these impacts could be reversed through on the ground management and restoration. We present a novel spatial analysis to (1) assess interior erosion in the high tidal marsh zone across caused by waterlogging, and (2) identify sites where eroding waterlogged marsh has the potential to drain, and potentially revegetate, if connected to the tidal creek network by artificially created drainage channels (i.e. tidal creek extension). The National Audubon Society piloted this restoration technique in 2018 at Farm Creek Marsh, a sanctuary owned by the Chesapeake Audubon Society in Dorchester County, Maryland, where soil waterlogging has resulted in interior marsh erosion and increased surface inundation over recent decades (Fig. 1). We find that several other sites in the region have similar conditions, indicating that they are vulnerable to loss and may benefit from actions to protect against the impacts of sea level rise. Although not widely documented, these conditions are likely to be relevant to other low-lying temperate salt marsh systems with low accretion rates as well, including those in the North Sea, Gulf of Mexico, and Australian Coast (Giuliani and Bellucci 2019). Connection to tidal creeks can assist marsh recovery at these sites by removing surface water and reinstating conditions conducive for plant growth. Ultimately, restoring these sites could slow marsh decline and facilitate marsh migration with sea level rise.

Methods

Input datasets and criteria

We conducted a spatial overlay analysis to identify sites that are currently high marsh, and are predicted to at least partially remain marsh under future sea level rise, but have become waterlogged over recent decades and are unable to drain (Table 1). This analysis encompasses the greater Chesapeake and Delaware Bay areas, in the U.S. Atlantic states of southern New Jersey, Delaware, Maryland, and Virginia (Fig. 2). We used the National Wetlands Inventory (NWI) to identify present-day high marsh in the region (US Fish and Wildlife Service 2013). NWI is a nationwide inventory of wetlands identified through aerial imagery analysis and produced at a scale of 1:24,000 (Wilen and Bates 1995). NWI classifies wetlands according to their tidal system, vegetation, salinity, and flooding regime. While low marsh is flooded on a daily basis, high marsh is flooded irregularly by high tides during coastal storms. We selected the E2EM1P class, representing wetlands in estuarine intertidal systems (E2) with persistent emergent vegetation (EM1) that are irregularly flooded by saltwater tides (P) to categorize current high marsh (Cowardin et al. 1979).

To identify sites where high marsh is waterlogged and eroding to open water, we applied the Global Surface Water Dataset, a Landsat satellite imagery product that maps the spatial and temporal distribution of surface water at a 30-m resolution (Pekel et al. 2016). We used their classified surface water change product (1984–2014) and selected classes representing transitions towards an increase in surface inundation (i.e. New Permanent, New Seasonal, and Seasonal to Permanent surface water classes). This dataset represents a comprehensive and high-resolution examination of where surface water has increased over a 30-year period. We intersected this dataset with our NWI marsh layer to identify where high marsh has recently transitioned to open water.

In order to identify sites with the elevation capital to drain through tidal creeks, we included sites that are predicted to remain high marsh through 2050 based on one of two sea level rise projections depending on location. For Maryland's eastern shore, projections of habitat transitions under sea level rise were developed by the Maryland Department of Natural Resources

Table 1 Variables used to identify waterlogged marshes in need of restoration, and the datasets and criteria chosen to represent them in the spatial overlay analysis

Variable	Dataset	Criteria
Marsh in the present	National Wetlands Inventory (NWI)	Irregularly flooded estuarine emergent wetlands (class E2EM1P)
Marsh in the future	Sea Levels Affecting Marshes Model (SLAMM; eastern Maryland), NOAA Marsh Migration (other areas)	Estuarine, irregularly flooded, or transitional wetlands
Increase in standing surface water	Global Surface Water Dataset	Transitions towards an increase in surface water (new permanent, new seasonal, or seasonal to permanent)
Poor soil drainage	Area- and depth- weighted SSURGO variables	Proportion silt $\geq$ 50 or proportion clay $\geq$ 35
Lack of connectivity to tidal creeks	National Hydrography Dataset (NHD) and National Wetlands Inventory (NWI)	$>$ 30 m away from NHD flowline features, and NWI deepwater features that intersect NHD

