***Harnessing sea level rise to create marshes: A literature review defining potential metrics and ideal landscape characteristics for healthy marsh migration***

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Sea level rise threatens the persistence of coastal wetlands and the ecosystem services they provide. However, sea-level driven marsh migration into adjacent uplands may help offset losses, particularly in rural, gently sloping regions of the Chesapeake Bay. The two biggest challenges to the long-term success of marsh migration are poor drainage, which leads to reduced ecosystem function and increased marsh vulnerability, and the expansion of the invasive species, *Phragmites australis*, which is undesirable for targeted bird species. Landscape characteristics (tidal range, salinity, upland slope, and channel network extent) that enable hydrological connectivity with marine environments may favor the development of native marsh vegetation, while enhancing the flow of water and sediment that is essential for long-term survival in the face of sea-level rise. Remote sensing analyses were used to quantify aboveground biomass trends in retreating coastal forests from 1984-2020, and to find examples of healthy marsh migration from the Maryland portion of the Chesapeake Bay. These examples illustrate a variety of outcomes, where unhealthy migration consists of forest mortality accompanied by degrading or unvegetated marshes (e.g. Beachground Swamp; Blackwater National Wildlife Refuge), and healthy migration consists of forest mortality accompanied by marshes that increase in aboveground vegetation through time (e.g. Eastern Neck National Wildlife Refuge; Monie Bay region). *Phragmites* was the dominant plant species in all areas of forest loss, although the literature review indicates it has a positive effect on many metrics of marsh health. Gradients in successful marsh migration generally followed the landscape characteristics identified in the literature review, where healthy marsh was more commonly associated with moderate upland slopes, larger tidal ranges, and proximity to tidal channels and embayments.

## *Introduction*

Sea level threatens the size and function of a variety of coastal ecosystems, and in particular the marshes and coastal forests of the mid-Atlantic coast (He and Silliman, 2019; Kirwan and Gedan, 2019). Marsh vulnerability is fundamentally tied to sediment supply and tidal range, with the most extensive marsh loss occurring in regions of the world with low sediment inputs and tidal ranges (Kirwan and Megonigal, 2013). Chesapeake Bay wetlands are uniquely threatened because they are microtidal, sediment deficient, and located in a hotspot of accelerated sea level rise (Stevenson et al., 1986; Ganju et al., 2017; Sallenger et al., 2012). Approximately 100,000 acres of wetlands have been lost to erosion since the 1850's across the Chesapeake Bay region (Schieder et al., 2018), and the region surrounding the Blackwater National Wildlife Refuge is an especially well-known location for marsh loss (Stevenson et al., 1986; Kearney et al., 2002; Schepers et al., 2017).

Conventional wetland restoration is largely focused on preserving existing wetlands, often in the context of altering physical processes that improve marsh resilience or ecological function. For example, common restoration strategies include the placement of dredged sediment directly on the marsh to increase its elevation relative to sea level and the construction of artificial or living shorelines to dissipate wave energy and prevent marsh erosion (Roman, 2017). Global meta-analysis suggests that the main determinant of restoration success is mineral sediment supply (Liu et al., 2021). Indeed, sediment placement and shoreline stabilization projects that do not consider sediment budgets have been criticized as short-term solutions that will require repeated effort to avoid inevitable marsh loss (Ganju, 2019). However, the marshes most vulnerable to sea level rise and other climate impacts are located in sediment limited systems (Kirwan et al., 2010). Thus, conventional restoration strategies have important limitations, especially in the Chesapeake Bay region.

Although sea level rise is a threat to existing marshes, sea level rise also presents an opportunity to create new marshes farther inland. Indeed, marsh migration into retreating coastal forests and agricultural fields has been extensive historically and predicted to accelerate with future sea level rise (Enwright et al. 2016; Schieder et al. 2018; Gedan et al., 2020; Ury et al., 2021) **(Figures 1-2)**. Marsh migration is most extensive in the mid-Atlantic and Chesapeake Bay regions of the United States, where rapid sea-level rise is inundating large portions of gently sloping, relatively undeveloped coasts (Kirwan and Gedan, 2019). In the Chesapeake Bay region, marsh migration has historically compensated for erosion (Schieder et al., 2018), is accelerating with the rate of sea level rise (Schieder and Kirwan, 2019), and is predicted to create new marshes that are larger than those observed today (Molino et al., in review). Even in the Blackwater region, marsh migration has compensated for about 60% of total losses (Scott et al., 2009). Thus, marsh migration can potentially be used to create marshes in places where the physical environment is otherwise unfavorable to marsh sustainability.

