Hidden levees: Small-scale flood defense on rural coasts

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Climate change, land subsidence, and coastal population growth are leading to increasing coastal flood risks and land use changes. Large-scale levee systems protect many urban areas from flooding, but much less is known about how rural coasts will respond to sea level rise and increasing flood risks. Here, we map and describe previously unreported, small-scale earthen levees that have been constructed for centuries by individual landowners in rural, low-lying portions of the Chesapeake Bay region. Levees are constructed from inorganic silt loam sediment consistent with adjacent terrestrial soils, extend above Highest Astronomical Tide, and are today surrounded by either marsh or low-lying terrestrial vegetation. Although preliminary measurements did not reveal consistent effects of levees on soil salinity or soil organic content, the landward side of levees are generally lower in elevation than the seaward side, and characterized by less flood tolerant vegetation and shallower organic-rich soils. These results suggest that small-scale levees may have historically impeded wetland development, though their effects today are ambiguous. This work highlights a historical approach to rural flood defense and suggests that, in some cases, the impact of small levees can be observed long after coastal retreat and levee abandonment.

Introduction

Climate change is altering the mosaic of global land cover and land use. In coastal regions, sea level rise (SLR) is the primary driver of land conversion whereby progressive tidal flooding leads to salinization of soils and salt-tolerant vegetation encroachment into freshwater ecosystems (Schieder & Kirwan, 2019; White et al., 2021). In natural systems, "ghost forests" consisting of dead trees surrounded by marsh, stand as a stark illustration of the rapid inundation of coastal forests and expansion of marshes landward (Kirwan & Gedan, 2019). Developed land uses more subtly reflect the impacts of salinization as residential lawns convert from terrestrial to marsh vegetation (Anisfeld et al., 2017) and agricultural fields produce reduced crop yields (Guimond & Michael, 2021; Tully et al., 2019). Economic losses from coastal flooding due to SLR could cost over 4% of the global economy each year by 2100 (Schinko et al., 2020). While many major urban centers which exist at or below high tide levels have undertaken measures to prevent widespread inundation (Oppenheimer et al., 2019), it remains uncertain how more rural coastal communities will respond to sea level rise.

Flood defenses along heavily developed, often urban coastlines are extensive. The “Great Sea Wall” of China extends for over 60% of the country’s 18,000 km^2 coastline (Ma et al., 2014), while 60% of the Netherlands exists below sea level, through a nationalized system of dikes and storm surge barriers (Kabat et al., 2005). Almost $15 billion in federal aid was allocated to Louisiana, USA after Hurricane Katrina in part to strengthen the 214-kilometers of levees, flood gates, and pump stations surrounding New Orleans (Gotham & Faust, 2020). An estimated 50% of global wetland loss is partially attributed to extensive diking and infilling that accompanies hard infrastructure projects for flood protection (Gedan et al., 2009; Ma et al., 2014; McLeod et al., 2011). In spite of this, global coastal wetlands are estimated to provide $447 billion a year in storm protection services (Costanza et al., 2021). Practices have shifted towards restoring or creating new wetlands to work in tandem with hard structures for more effective flood defenses (Arkema et al., 2013; Narayan et al., 2016). However, debate on how long into the future hard protection or coastal ecosystems can withstand increasing rates of SLR has also prompted discussions of systematic, managed retreat from the coast (Haasnoot et al., 2021; Oppenheimer et al., 2019).

Much less is known about how rural communities without extensive flood defense systems will respond to sea level rise. Without government funding, people in these communities are left to defend their own property (Van Dolah et al., 2020). In the Chesapeake Bay region, small-scale flood defenses built around individual properties have existed in the region for centuries, yet little is known about their effectiveness in preventing inundation. Marsh survival in the face of sea level rise and declining sediment availability depends in large part on the ability of marshes to migrate landward (Kirwan et al., 2016; Schuerch et al., 2018). Given coastal squeeze along already hardened coastlines in urban areas (Borchert et al., 2018; Kirwan and Megonigal, 2013; Torio & Chmura, 2013), the response of rural communities to SLR will play a disproportionate role in the fate of marshes globally.

Methods

Background

In this study, we map and describe the impact of small, private levee systems in the Chesapeake Bay region of the United States (Figure 1). The mid-Atlantic region experiences rates of relative sea-level rise 2 to 3 times the global average due to rapid land subsidence (Engelhart et al. 2009). The gently sloping coastal plain topography and high rates of relative sea-level rise have led to the rapid transition of forests and agricultural fields into marsh. Since the late 19th century, more than 400 km^2 of Chesapeake Bay uplands have been replaced by marshes (Schieder et al. 2018), and rates of land conversion are accelerating (Schieder and Kirwan, 2019).