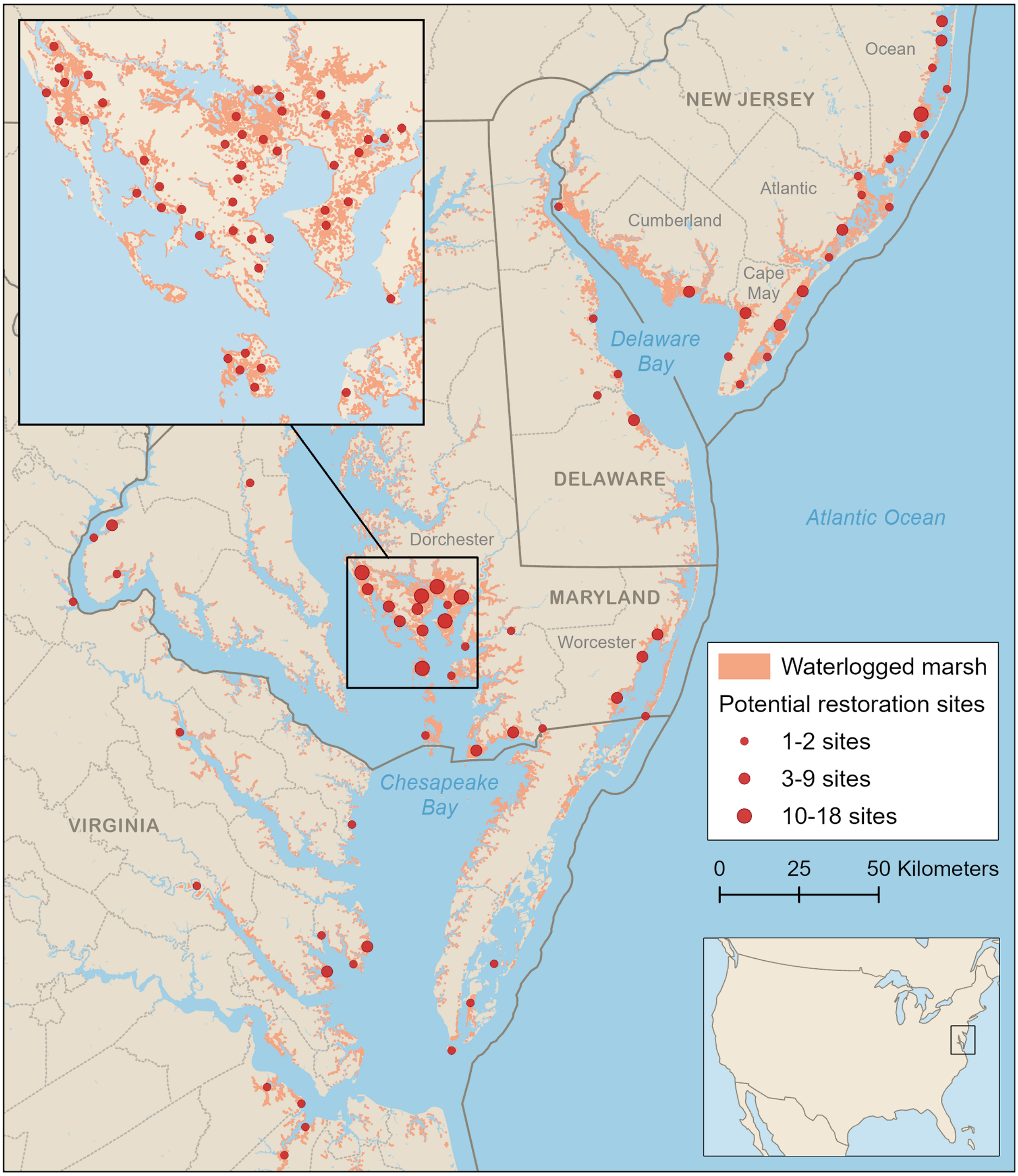

Fig. 2 Waterlogged marsh and potential restoration sites in the study area as identified by the spatial model. The locator map in the lower right shows the study area in relation to the coterminous United States. The inset map in the upper left shows a close-up of Dorchester County, Maryland, where the majority of sites were located. Sites within 2 km of each other in the main map and within 500 m of each other in the inset map have been co-located for cartographic purposes

(Edmonds 2011) based on the Sea Levels Affecting Marshes Model (SLAMM). SLAMM uses local data on elevation, accretion and erosion rates, and sea level rise to predicatively model long-term habitat transitions. Outputs were generated for Maryland's coastal counties at a 30-m spatial resolution under two sea level rise scenarios: 0.4 m by 2050 and 1 m by 2100 (Edmonds 2011). For other regions in our study area where SLAMM outputs were not available, projections were based on NOAA's Marsh Migration dataset (Marcy et al. 2011). NOAA uses a modified bathtub approach that incorporates LIDAR-derived elevation data and attempts to account for local and regional tidal variability. Outputs are available for the conterminous US at a 10-m spatial resolution with scenarios of up to 10 ft ($\sim$ 3 m) provided in half-foot increments. We selected outputs to match the SLAMM parameters for 2050, choosing a future sea level rise scenario of 1 ft (0.3 m). This rate of sea level rise is consistent with an intermediate scenario (0.34 m by 2050) from the federal Interagency Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Task Force's most recent technical report (Sweet et al. 2017). We included irregularly flooded, estuarine and transitional estuarine shrub/scrub wetland landcover classes from both datasets to represent future marsh.

We assessed current drainage ability by considering both underlying soil composition and isolation from tidal creeks. We used area- and depth- weighted averages of Soil Survey Geographic Database (SSURGO) variables to map soils (Wieczorek 2014), retaining sites where soil texture would impede drainage due to high levels of silt (at least 50%) or clay (at least 35%). We then assessed distance to tidal creeks, as represented by the National Hydrography Dataset (NHD) (US Geological Survey 2017). NHD is the most current and comprehensive hydrography data for the nation, mapping all drainage networks at a scale of 1:24,000 or better. We incorporated the NWI deepwater class to also include area features that intersected the linear NHD drainage network. We used a distance of 30 m or greater to classify waterlogged sites as isolated from tidal creeks, based on the spatial resolution of the Global Surface Water Dataset.

Spatial overlay analysis

We used ArcGIS Pro version 2.1 to construct a spatial model that overlaid these datasets to identify potential restoration sites (i.e. target sites, Fig. 3). We first clipped current marsh by areas of surface water increase to identify waterlogged areas, and then aggregated the resulting sites to group features that were small and close together, using a minimum size of 0.5 ha and a distance of 30 m to match our mapping resolution. We selected sites that intersected marsh in the future based on a spatial join to retain locations where restoration could have a lasting impact. We kept sites with poorly drained soils based on a spatial join with the soils layer. Finally, we calculated distance to the nearest stream or drained deepwater feature, keeping only disconnected sites.

Validation

We reviewed aerial photographs and conducted field visits to validate our approach. We implemented a random stratified sampling design to survey an equal number of locations that met and did not meet model criteria for potential restoration sites. All validation sites were located in our target marsh class as identified by NWI, and along public roads to ensure access. Because we could not assess future land cover or underlying soils through visual observation, we also limited validation sites to areas predicted to remain marsh in the future and with poor soil drainage. We surveyed 50 locations total, separated at least 1 km apart. Field visits occurred in November and December 2018, several days after rains in order to give sites sufficient time to drain and allow us to accurately distinguish waterlogged conditions. We reviewed high resolution aerial photography for all sites from both Google Maps (data from 2019, 0.5-m resolution; Google 2019) and the National Agriculture Imagery Program (NAIP, data from 2010 to 2017, 1-m resolution; USDA Farm Service Agency 2017) (Fig. 4). We looked for the following conditions when validating our model: (1) dominance of typical high marsh vegetation (e.g. *Spartina patens* and *Distichlis spicata*), (2) surface inundation, and (3) isolation from tidal creeks. We considered sites meeting these criteria as true positives; all others were true negatives.