Nevertheless, questions remain about the viability of inland marsh migration. Concerns are typically related to anthropogenic barriers and landowner resistance to marsh migration (Enwright et al., 2016; Field et al., 2017), ecological integrity of the newly formed marshes (Smith et al., 2013), and the sustainability of those marshes in the face of ongoing and accelerating rates of sea level rise (Tornqvist et al., 2021). Land management could play a role in overcoming each of these primary challenges, and ensuring that marsh migration occurs in a socially and ecologically desirable way. However, as discussed below, conventional metrics of marsh health are mostly based on the premise that marshes must survive in-place, rather than by migrating inland. Thus, new metrics are needed to define healthy marsh migration and to evaluate landscape characteristics and management actions that lead to successful migration.

Here, we review the relevant scientific literature to address the following questions:

- What does a healthy mosaic of connected coastal habitat look like in terms of vegetation types and hydrology?
- What biophysical processes help promote these ideal conditions, particularly in regards to long-term persistence of healthy marshes in the face of continued sea level rise?
- At the site-scale, what are the ideal upland conditions for promoting marsh migration?
- Does a healthy mosaic of coastal habitat exist in Maryland today that can serve as an example?

### ***Marsh migration in the context of connected coastal ecosystems***

Tidal marshes are well recognized for contributing a variety of ecosystem services, including storm protection, habitat provision, erosion control, carbon and nutrient cycling, and forming the base of estuarine and marine food webs (Barbier et al., 2011). Though there are no standard metrics of marsh health, measures of success in wetland creation and restoration projects may serve as a guide for defining successful, “healthy” marsh migration. Goals of conventional projects typically center around restoring the ecological function of degraded marshes to that of natural or pristine reference marshes (Craft et al., 1999). Likewise, healthy marsh migration may be defined by metrics of ecological function in comparison to older reference marshes (Langston et al., 2021) **(Table 1)**. While metrics borrowed from the marsh creation and restoration literature focus on current health, successful marsh migration should also consider resilience, so that long-term ecosystem function is maintained even in the face of continued, accelerating sea level rise.

A healthy mosaic of connected coastal habitat consists of open water, marshes, and uplands that are highly productive, biodiverse, and poised for long-term survival in the face of sea level rise and disturbance events (Ford et al., 2016; Kirwan et al., 2016; Wang et al., 2021). Connectivity is achieved primarily through tidal channels, which transport water, salt, sediment, and nutrients throughout the coastal system (Friedrichs and Perry, 2001). The recognition of estuaries as hot-spots for primary productivity was originally explained as the result of pulses of energy from tides, storms, and river floods that act as subsidies for primary productivity and the ecosystem services that follow (Odum et al., 1979; Odum et al., 1995). However, where anthropogenic or natural processes limit the free-flow of water, stagnant water leads to oxygen depletion, the accumulation of salts and toxins such as hydrogen sulfide, and reduced ecosystem function. Collectively known as the “stress-subsidy gradient” (Odum et al., 1979), these observations are consistent with observations today that ecosystem function is maximized for intermediate flooding durations that favor productivity (Morris et al., 2002), soil accretion (Kirwan and Megonigal, 2013), and nutrient cycling (Knights et al., 2020). Marshes disconnected from tides due to their natural position on the landscape (i.e. the interior of large marshes, far from tidal channels) or anthropogenic factors (levees, impoundments, dams) tend to suffer from waterlogged soils, low rates of carbon and nutrient sequestration, and degradation in the form of ponding and eventual marsh loss (Redfield, 1972; Drexler et al., 2013; Knights et al., 2020).

The concept of connected ecosystems is particularly important in the context of marsh migration. Both natural (e.g. steep topography) and anthropogenic (e.g. levees, impervious surfaces) barriers to marsh migration reduce connectivity of the landscape, such that sea level rise may lead to coastal squeeze and reductions in marsh area and ecosystem function (Torio and Chmura, 2013; Enwrigh et al., 2016, Mitchell et al., 2020) **(Figure 3)**. On the other hand, sea-level rise may lead to marsh expansion where connected ecosystems are free to transgress inland, resulting in larger marshes and enhanced rates of soil carbon accumulation (Kirwan et al. 2016; Valentine et al., in review) **(Figure 4)**. The limits of marsh size and ecosystem function also depend on more subtle indicators of connectivity. For example, rapidly migrating marshes tend to form in portions of the landscape far from tidal channels, so that the resulting marsh is largely disconnected from marine sources of water, sediment, and nutrients that would otherwise aid marsh development. Without an established channel network, water logged soils inhibit marsh development, leading to plant mortality and the formation of ponds (Taylor et al., 2020) (**Figure 5**).