Small rural levees are found in varying conditions around the Chesapeake Bay, ranging from well-maintained along functional farms, to significantly degraded and overgrown with shrubs and trees (USACE, 2017). As described in the Results, individual earthen levees are generally between 100-200m in length and 0.5-1.0m in height (Figure 2). Although their history is poorly described, anecdotal accounts date their origin in some cases to prior to the Civil War, where their purpose was either to reclaim wetlands, or to protect low lying but arable land from flooding. Our observations of largely inorganic soils in sediment cores from the levees and the landward sides of levees (i.e. no peat at depth; see Results) favor the interpretation that levees were built to protect low lying terrestrial land, although the levees themselves are composed of more silt and less sand than soils of adjacent uplands (USDA Service Center Agencies, 2019). Many levees were constructed in a "ditch-bank" fashion, in which a ditch was dug by hand and the spoil was deposited immediately next to the ditch, resulting in a raised, high elevation bank around the perimeter and/or the seaward edge of a property. Although these small levees are inconsistently mapped across the Chesapeake Bay, some levees appear to be identified in late-19th century coastal T-sheets, and in U.S. Geological Survey (USGS) topographic maps throughout the mid-20th century (Figure 3). Today, levees occur around farmland and residences, as well as in the middle of marshes as a historical relict of farmland that has since converted to marsh.

Levee Mapping

Levee locations in the Chesapeake Bay were identified using a combination of aerial imagery and digital elevation models (DEMs) (Figure 1). In addition to coarse mapping across the entire Bay, we focused on small levees in the southeastern portion of Gloucester County, Virginia, a rural county at the mouth of the York River, a tributary of the Chesapeake Bay (Figure 1, Figure 4). This region was chosen for more detailed study (Figure 4) due to its long history of human land-use and sea-level driven land conversion (Scheider et al, 2019). Potential levees were first identified using aerial photographs in Google Earth as linear features near water bodies with strong visible color and vegetation differences. Features from Google Earth were then delineated by hand in ArcPro and verified with elevation, slope, and curvature observations derived from the USGS topobathymetric Coastal National Elevation Database (CoNED) dataset (Danielson & Tyler, 2016) (Figure 5). This topographic data was also used to find levees that had been missed when identifying possible features from aerial imagery. We excluded features that were non-linear and that were not higher than the surrounding area. This approach is conservative, as we likely excluded some extremely degraded historically levees, and missed others entirely.

Biophysical Characteristics

We measured a variety of biophysical characteristics of levees and surrounding marsh and uplands in the Gloucester County, VA study area (Figure 4). A total of five levees were selected at four distinct sites, including two levees at the Captain Sinclair site, and individual levees at the Kings Creek, Eagle Point, and Belvin Farm sites (Figure 4b-e). At each site, we established 4 replicate transects spanning the seaward and landward side of each levee.

Vegetation type and the elevation of the soil surface were measured every 5m along each transect, with higher frequency measurements across areas of rapid elevation change (i.e. the levees and ditches). Elevation was measured with a real time kinematic global positioning system (RTK GPS) and included a minimum of 30m of measurements on either side of the levee. The dominant vegetation type was recorded as the species with >50% relative cover and classified according to flood tolerance. Dominant vegetation was used to assign a flood tolerance score from 0 to 3: 0 consisted of mainly upland grasses; 1 represented succulents with low flood tolerance such as *Salicornia virginica*; 2 represented high marsh species with moderate flood tolerance such as *Distichlis spicata*, *Spartina patens*, and *Juncus roemerianus*; and 3 represented low marsh species with high flood tolerance such as *Spartina alterniflora* (Bertness and Pennings, 2000).

Sediment cores and surficial soils were collected every 10m along each transect using a 5cm diameter Russian peat corer. At each core location, we measured the depth to parent material as the depth corresponding to a contact between organic rich, loosely compacted sediment representing a wetland environment and the more inorganic, compacted parent material below. The thickness of organic rich soils acted as a proxy for marsh age, as recently converted uplands have thinner organic soils relative to older, more established marshes. Surface samples (~5cm thick) were analyzed for salinity by drying and re-saturating subsamples with deionized water, filtering the slurry, and measuring the salinity of the filtered water with a salinity probe (Hardie & Doyle 2012). Four seaward and four landward cores were collected along transects at each site, located approximately 10m and 30m in each direction away from the levee, and an additional core was taken at the high point of the levee on each transect. Seaward and landward cores were analyzed for dry bulk density and organic content, and levee cores were additionally sampled for grain size using a Beckman Coulter LS 13 320 Laser Diffraction Particle Size Analyzer. We report sediment characteristics averaged over the upper 10 cm (i.e. 0-10cm) to reflect largely modern soil conditions for the seaward and landward cores. For the levee cores, we aimed to measure the composition of the material used to build the levee itself, so report average sediment characteristics from depths of 10-20 cm, to minimize the effects of modern overprinting from tidal deposition and vegetation growth.