Results

Increase in surface inundation

High marsh currently covers nearly 190,000 ha across the study region according to NWI data, and marsh migration projections indicate that this area could

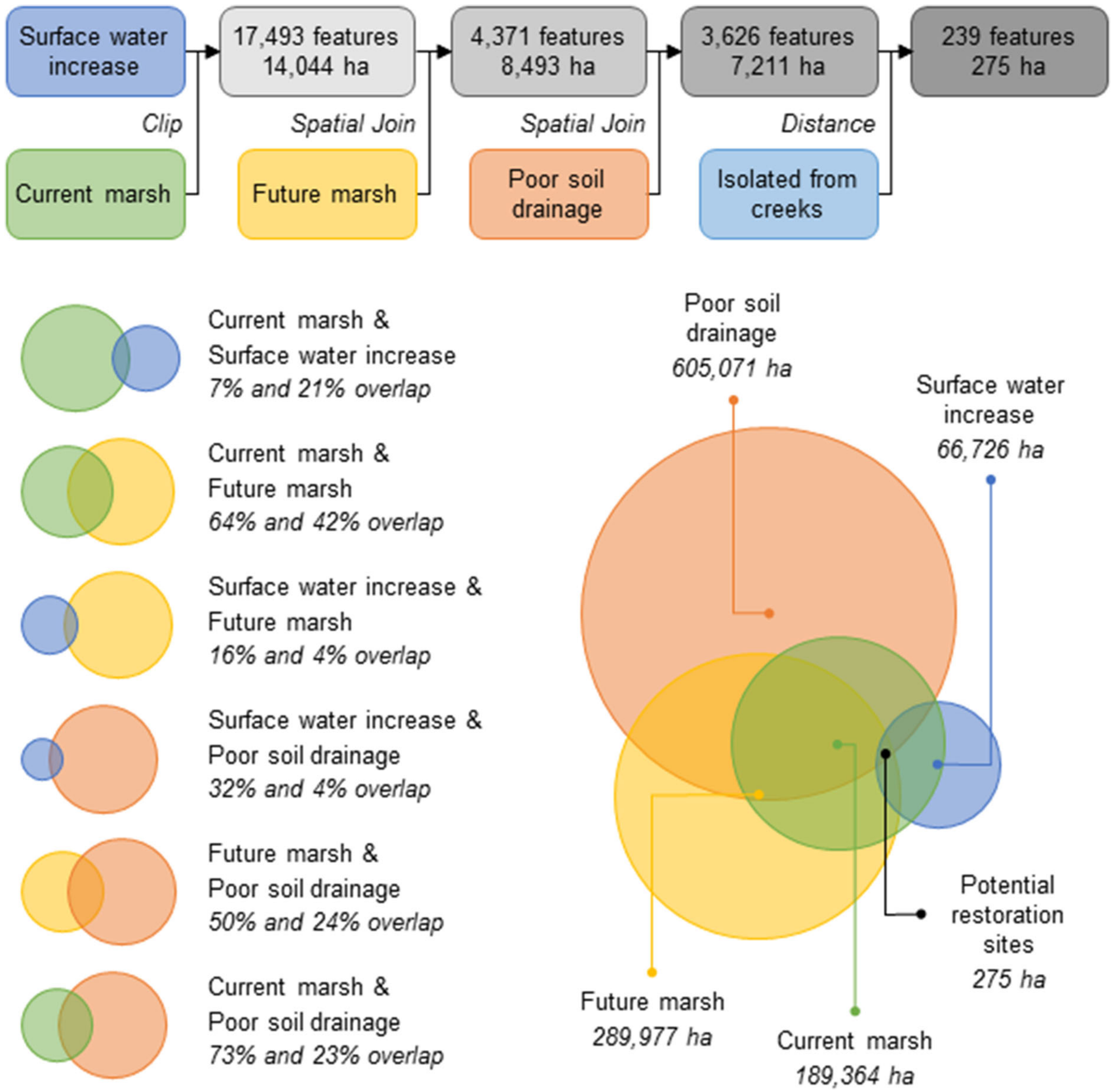

Fig. 3 Conceptual diagram of the input data layers, relationships between them, and how they were incorporated in the spatial model. The flowchart at the top shows the steps of the overlay analysis, with the number of features and their area in hectares after each step. Below, Venn diagrams show the relative area and degree of overlap among the four categorical input layers: current marsh (green), future marsh (yellow), surface water increase (blue), and poor soil drainage (orange). On the left, overlap between pairs is shown and expressed as a percentage of both the first and second layer listed respectively. Graphic sizes are approximate

expand by over 100,000 ha (Fig. 3). However, overlays with NWI and Global Surface Water Data indicate that surface inundation has already degraded over 14,000 ha (7%) of high marsh in the study area since 1984, including in places forecasted to remain marsh (Figs. 2–3, Table 2). The largest areas of surface inundation are along the eastern shores of the middle Chesapeake Bay in Dorchester County, Maryland (1958.7 ha), and along the Atlantic Coast of New Jersey, in Cape May (1734.2 ha), Atlantic (1638.9 ha), and Cumberland (1,426.9 ha) counties. By state, New Jersey accounts for the greatest area of