Poor drainage is likely the biggest challenge to the ecological function and long-term maintenance of marshes forming near the upland edge (Taylor et al., 2020). Newly developing marshes in all six of my lab group’s Chesapeake Bay study sites suffer from poor drainage (Goodwin Island, Gloucester marshes, Phillips Creek in Virginia; Monie Bay and Moneystump Swamp in Maryland) **(Figure 1, Figure 6)**. Characteristics of poor drainage include waterlogged soils, elevated hydrogen sulfide concentrations, reduced soil shear strength, and in some cases hypersaline soils (Reed and Cahoon, 1992). At the landscape scale, poor drainage is indicated by the presence of standing water long after tidal or meteorological events, extensive ponding, and reduced plant biomass. Although the ecological implications of poor drainage have not yet been studied in the context of marsh migration, observations of poor ecosystem function in impounded wetlands elsewhere (Brockmeyer et al., 1996; Drexler et al., 2013) suggest that poor drainage will limit the function of rapidly migrating marshes as well. Moreover, expansion of interior ponds is a primary driver of marsh loss in most microtidal estuaries (Kearney and Turner 2016; Mariotti, 2016; Wang et al., 2021b), including the Chesapeake Bay (Stevenson et al., 1985; Schepers et al., 2017), suggesting that the formation of ponds in migrating marshes likely threatens their long-term survival in the face of sea level rise.

The landscape characteristics and biophysical processes leading to poor drainage of migrating marshes is also poorly studied. Poor drainage is likely inevitable given the location of upland-marsh far from established channel networks. Indeed, ponding in other marsh types is most extensive in the interior of marshes, far from channels (Redfield, 1972; Schepers et al., 2017) (**Figure 7**). Ponding is thought to lead to biogeochemical degradation of organic matter and eventual erosion that tends to lead to runaway loss of marshes (Himmelstein et al., 2021; Duran Vinent, 2021). At the marsh-forest boundary, poor drainage may also be enhanced by loss of soil elevation associated with the mortality of trees and roots zone collapse (Miller et al., 2020; Carr et al., 2020; Walters et al., 2021). In addition to limiting their long-term survival, poorly drained marshes are considered especially poor habitat for target bird species (Taylor et al., 2020). Therefore, management efforts to improve marsh migration include constructing ditches to extend natural tidal channels towards the marsh-upland boundary to restore hydrologic connectivity (Taylor et al., 2020) **(Figure 5)**. Ditching marshes to improve drainage was a common practice in the early 20$^{th}$ century (Bromberg Gedan et al., 2009). However, ditching is widely out of favor today, and in some places, environmental restoration efforts include plugging historical ditches (Vincent et al., 2013).

### *Metrics of successful, "healthy" marsh migration*

Though many metrics of traditional wetland restoration success have been proposed (see Zhao et al., 2016 for a comprehensive list), most focus on the structure and function of soils, biota, and hydrology. In a 25-year comparison of created marshes and natural marshes, Craft et al. (1999) quantified plant biomass, the abundance and accumulation rate of soil organic carbon, nitrogen, and phosphorous, and benthic infauna density and species richness **(Table 1)**. Two studies of ecosystem function in migrating marshes suggest these same metrics of restoration success (i.e. plant biomass and soil characteristics) could also be applicable to defining healthy marsh migration. Like Craft et al. (1999), Anisfeld et al. (2017) observed that in marshes migrating into suburban lawns, vegetation metrics responded more quickly than soil-based metrics. Langston et al. (2021) observed that plant biomass, soil accretion rates, and the abundance and accumulation rates of soil organic carbon, nitrogen, and phosphorous depended more on marsh elevation than its age, where young marshes resembled old marshes after controlling for the effects of elevation. Interestingly, invasive *Phragmites australis* marshes near the marsh-upland boundary (regardless of age) tended to have maximum rates of biomass and soil accretion rates (Langston et al., 2021). Together, these results suggest that marsh migration may indeed be useful in preserving ecosystem function, and that even non-native marsh migration can maximize the value of some ecosystem services.

These metrics, however, do not include evaluation of habitat quality. *Phragmites australis* is an invasive species that is the most common plant migrating into retreating coastal forests in the mid-Atlantic (Smith et al., 2013) (**Figure 1, Figure 8**). Its abundance correlates with shoreline development and the removal of woody vegetation adjacent to marshes (Silliman and Bertness, 2004). Marshes dominated by *P. australis* typically have very high rates of primary productivity, soil elevation change, and carbon and nutrient accumulation (Windham and Lathrop, 1999; Rooth and Cornwell, 2013; Langston et al., 2021). Therefore, conventional soil and plant-based metrics of marsh health would favor *P. australis* marshes. However, *P. australis* is considered undesirable as habitat for targeted bird species, such as the saltmarsh sparrow (Benoit and Askins, 1999; Chambers et al., 1999). Thus, soil and plant-based metrics of marsh health should be supplemented with those that include habitat quality for targeted species (e.g. species richness, diversity, or simply presence/absence of *P. australis*).