Results

Coarse mapping around the Chesapeake Bay indicates that small-scale levees are prevalent throughout the Chesapeake Bay and its tributaries, especially in gently-sloping, low elevation regions (Figure 1). Within the focused study area of Gloucester County, 40 km of levees were mapped (Figure 4). Levees were concentrated along tidal creeks and from analysis of historical T-Sheets, appear to be concentrated in areas that converted from agricultural land into marsh within the last 100 years. From modern aerial imagery, levees appear to have little to no active maintenance, often accompanying unoccupied land parcels with shrub and tree growth atop the levees. Few were identified in dense residential areas.

The five studied levees ranged in elevation from 0.67 to 0.97m (NAVD88) (Figure 6a), which exceeds the Highest Astronomical Tide (HAT) datum of 0.605m as recorded at the nearest tide gauge (Yorktown USCG Training Center, VA [8637689]) (https://tidesandcurrents.noaa.gov/). Levees were composed of silt loam soils (average silt content ranged 53-67%, sand 10-26%, clay 11-25%). These soils were mostly dominated by inorganic sediment (4.5-10.3% organic matter), except for the lowest elevation levee (14.2% organic matter), which was colonized by marsh vegetation.

On the seaward side of each levee, the elevation of the soil surface increased, vegetation types became more flood intolerant, and the depth of organic rich soils decreased as distance from open water increased (Figure 6). Once a transect crossed a levee to the landward side, the elevation tended to decrease. Despite lower elevations on the landward side, vegetation flood tolerance and organic rich soil depth continued to decrease with distance from open water (Figure 6).

Elevations measured on the landward sides of levees were lower at three of the five sites with the exception of Belvin Farm and Eagle Point, both of which increased by approximately 0.2m across the levee. The Kings Creek levee had the largest decrease in elevation across the levee , from 0.70 m on the seaward side to 0.58 m on the landward side (Figure 6b). Low elevations adjacent to open water (i.e. low marsh) were dominated by flood tolerant *Spartina alterniflora*, and high elevations (i.e. high marsh) were dominated by flood intolerant *Spartina patens* and *Distichlis spicata* on the seaward side of the levee. Low elevations on the landward side of the levee were dominated by flood intolerant succulent species *Salicornia virginica,* rather than *Spartina alterniflora.* High elevations, including the levees themselves, were dominated by the least flood tolerant vegetation and contained upland grasses, shrubs, and trees, including *Iva frutescens* and *Juniperus virginiana.*

Although statistical significance varied among sites, the flood tolerance of vegetation tended to be lower on the landward side of levees than seaward side of levees (Figure 7a). Average soil salinity values ranged from 1.11-10.38ppt, and differences in soil salinity between seaward and landward sides of the levees were variable (Figure 7b). The depth to parent material ranged from 0.05-0.50 m, and the average depth on the landward sides of levees was consistently less than the depth on seaward sides of levees (Figure 7c). For example, average depth to parent material seaward of the Kings Creek levee was 5.1cm, but decreased to 2.3cm landward of the levee (Figure 6b). Organic content ranged from 6-61%. Levee effects on organic matter content were insignificant except at the seaward levee of Captain Sinclair and Eagle Point, where landward cores had significantly higher organic matter content (Figure 7d).

Discussion

Levees responsible for the protection of large populations and essential infrastructure are well mapped and highly studied. In Europe, Asia, and North America, the implementation and consequences, both intended and unintended, of extensive networks of dikes are under continuous scrutiny (Blum & Roberts, 2009; Doody, 2013; Enwright et al., 2016; Ma et al., 2014). In contrast, private levee systems are widespread throughout the Chesapeake Bay, the largest estuary in the United States, but are inconsistently mapped and largely unstudied. Despite the age and uncertain history of maintenance, these relic features have at least subtle impacts on the natural and developed land uses within the region.

In natural coastal marshes, a variety of biophysical characteristics tend to follow predictable gradients associated with elevation, flooding frequency, and salinity. In rapidly transgressing systems, the dominance of flood-tolerant vegetation, the mineral content of soils, and the depth to parent material all decrease with increasing distance from open water (i.e. towards migrating uplands), reflecting higher elevation marshes of progressively younger age (Brinson et al., 1995; Hussein, 2009; Langston et al., 2021; Schieder et al., 2018). Observations of decreasing flood tolerant vegetation and depth to parent material with distance inland are consistent with naturally transgressive ecosystems at all five of our study sites (Figure 7a,c). However, elevation, organic content, and salinity trends were inconsistent between sites, and each site had at least one biophysical characteristic which deviated from expected trends. For example, we measured elevations that decreased with distance inland on the landward side of three levees (Kings Creek and both Captain Sinclair levees) (Figures 6). Expected increases in organic content with distance inland (i.e. on the landward side of levees) were only observed for two levees (Eagle

Point, seaward Captain Sinclair), and differences in salinity were insignificant at all sites (Figure 7b,d).