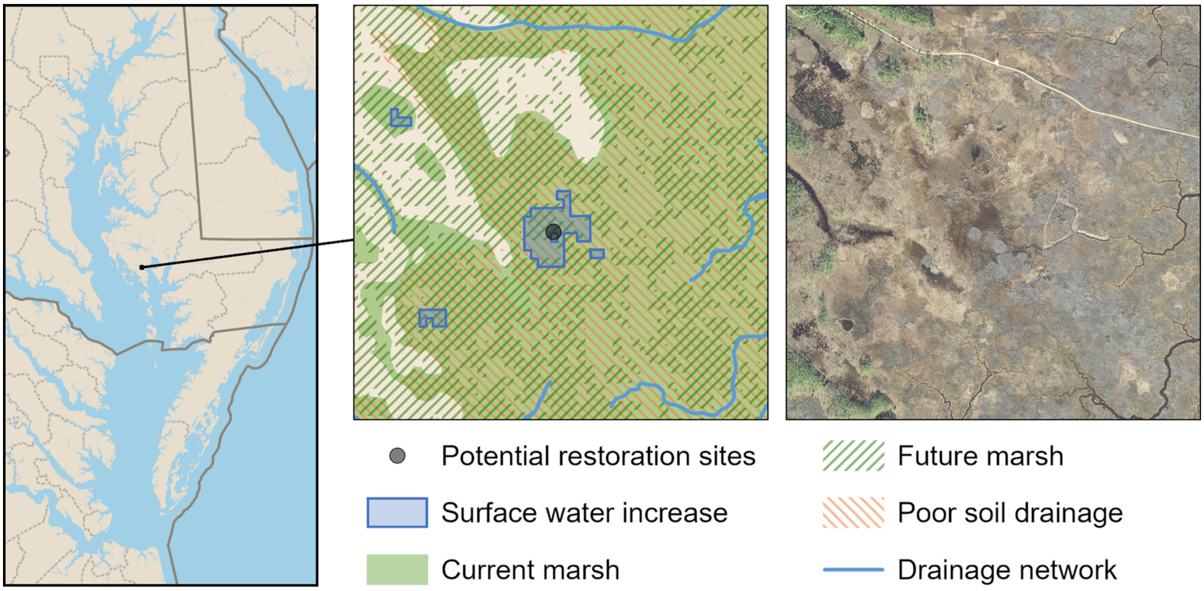

Fig. 4 Side-by-side comparison of inputs to the spatial model (left) and waterlogged conditions as seen from NAIP aerial photography (USDA Farm Service Agency 2017) (right). Both maps show Farm Creek Marsh in Dorchester County, MD, one of the sites identified by this analysis where the tidal creek extension strategy has been piloted, at a scale of 1:24,000. Darker areas in the center of the image indicate waterlogged conditions (Kearney et al. 2002)

waterlogged high marsh in the region (5810.7 ha, 41% of the waterlogged high marsh identified), followed by Maryland (5149.2 ha, 37%), Virginia (2684.2 ha, 19%), and lastly Delaware (400.0 ha, 3%).

Potential restoration sites

Within these waterlogged areas, our model identified 239 sites totaling approximately 275 ha of surface inundation that are also predicted to remain as high marsh through 2050 but are isolated from the tidal creek network, and as such may benefit from restoration techniques such as tidal creek extension (Fig. 2, Table 2, and Table S1). On average, these target sites included an inundated area of 1.1 ha (range 0.5–10.5 ha) at an elevation of 0.3 m above NAVD 1988 (range -0.1 – 1.5 m).

The majority of target sites were located along the Chesapeake Bay's eastern shore: Dorchester County, MD, alone accounted for almost half of the output in terms of both number of sites (110) and area of surface inundation (139.9 ha). Coastal New Jersey also stood out, with a combined 57 sites covering 64.6 ha of surface inundation in Ocean, Cape May, and Atlantic Counties. Fewer sites were identified along the western shores of the Chesapeake and Delaware Bays, and no sites were identified in the upper Chesapeake Bay.

Most target sites (122, 51%) fall on publicly protected lands under federal, state, or local government ownership, including a high proportion of sites on U.S. Fish and Wildlife Service National Wildlife Refuges (53 sites, 62 ha) and state wildlife management areas owned by Maryland (29 sites, 27 ha), New Jersey (15 sites, 13 ha), Virginia (3 sites, 2 ha), and Delaware (2 sites, 3 ha). An additional 17 sites (7%) are located on privately owned protected lands.

Validation

Field surveys and review of aerial photography indicate our model had relatively high accuracy in identifying target sites, with a true positive rate of 76% and a true negative rate of 96% (Table S2). Of the 50 sites surveyed, six were identified as suitable for restoration when they were actually unsuitable (commission errors) and only one was identified as unsuitable for restoration when it was actually suitable (omission error). Commission errors were entirely due to inaccuracies in assessing existing drainage networks, owing to errors in the input data in certain locations: tidal creeks run through four of the

Table 2 Results by state and county showing total area of waterlogged marsh (ha), number of potential restoration sites, total potential restoration area (ha), and mean elevation of potential restoration sites (m above NAVD 1988)

State	County	Waterlogged marsh area (ha)	Potential restoration sites	Potential restoration area (ha)	Mean site elevation (m above NAVD 1988)
Delaware	All	400.0	8	8.2	0.6
	Kent	107.2	5	5.4	0.7
	New Castle	70.2	–	–	–
	Sussex	222.6	3	2.8	0.3
Maryland	All	5,149.2	144	177.3	0.2
	Anne Arundel	32.6	–	–	–
	Baltimore	31.8	–	–	–
	Calvert	60.1	1	0.6	− 0.1
	Caroline	87.3	–	–	–
	Cecil	40.6	–	–	–
	Charles	135.1	6	6.2	0.1
	Dorchester	1,958.7	110	139.9	0.2
	Harford	135.7	–	–	–
	Kent	83.1	–	–	–
	Prince George’s	34.4	–	–	–
	Queen Anne’s	107.7	–	–	–
	Somerset	888.1	14	16.7	0.3
	St. Mary’s	66.7	–	–	–
	Talbot	87.6	–	–	–
	Wicomico	177.3	1	0.8	0.2
	Worcester	1,222.4	12	13.1	0.1
New Jersey	All	5,810.7	61	67.8	0.4
	Atlantic	1,638.9	10	8.3	0.5
	Burlington	17.3	–	–	—
	Cape May	1,734.2	16	13.3	0.7
	Cumberland	1,426.9	3	2.7	0.3
	Ocean	541.0	31	43.0	0.3
	Salem	452.4	1	0.5	1.5
Virginia	All	2,684.2	26	21.3	0.4
	Accomack	757.6	–	–	–
	Chesapeake	15.2	–	–	–
	Essex	90.6	1	0.7	0.2
	Fairfax	3.9	–	–	–
	Gloucester	205.9	8	7.7	0.4
	Hampton	53.6	–	–	–
	Isle of Wight	216.5	2	1.4	0.4
	James City	25.8	–	–	–
	King and Queen	70.4	–	–	–