Some of the deviations between natural gradients and those observed at our sites may be explained by anthropogenic levees that disrupt the natural flow of water and sediment that drive gradients in vegetation type, salinity, and organic matter accumulation. For example, the decrease in elevation landward of levees at three sites suggests that levees are, in some cases, accelerating land subsidence or inhibiting sediment deposition and organic matter accumulation. Impounded marshes in other regions are well known to accrete more slowly than natural marshes because they are disconnected from natural sediment sources, and because stagnant water limits vegetation productivity (e.g. Kennish, 2001). Despite their age and lack of maintenance, all five levees in our study are currently higher than HAT (Figure 6a), indicating that they reduce sediment deposition during at least regular tidal flooding events. Hydrological disconnectivity is also consistent with the observation of more flood-intolerant vegetation landward of the levees, despite their lower elevation than marsh seaward of levees at three sites (i.e. Kings Creek, both Captain Sinclair levees) (Figure 6b,c). Finally, the decrease in depth to parent material with distance inland, even when accompanied by lower elevations, suggests that levees historically prevented marsh migration, and that young marshes and organic rich soils developed only after levees were breached and/or abandoned.

However, observations at several levee sites do not fit neatly with the interpretation that levees have historically been, or continue to be, effective at reducing inundation. High marsh vegetation and ponding were observed landward of the levees at multiple sites (Figure 6b,c). Moreover, soil salinity was not significantly different landward and seaward of the levee at any site, indicating that saline water regularly breaches the levees today (Figure 7b). Interestingly, these observations suggest a counterintuitive hypothesis that historical levees may have in some cases accelerated marsh migration by enhancing subsidence, restricting sediment deposition, and by trapping saline water that is only flushed during extreme high tides.

Nevertheless, the role of levees in either impeding or accelerating marsh migration is difficult to assess, and likely tied to individual site history and levee maintenance. Overall, the observed levees were not actively maintained, and their condition was poor. Marsh vegetation and shrubs were growing on all levees. The two sites with continuous occupation by landowners (Belvin Farm and Eagle Point) appear to differ from sites that were abandoned decades ago. Belvin Farm and Eagle Point were the only two sites with elevations that were higher landward of the levee than seaward of the levee, and to have significant reductions in organic matter content landward of the levee. Finally, Belvin Farm was the only site with terrestrial vegetation growing on the landward side (Figure 7). Thus, these levees may have been maintained for a longer duration of time, and been more effective at impeding marsh migration.

The pair of parallel levees at the Captain Sinclair site also points to an interesting history of levee maintenance and ultimate abandonment. The seaward levee (CS_s) is lower in elevation and completely colonized by low marsh vegetation, whereas a second levee (CS_l), approximately 50m inland, is higher in elevation and vegetated with high marsh vegetation, trees, and shrubs (Figure 2; Figure 4b). The significant reduction in depth to parent material between the two levees, and on the landward side of the landward levee, suggests that the marsh landward of CS_l is younger than that between the levees (Figure 7c), and that the landward levee, CS_l, may have been constructed after CS_s. Examples of parallel sets of abandoned levees are common throughout the region. If our interpretation that they represent levees of different age is correct, then parallel levees suggest landowner retreat from the coast has occurred gradually rather than abruptly, and that eventual abandonment of farmland was punctuated by periods of renewed flood defense.

Large levee systems on developed coasts are well known to disrupt natural ecosystem processes and inhibit marsh migration (Enwright et al., 2016), but this study suggests a more ambiguous role of small privately-owned levees on rural coasts. Indeed, our results leave room for multiple interpretations of the effectiveness of the levees historically and today. However, the mere presence of these features throughout the Chesapeake Bay coastal plain is a clear indication that sea level rise has been driving land use and land cover change in the region for centuries, and has forced rural landowners to develop local adaptation strategies that include both flood defense and inland retreat. Our observations uniquely indicate that relic flood defense structures left behind after coastal retreat persist in the landscape for centuries. More work is needed to better characterize the extent and impact of these structures. However, our preliminary investigation highlights a historical approach to rural flood defense, and suggests, at least in some cases, that their imprint on ecosystem processes can be observed long after their abandonment.

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Data Availability

Elevation, vegetation, and sediment data are archived and freely accessible through the Environmental Data Initiative. Dataset reference: Messerschmidt, T.C. and M.L. Kirwan. 2021. Levee Soil Characteristics of Gloucester County, VA ver 2. Environmental Data Initiative. https://doi.org/10.6073/pasta/d8db4839f95e518ace2cfe7b97ce8949.

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Figures

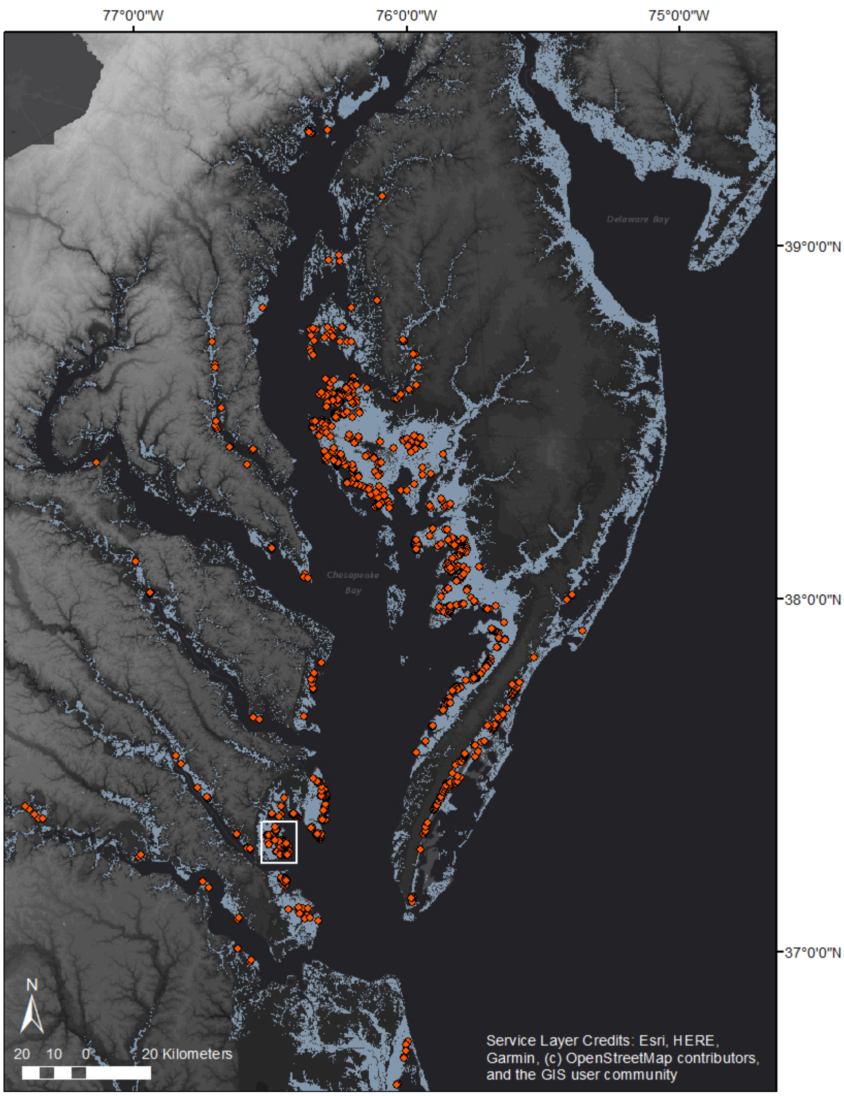

Figure 1. Levee locations across the Chesapeake Bay region. Levee locations are shown with orange points and were identified from aerial imagery and CoNED data (Danielson & Tyler, 2016). Light blue shading indicates elevations <3 m NAVD88, where NAVD88 approximates mean sea level in the region. The white box outlines the study focus area near the mouth of the York River.

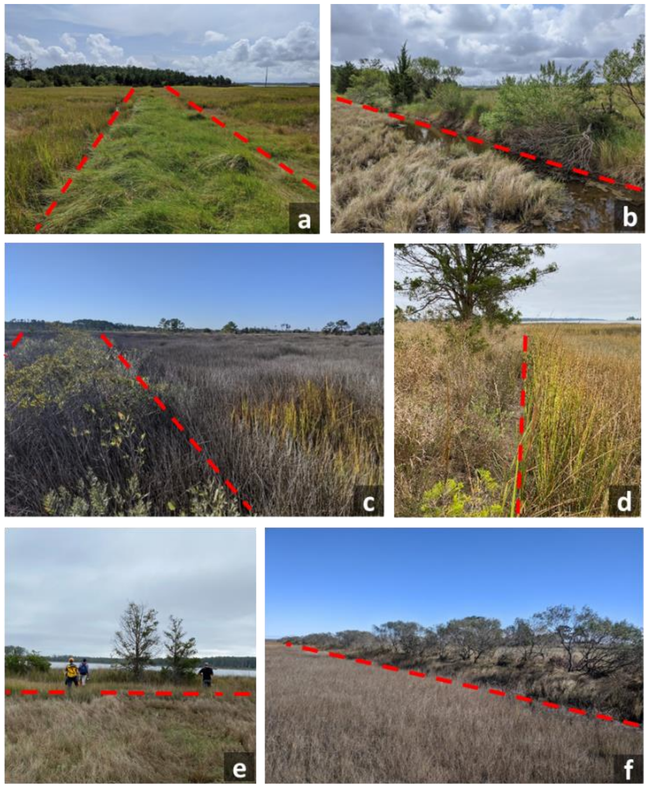

Figure 2. Examples of small-scale rural levee systems. Dashed red lines denote levee edges. Photographs were taken in 2020 from levee sites in the focus study area. Site locations are identified in Figure 4. **a**. Photograph from the top of the oldest, most seaward levee at the Captain Sinclair site (CS_s). Photograph shows that marsh vegetation is growing on top of the entire length of the levee. **b**. Oblique view across the younger, more landward Captain Sinclair levee (CS_l) from the landward side, showing shrub and trees growing on top of the levee. **c**. Longitudinal view from the top of the Kings Creek levee (KC). Marsh vegetation visible on the seaward (right) side of photo. **d**. Longitudinal view from the top of the Eagle Point levee (EP), with terrestrial vegetation growing on top of the levee (left side) and marsh vegetation on the seaward side (right). **e**. Photograph from the landward side of the EP, looking seaward, with people for scale. **f**. Oblique view of the Belvin Farm levee (BF) from the seaward side looking across the marsh (foreground) and levee to the landward side (background).