Table 2 continued

State	County	Waterlogged marsh area (ha)	Potential restoration sites	Potential restoration area (ha)	Mean site elevation (m above NAVD 1988)
	King George	19.5	–	–	–
	King William	44.2	–	–	–
	Lancaster	45.7	–	–	–
	Mathews	123.0	6	5.0	0.2
	Middlesex	18.7	–	–	–
	New Kent	168.1	1	0.8	0.2
	Newport News	118.3	–	–	–
	Norfolk	6.3	–	–	–
	Northampton	88.5	4	3.0	0.5
	Northumberland	32.6	1	1.0	0.2
	Poquoson	56.7	–	–	–
	Portsmouth	16.4	–	–	–
	Prince William	6.6	–	–	–
	Richmond	122.9	–	–	–
	Stafford	13.7	1	0.6	0.4
	Suffolk	101.4	2	1.1	0.5
	Surry	10.5	–	–	–
	Virginia Beach	170.7	–	–	–
	Westmoreland	44.2	–	–	–
	Williamsburg	0.7	–	–	–
	York	36.0	–	–	–

six false positive sites, and the remaining two are adjacent to coastal lagoons. The single omission error was likely an artifact of the model's spatial resolution: water had ponded in tire ruts at the site, indicating waterlogging, but covering an area too small to be identified by this analysis. Overall, the model results and validation data had substantial agreement (Cohen's Kappa Statistic = 0.72).

Discussion

Need for restoration

Widespread increase in surface inundation of high marsh throughout the U.S. Mid-Atlantic indicates the damage caused by climate-driven sea level rise, and emphasizes the need for adaptation efforts to restore and protect these habitats in the face of future change. As forecasted elsewhere, marsh migration is projected to more than compensate for the area lost due to sea level rise, but increases in surface water at a number of these sites indicate they are more vulnerable to loss than land cover predictions suggest. The central eastern Chesapeake Bay stands out as particularly threatened, consistent with previous findings that sea level rise has already caused substantial damage to Dorchester County marshes (Kearney et al. 2002), which are also highly vulnerable to future decline (Titus and Richman 2001). Results from this analysis suggest rates of marsh loss may have nearly doubled in Dorchester County: annual marsh conversion to open water averaged 32.7 ha between 1938 and 1989 (Kearney et al. 2002), but increased to 61.2 ha between 1984 and 2015. Increases in marsh loss are consistent with findings that relative sea level rise has been accelerating in the Chesapeake Bay in recent decades (Ezer and Corlett 2012; Sallenger et al. 2012).

Tidal flows are necessary for self-maintenance of marshes, as they establish a fluctuating regime of water, oxygen, and salinity levels that determine plant and animal communities (Silliman et al. 2009). The target sites identified by our model do not represent all cases of interior tidal marsh erosion, but rather a subset of these locations at elevations above the reach of daily tides, where surface inundation would not persist if sites were drained effectively by the tidal creek network. Many such sites are located near the landward boundary of tidal marshes that have recently transitioned from uplands (e.g. Figs 1a–c, 4). Tidal marsh vegetation can establish quickly in upland-marsh transition zones once saltwater has weakened or eliminated terrestrial ground flora, but the establishment of tidal marsh hydrology generally lags this process because the heads of tidal creeks are slow to extend inland in particularly flat terrain, leaving such sites vulnerable to waterlogging.

Similar cases of waterlogging have been documented in coastal marshes with low accretion rates in the Mississippi Delta (Nyman et al. 1993; Day et al. 2011). In these systems, increased flooding stresses marsh vegetation, reducing productivity and sediment capture ability. Plants eventually die as these conditions worsen, further destabilizing the soil and increasing the potential for erosion from storms and tides. The loss of soil and plant biomass eventually leads to elevation collapse, forming basins that are more prone to flooding (Nyman et al. 1993; Kirwan and Guntenspergen 2012). As a result, waterlogging ultimately creates a positive feedback loop by damaging the ability of marshes to keep pace with sea level rise, thereby creating conditions that are more prone to flooding.

Restoration efforts are needed in these cases to break the feedback loop (Day et al. 2011). Waterlogged conditions can be alleviated if the depressed basins they occupy are able to regain their elevation within the marsh platform. Experimental manipulations have shown that artificial ditches can successfully drain ponded areas by increasing sediment delivery and accumulation, successively leading to mudflat formation and plant colonization as surface inundation decreases (Wilson et al. 2014). The actual area of high marsh that could benefit from restoration is significantly greater than the area of surface inundation because waterlogged soil conditions often extend far beyond the boundaries of surface inundation. Surrounding ecosystems, including forested uplands and low marsh, are also likely to benefit from improved drainage that prevents high marsh from eroding to open water, thereby allowing marsh migration to proceed.

Choice of restoration strategy

Today, many marsh restoration efforts are aimed at reversing widespread damage caused by human activities over the past century. On the U.S. Atlantic Coast, over 90% of salt marshes from Virginia to Maine have been impacted by intensive grid ditching in an effort to control mosquitos, a practice that became prevalent in the 1930s (Kennish 2001; Gedan et al. 2009). Ditching has had mixed effects, but generally results in drier conditions, including loss of ponds, changes from herbaceous towards woody or invasive vegetation, and declines in some wildlife species, including semiaquatic invertebrates and waterbirds (Tonjes 2013). Some restoration strategies suggest filling these man-made ditches (e.g. Corman et al. 2012), which in some regions has led to increases in surface water ponding due to reduced drainage (Vincent et al. 2013; Wilson et al. 2014). In contrast, other human impacts like the construction of roads, dikes, and levees have restricted marsh drainage (Kennish 2001; Gedan et al. 2009), and restoration strategies in these locations might emphasize constructing channels to reinstate tidal flows and restore hydrologic function (e.g. Raposa 2008).

Against a backdrop of widespread human modification, effective restoration will depend on an understanding of local ecological conditions and targets. In some settings marsh ponds are an indicator of degradation, while in others they are a characteristic feature of intact systems, providing habitat for diverse wildlife assemblages as they go through dynamic cycles of formation, expansion, tidal connection, and revegetation (Wilson et al. 2014; Mariotti 2016). Evaluating whether increased surface water represents runaway erosion or a recurring landscape feature is a necessary step before selecting and implementing an appropriate response (Smith and Niles 2016). At the target sites identified here, where waterlogging has increased, actions are needed to promote drier conditions. Rather than remove all human influence, here drainage channels can be constructed to prolong marsh persistence and protect against future impacts.

Restoration techniques such as tidal creek extension are a form of climate change adaptation, as they aim to reduce vulnerability to the harmful impacts of climate change (Pachauri and Mayer 2015); in this case, increased flooding from sea-level rise. Adaptation efforts can be classified into three general strategies based on how they manage climate change impacts: (1) resistance (forestalling negative impacts), (2) resilience (promoting recovery after disturbance), and (3) response (facilitating transitions to new conditions) (Millar et al. 2007). Connecting waterlogged marsh to tidal creeks integrates these strategies by (1) alleviating current waterlogging, (2) improving drainage ability in future flooding events, and (3) assisting the effective transition of uplands to hydrologically-functioning tidal marsh. This strategy also aligns with best practices for restoration under climate change, which recommend enabling natural processes with the goal of improving resilience or ecosystem function, rather than attempting to preserve static reference conditions (Harris et al. 2006; Mawdsley et al. 2009; McDonald et al. 2016). By improving drainage ability, this approach will supplement natural processes to the extent they are impaired, and in doing so, repair current degradation and facilitate future transitions under climate-driven sea level rise.

If successful, tidal creek extension projects are anticipated to halt pond expansion, encourage revegetation, and prevent the degradation of surrounding high marsh. Revegetated marsh can become suitable habitat for wildlife species of concern, such as Saltmarsh Sparrow, a songbird that depends on tidal marshes in the U.S. Atlantic throughout its annual cycle, and is at high risk of extinction before the end of the century if current trends continue (Correll et al. 2017). Breeding Saltmarsh Sparrows prefer drier marsh conditions, as flooding is a major cause of nest failure (Bayard and Elphick 2011). Tidal restriction has likely accelerated the decline of this and other specialist bird species by limiting marsh accretion and resilience to sea level rise (Correll et al. 2017). While tidal reconnection could alleviate these pressures by promoting vertical accretion and reducing the duration of flooding, flood frequency may actually increase as the new channel carries incoming tidal flows, potentially putting nests at risk. Monitoring and adaptive management will be necessary to ensure the restoration strategy has its intended effects.

Challenges and limitations

Despite the growing interest in climate adaptation efforts, few adaptation plans are actually implemented because of barriers throughout the process, including leadership to initiate and sustain the process, financial and technical resources to plan and implement a response, and knowledge about the problem and possible solutions (Moser and Ekstrom 2010). Although this analysis provides information to help understand the problem of waterlogging and suggest a restoration response, additional resources will be necessary to successfully implement this solution. These efforts may be more feasible for the majority of sites located on protected lands, especially those managed for wildlife (102 sites, 107 ha), where there is likely to be more interest in restoring damaged habitat and forestalling future loss.

Uncertainties are inherent when planning for the future, and climate adaptation strategies should account for these uncertainties (Hallegatte 2009). Restoration sites identified in this analysis are predicted to remain high marsh through 2050 based on sea level rise and marsh migration projections, but future sea level rise estimates vary by emissions scenario and the anticipated behavior of ice sheets (Nicholls and Cazenave 2010). Under the most extreme scenario, sea level rise could surpass 0.4 m by 2040 (Sweet et al. 2017), shortening the restoration time frame by a decade, but still affording time to slow marsh decline and facilitate migration under sea level rise.

As in any computer model, discrepancies exist between what the model shows and what exists on the ground. While validation data suggest that our spatial model had reasonably high accuracy in identifying potential restoration sites, it was generally better at recognizing waterlogged conditions than evaluating a site's drainage ability. This issue is likely due to both varying exactness of the underlying datasets used in the analysis, as well as challenges in assessing processes versus occurrences from a Geographic Information System. On-the-ground activities should assess the accuracy of local conditions as identified by this analysis and the appropriateness of the restoration strategy proposed here.

Lastly, reinstating tidal flows at the target sites may not always lead to recovery of waterlogged marsh. Irreversible marsh loss can occur where ponds, even once reconnected to tidal creeks, do not have sufficient sediment delivery to increase their relative elevation (Mariotti 2016) or where areas of surface inundation reach a critical size susceptible to wind-induced wave erosion (Schepers et al. 2017). While data limitations prevented us from evaluating these additional site-specific criteria, such conditions have been found in marshes along the Blackwater River in Dorchester County (Schepers et al. 2017), and may also occur at other locations in our study area. In these cases, connection to tidal creeks may even aggravate water-logged conditions through increased tidal flooding and erosion. Tidal creek extension efforts should prioritize sites where vegetation recovery is more likely based on adequate sediment supply, larger tidal range, and smaller pond size (Mariotti 2016), and may need to work in concert with complementary restoration activities, like adding dredged sediment to raise the marsh elevation (Smith and Niles 2016) or protecting adjacent uplands to assist marsh migration (Smith 2013). Given that waterlogging tends to exacerbate erosion and pond growth, early restoration actions will likely improve chances of success.

Conclusion

High marsh in the Mid-Atlantic has already declined under sea level rise, and future loss appears inevitable. Pervasive waterlogging as identified in this analysis reveals the degradation caused by sea level rise, and emphasizes the need for climate adaptation efforts to alleviate past damage and minimize future vulnerability. The results and recommendations presented here provide information to better understand the impacts of sea level rise on Mid-Atlantic marshes and suggest a response, but additional on-the-ground efforts will be necessary to conserve tidal marshes in the face of climate-driven sea level rise. Considering both greater regional rates of relative sea level rise and limited capacity for natural adaptation in the U.S. Mid-Atlantic, the conditions identified here may serve as early warning signs to other regions of the world with low-lying salt marshes that have not yet felt these impacts. Additionally, given the globally or at least nationally available input data, the model developed here could easily be applied to other regions as well. If tidal connection projects can be launched, the high marsh sites identified in this analysis could remain stable through mid-century, continuing to provide substantial economic value to humans and vital habitat to species of conservation concern.