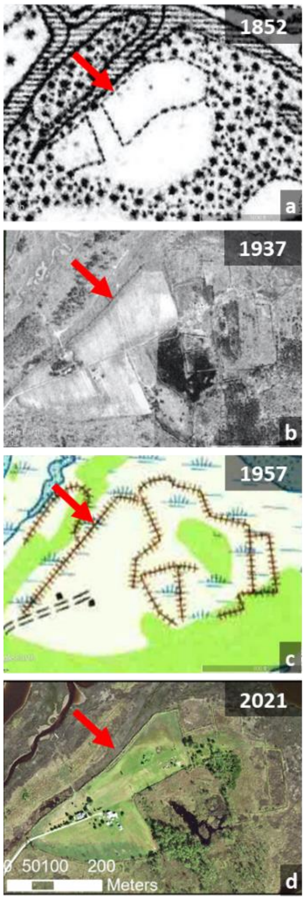

Figure 3: Historical maps and aerial photographs of the Belvin Farm levee. **a**. 1852 NOAA T-sheet**. b**. 1937 aerial imagery. **c**. 1957 USGS topographic map. **d**. 2019 aerial NAIP imagery. The red arrow marks the same point on the levee in each image.

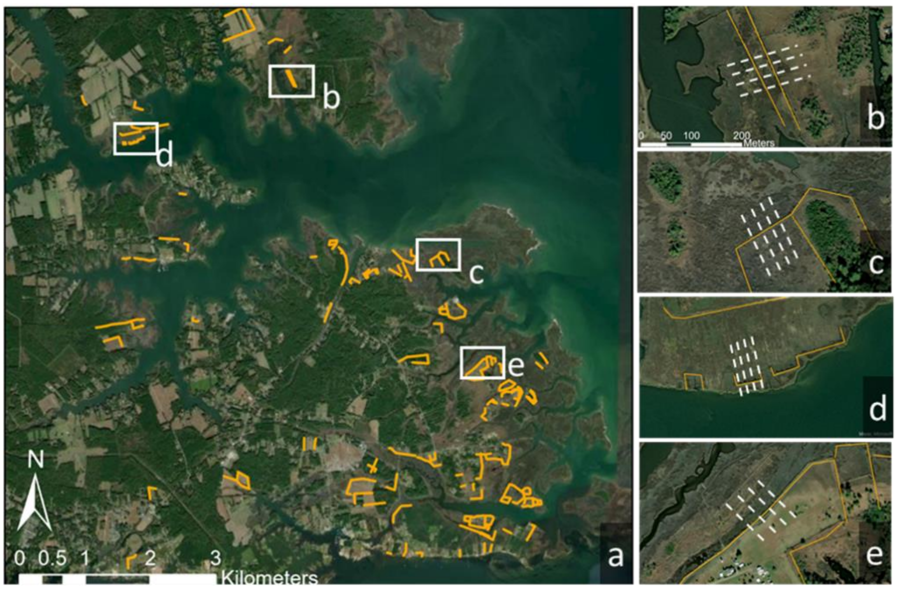

Figure 4: Study area and sampling approach. a. Aerial photograph showing the focus study area near the mouth of the York River, with an extent defined in Figure 1. Mapped levees are indicated with orange lines, and each field site is indicated with a white box. **b-e**. Insets showing each field site, with 4 transects (dashed white lines) oriented perpendicular to levees (orange lines). From top to bottom: **(b)** Captain Sinclair site, with a seaward (CS_s) and landward (CS_l) levee, **(c)** Kings Creek (KC) , **(d)** Eagle Point (EP), and **(e)** Belvin Farm (BF).