Acknowledgements We thank Andrew LaMotte for providing insight and expertise that improved the study; Man Qi, Matt Kirwan, and an anonymous reviewer for providing comments that improved the manuscript; and Dominic Serino for providing technical assistance. This research was supported by generous grants from the Wildlife Conservation Society Climate Adaptation Fund, the National Fish & Wildlife Foundation's Chesapeake Bay Stewardship Fund, and the France-Merrick Foundation.

Author contributions All authors contributed to the study conception and design, data collection, and analysis. The first draft of the manuscript was written by LT and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding Major funding for this research includes generous grants from the Wildlife Conservation Society (WCS) Climate Adaptation Fund, the National Fish & Wildlife Foundation's Chesapeake Bay Stewardship Fund, and the France–Merrick Foundation. Support to establish the WCS Climate Adaptation Fund was provided by a grant from the Doris Duke Charitable Foundation (DDCF). This material is based on work supported by the U.S. Environmental Protection Agency and the Chesapeake Bay Program's Innovative Nutrient and Sediment Reduction grants program, which support efforts within the Chesapeake Bay watershed to accelerate nutrient and sediment reductions with innovative, sustainable, and cost-effective approaches. Other grants were provided by the Bancroft Foundation, CSX, and Chesapeake Audubon Society.

Data availability The datasets analyzed in the current study are publicly available from the following sources: Global Surface Water Dataset, https://global-surface-water.appspot.com/download, NOAA Marsh Migration projections, https://coast.noaa.gov/, USFWS National Wetlands Inventory, https://www.fws.gov/wetlands/data/Data-Download.html, USGS Area- and depth- weighted SSURGO variables, https://water.usgs.gov/GIS/metadata/usgswrd/XML/ds866_ssurgo_variables.xml#stdorder, USGS National Hydrography Dataset, https://catalog.data.gov/dataset/usgs-national-hydrography-dataset-nhd-downloadable-data-collection-national-geospatial-data-as

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Adam P (2002) Saltmarshes in a time of change. Environ Conserv 29:39–61

Bayard TS, Elphick CS (2011) Planning for sea-level rise: quantifying patterns of saltmarsh sparrow (Ammodramus Caudacutus) nest flooding under current sea-level conditions. Auk 128:393–403

Blum L, Christian RR, Brinson MM (2002) Salt marsh transgression and tidal creek development: the role of ecological processes. AGU Spring Meeting Abstracts 21:OS21A-05.

Brinson MM, Christian RR, Blum LK (1995) Multiple states in the sea-level induced transition from terrestrial forest to estuary. Estuaries 18:648–659

Church JA, White NJ (2006) A 20th century acceleration in global sea-level rise. Geophys Res Lett 33:L01602

Corman SS, Roman CT, King JW, Appleby PG (2012) Salt marsh mosquito-control ditches: sedimentation, landscape change, and restoration implications. J Coast Res 28:874–880

Correll MD, Wiest WA, Hodgman TP, Shriver WG, Elphick CS, McGill BJ, O'Brien KM, Olsen BJ (2017) Predictors of specialist avifaunal decline in coastal marshes. Conserv Biol 31:172–182

Cowardin LM, Carter V, Golet FC, LaRoe ET et al (1979) Classification of wetlands and deepwater habitats of the United States. Fish and Wildlife Service, US Department of the Interior Washington

Crosby SC, Sax DF, Palmer ME, Booth HS, Deegan LA, Bertness MD, Leslie HM (2016) Salt marsh persistence is threatened by predicted sea-level rise. Estuar Coast Shelf Sci 181:93–99

Day JW, Kemp GP, Reed DJ, Cahoon DR, Boumans RM, Suhayda JM, Gambrell R (2011) Vegetation death and rapid loss of surface elevation in two contrasting Mississippi delta salt marshes: The role of sedimentation, autocompaction and sea-level rise. Ecol Eng 37:229–240

Edmonds G (2011) GIS methodology for the sea level vulnerable wetland areas project. Technical documentation, Maryland Department of Natural Resources, Towson

Erwin RM, Sanders GM, Prosser DJ, Cahoon DR (2006) High tides and rising seas: potential effects on estuarine waterbirds. Stud Avian Biol 32:214

Ezer T, Corlett WB (2012) Is sea level rise accelerating in the Chesapeake Bay? A demonstration of a novel new approach for analyzing sea level data. Geophys Res Lett 39:L1960

Gedan KB, Silliman BR, Bertness MD (2009) Centuries of human-driven change in salt marsh ecosystems. Ann Rev Marine Sci 1:117–141

Giuliani S, Bellucci LG (2019) Salt marshes: their role in our society and threats posed to their existence. In: Sheppard C (ed) World seas: an environmental evaluation, 2nd edn. Academic Press, Cambridge, pp 79–101

Glick P, Clough J, Nunley B (2008) Sea-level rise and coastal habitats in the Chesapeake Bay region: technical report. National Wildlife Federatio

Google (2019) Google Maps. https://www.google.com/maps/. Accessed 30 Jan 2019.