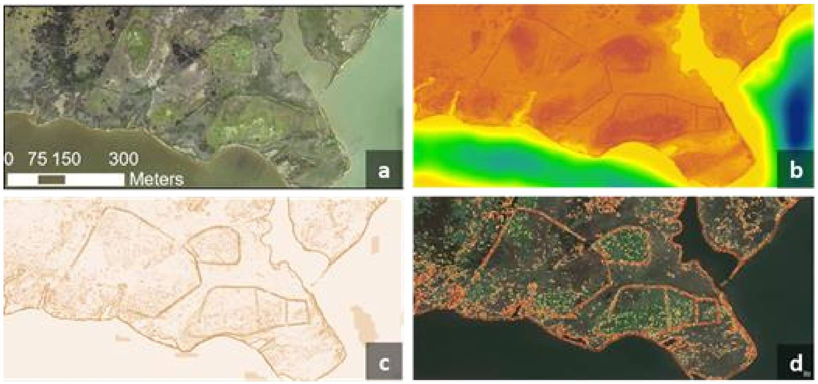

Figure 5: Geospatial indicators of levee extent. a. Aerial image of the southeastern portion of the focus study area. Levees are visible as linear features that separate brown marsh vegetation from green upland vegetation, including on the levees themselves (NAIP, 2019). **b**. CoNED Digital Elevation Model (DEM), in which levees are visible as local topographic highs**. c.** Topographic slope calculated from the CoNED DEM, where levees are visible as dark colors that correspond to slopes of about 20 degrees. **d**. Maximum curvature calculated from the CoNED DEM, where levees are visible as local curvature highs that correspond to 60-80 degrees and include more degraded levees that are difficult to observe with other methods.

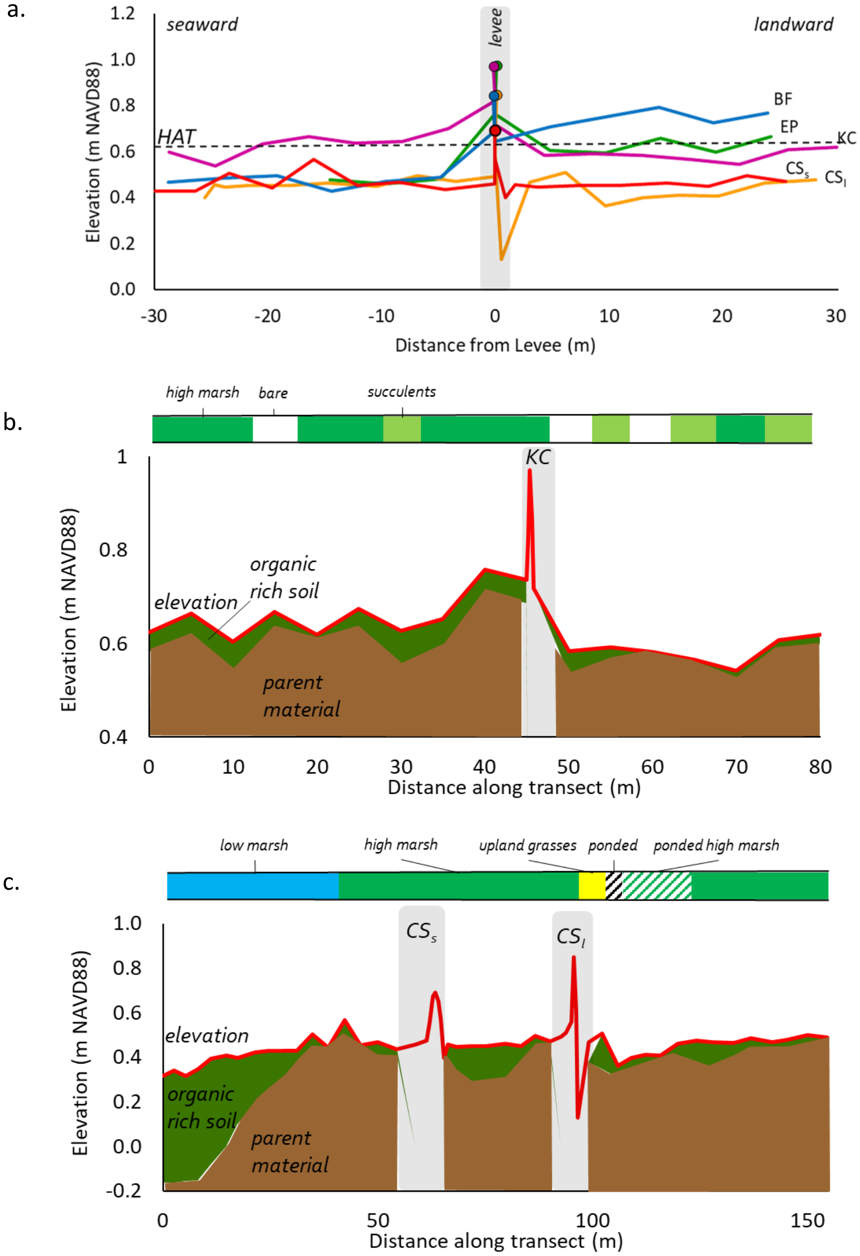

Figure 6: Elevation profiles and generalized cross sections for representative levee sites. **a.** One elevation profile from a representative transect at each levee site. Distance from levee is negative in the seaward direction, and positive in the landward direction. Elevation is relative to NAVD88, which approximates MSL in the study region. The dashed black line denotes the local Highest Astronomical Tide (HAT) datum. **b-c**. Generalized cross-sections of the Kings Creek (KC) (**b**) and Captain Sinclair (CS) levees (**c**). Green coloring represents loosely compacted, organic rich sediment associated with marshes, while the brown coloring represents mineral rich, more highly compacted sediment associated with a historical, terrestrial environment. In panel ***c***, the cross section includes both a seaward (Cs_s) and landward (Cs_l) levee, which we interpret to be older and younger, respectively.