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. Glob Environ Change 19:240–247

Harris JA, Hobbs RJ, Higgs E, Aronson J (2006) Ecological restoration and global climate change. Restor Ecol 14:170–176

Kearney MS, Rogers AS, Townshend JR, Rizzo E, Stutzer D, Stevenson JC, Sundborg K (2002) Landsat imagery shows decline of coastal marshes in Chesapeake and Delaware Bays. Eos Trans Am Geophys Union 83:173–178

Kennish MJ (2001) Coastal salt marsh systems in the U.S.: a review of anthropogenic impacts. J Coastal Res 17:731–748

Kirwan ML, Guntenspergen GR (2012) Feedbacks between inundation, root production, and shoot growth in a rapidly submerging brackish marsh. J Ecol 100:764–770

Kirwan ML, Megonigal JP (2013) Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504:53

Kirwan ML, Gedan KB (2019) Sea-level driven land conversion and the formation of ghost forests. Nat Clim Change 9:450–457

Kirwan ML, Temmerman S, Skeehan EE, Guntenspergen GR, Fagherazzi S (2016a) Overestimation of marsh vulnerability to sea level rise. Nat Clim Change 6:253–260

Kirwan ML, Walters DC, Reay WG, Carr JA (2016b) Sea level driven marsh expansion in a coupled model of marsh erosion and migration. Geophys Res Lett 43:4366–4373

Lerner JA, Curson DR, Whitbeck MW, Meyers EJ (2013) Saving the tidal marshes of blackwater national wildlife refuge: final report on assessing sea level rise impact and recommending comprehensive strategies for marsh management and migration in southern Dorchester County, Maryland. The Conservation Fund, Arlington, VA and Audubon Maryland-DC, Baltimore

Marcy D, Brooks W, Draganov K, Hadley B, Haynes C, Herold N, McCombs J, Pendleton M, Ryan S, Schmid K et al. (2011) New mapping tool and techniques for visualizing sea level rise and coastal flooding impacts. pp 474–490 in. Solutions to Coastal Disasters 2011

Mariotti G (2016) Revisiting salt marsh resilience to sea level rise: are ponds responsible for permanent land loss? J Geophys Res 121:1391–1407

Mawdsley JR, O'Malley R, Ojima DS (2009) A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. Conserv Biol 23:1080–1089

McDonald T, Gann G, Jonson J, Dixon K (2016) International standards for the practice of ecological restoration—including principles and key concepts. Society for Ecological Restoration, Washington

Millar CI, Stephenson NL, Stephens SL (2007) Climate change and forests of the future: managing in the face of uncertainty. Ecol Appl 17:2145–2151

Moser SC, Ekstrom JA (2010) A framework to diagnose barriers to climate change adaptation. Proc Natl Acad Sci 107:22026–22031

Nicholls RJ, Cazenave A (2010) Sea-Level Rise and Its Impact on Coastal Zones. Science 328:1517–1520

Nyman JA, DeLaune RD, Roberts HH, Patrick WH Jr (1993) Relationship between vegetation and soil formation in a rapidly submerging coastal marsh. Marine Ecol Progress Ser 96:269–279

Pachauri RK, Mayer L (eds) (2015) Climate change 2014: synthesis report. Intergovernmental Panel on Climate Change, Geneva

Pekel J-F, Cottam A, Gorelick N, Belward AS (2016) High-resolution mapping of global surface water and its long-term changes. Nature 540:418–422
Raposa KB (2008) Early ecological responses to hydrologic restoration of a tidal pond and salt marsh complex in Narragansett Bay, Rhode Island. J Coast Res 55:180–192
Rizzetto F, Tosi L (2011) Aptitude of modern salt marshes to counteract relative sea-level rise, Venice Lagoon (Italy). Geology 39:755–758
Sallenger AH, Doran KS, Howd PA (2012) Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nat Clim Change 2:884–888
Schepers L, Kirwan M, Guntenspergen G, Temmerman S (2017) Spatio-temporal development of vegetation die-off in a submerging coastal marsh. Limnol Oceanogr 62:137–150
Schieder NW, Walters DC, Kirwan ML (2018) Massive upland to wetland conversion compensated for historical marsh loss in Chesapeake Bay, USA. Estuar Coasts 41:940–951
Silliman BR, Grosholz ED, Bertness MD (2009) Human impacts on salt marshes: a global perspective. University of California Press, California
Simas T, Nunes JP, Ferreira JG (2001) Effects of global climate change on coastal salt marshes. Ecol Model 139:1–15
Smith JAM (2013) The role of Phragmites australis in mediating inland salt marsh migration in a mid-atlantic estuary. PLoS ONE 8:e65091
Smith J, Niles L (2016) Are salt marsh pools suitable sites for restoration? Wetl Sci Pract 33:101–109
Sweet WV, Kopp RE, Weaver CP, Obeysekera J, Horton RM, Thieler ER, Zervas C (2017) Global and regional sea level rise scenarios for the United States.
Titus JG, Richman C (2001) Maps of lands vulnerable to sea level rise: modeled elevations along the US Atlantic and Gulf coasts. Clim Res 18:205–228
Tonjes DJ (2013) Impacts from ditching salt marshes in the mid-Atlantic and northeastern United States. Environ Rev 21:116–126
US Fish and Wildlife Service (2013) National Wetlands Inventory. Version 2. US Department of the Interior, Fish and Wildlife Service, Washington, DC. https://www.fws.gov/wetlands/.
US Geological Survey (2017). National Hydrography Dataset. US Department of the Interior, Geological Survey, Washington, DC. https://nhd.usgs.gov/.
USDA Farm Service Agency (2017) National agriculture imagery program. US Department of Agriculture, Farm Service Agency, Washington, DC. https://gis.apfo.usda.gov/arcgis/rest/services/NAIP.
Vincent RE, Burdick DM, Dionne M (2013) Ditching and ditch-plugging in New England salt marshes: effects on hydrology, elevation, and soil characteristics. Estuar Coasts 36:610–625
Wieczorek M (2014) Area- and depth- weighted averages of selected SSURGO variables for the conterminous United States and District of Columbia. Data Series, USGS Numbered Series, U.S. Geological Survey, Reston, VA. https://pubs.er.usgs.gov/publication/ds866. Accessed 17 Jan 2019
Wilen, B. O., and M. K. Bates. 1995. The US fish and wildlife service's national wetlands inventory project. In: Classification and inventory of the world's wetlands. Springer, pp. 153–169.
Wilson CA, Hughes ZJ, FitzGerald DM, Hopkinson CS, Valentine V, Kolker AS (2014) Saltmarsh pool and tidal creek morphodynamics: dynamic equilibrium of northern latitude saltmarshes? Geomorphology 213:99–115