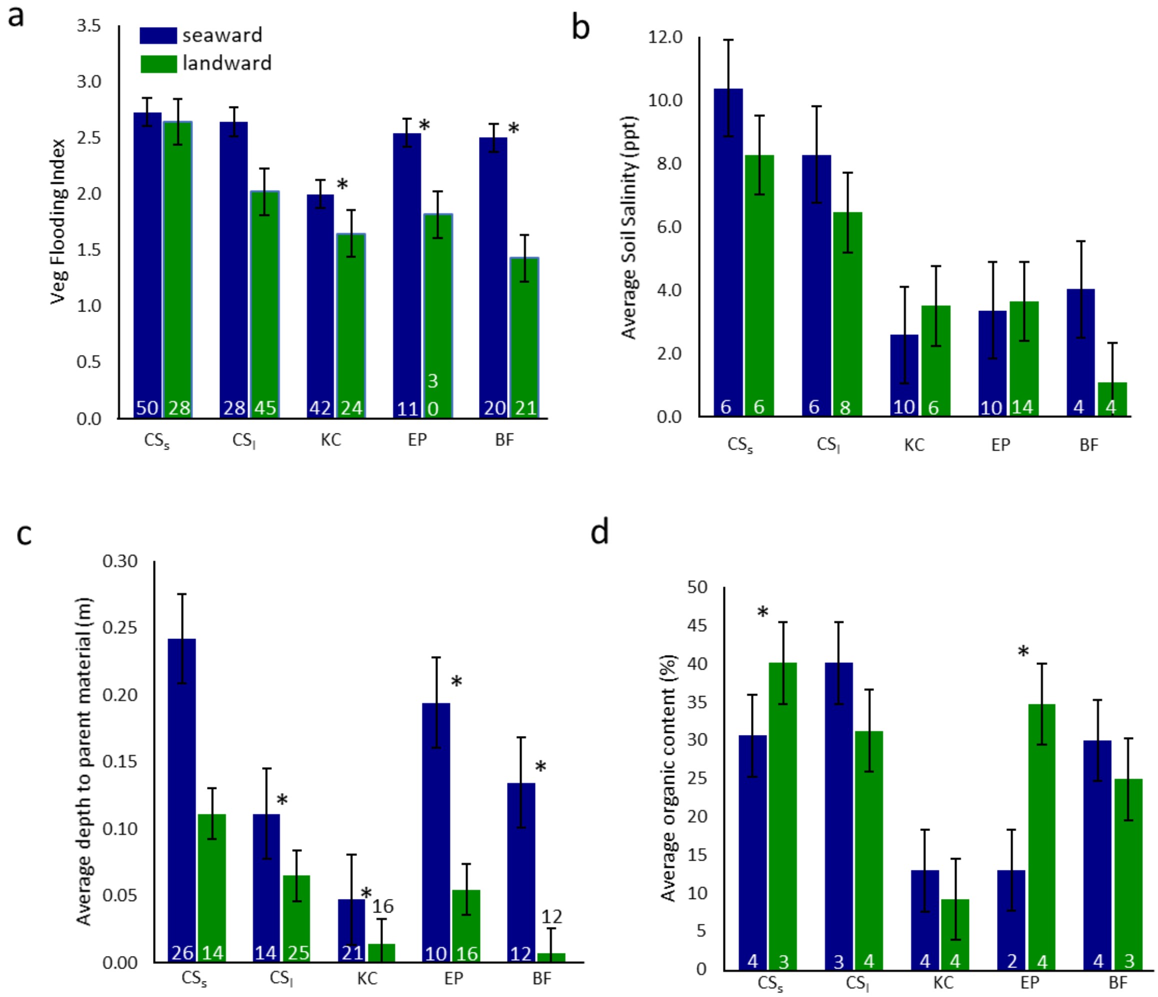

Figure 7: Effects of levees on vegetation type and soil characteristics. Blue bars represent the mean of all measurements on the seaward side of each levee, and green bars represent the mean of all measurements on the landward side of each levee. Standard error for each mean is shown with error bars, and sample sizes are shown at the bottom of each bar. Asterisks denote significant differences between seaward and landward sides of a levee, as calculated by a T-test assuming equal variance, using $p<0.05$ as a significance threshold. **a.** Average Vegetation Flood Tolerance Index inferred from dominant plant species, where a score of 0 indicates flood intolerant upland vegetation and a score of 3 indicates flood tolerant, low-marsh vegetation. **b.** Average soil salinity of surficial sediment (i.e. 0-5 cm). **c.** Average depth to parent material **d**. Average organic content of the upper 10 cm (i.e. 0-10 cm) of collected sediment cores.