Finally, metrics of marsh health as defined by hydrology are also needed. Conventional wetland restoration metrics focus on the morphology of channel networks, which facilitate the exchange of water, nutrients, and sediment throughout the system (Williams et al., 2002). As discussed in the previous section, migrating marshes are typically far from tidal channels, and therefore prone to waterlogged soils and the development of ponds (Talyor et al., 2020) **(Figure 1, Figure 5**). Waterlogged soils and ponding may also be indicative of altered hydrology associated with the construction of small levees by landowners seeking to prevent the flooding of agricultural fields and residences. The influence of these levees on marsh migration is inconclusive, but they almost certainly negatively influence the function and resilience of marshes (Hall et al., in review). Useful metrics of water logged soils and/or ponding include: hydrogen sulfide concentration, soil redox potential, the UVVR ratio (see *Metrics of marsh resilience*), and remote sensing products that calculate the prevalence and frequency of standing water.

***Metrics of marsh resilience to sea level rise***

The sustainability of marshes in the face of sea level rise has traditionally been viewed under the premise that marshes must build soil faster than rates of sea level rise to survive in place (Reed et al., 1995). The most common approach for assessing the vertical resilience of a marsh at a given location is to measure the soil vertical accretion rate (i.e. through sediment core dating, or repeated measurements of sediment elevation tables known as “SETs”) and directly compare it to the local rate of relative sea level rise (Webb et al., 2013; Holmquist et al., 2021). This technique quantifies whether marshes have historically accreted in pace with sea level rise. However, inundation often enhances plant productivity and sediment deposition so that marsh accretion rates tend to accelerate with sea level rise (Morris et al., 2002; Kirwan et al. ,2010), and historically based measurements will tend to overestimate marsh vulnerability in the future (Kirwan et al., 2016b).

The National Estuarine Research Reserve System (NERRS) developed a more extensive list of metrics designed to assess marsh stability across all NERRS sites (Raposa et al., 2016) **(Table 1)**. These metrics include direct measurements of soil accretion rates and the factors that influence them (turbidity, tidal range), but also metrics related to marsh elevation distributions (e.g. the percent of marsh located below Mean High Water), and the inter-annual variability in water level. Other metrics include numerical model output, historical wetland loss rates, elevation capital (the elevation of a marsh above the lowest elevation that vegetation can survive), and vegetation characteristics such as the number of abundant plant species (Cole Ekberg et al., 2016; Schepers et al., 2020). Together, these metrics all tend to highlight the fact that marshes around the Blackwater National Wildlife Refuge are among the world's most vulnerable to sea level rise, as evidenced by accretion deficits (Stevenson et al., 1985), rapid historical marsh loss (Schepers et al., 2017), small tidal ranges (Ganju et al. 2013), and extremely low marsh elevations relative to limits of vegetation growth (Schepers et al., 2020).

Nevertheless, these metrics are squarely centered around the health and survival of existing marsh rather than the inland migration of marshes (Kirwan et al., 2016b), and there are reasons to suspect that they will have limited capacity in the context of marsh migration. For example, marshes that form in newly inundated terrestrial ecosystems will almost always have elevation distributions that exceed Mean High Water, be located far from tidal sediment sources, and therefore exhibit accretion deficits. Conventional plant-centric metrics (biomass, height, species-richness) are usually based on native marsh species (e.g. *Spartina alterniflora*) (Cole Ekberg et al., 2022), whereas invasive *Phragmites australis* is the dominant plant species in locations with rapid marsh migration (Smith, 2013).

New research indicates that lateral processes are also critical to the fate of marshes, such that marsh size is fundamentally determined by the competition between erosion and migration (Kirwan et al., 2016b; Schuerch et al., 2018; Fitzgerald and Hughes, 2019). This emerging realization suggests that *spatially integrated* metrics of marsh resilience are needed (Schepers et al., 2020; Ganju et al., 2017). Indeed, in the region of the Blackwater National Wildlife Refuge with the most extensive marsh loss (i.e. Lake Blackwater), the conventional metrics discussed above tend to underestimate marsh vulnerability because they do not account for lateral erosion (Ganju et al., 2017; Schepers et al., 2020). At the same time, those conventional metrics may overestimate marsh vulnerability because they do not account for inland marsh migration, and the potential to offset losses due to erosion and vertical drowning (Kirwan et al., 2016b).

Two spatially integrated metrics of marsh resilience have recently been proposed that are potentially relevant to marsh migration. First, Ganju et al. (2017) proposed the Unvegetated to Vegetated Marsh Ratio (UVVR), which calculates the portion of a given marsh that is occupied by vegetation versus open water. Highly ponded or channelized marshes have high UVVR ratios and are considered vulnerable. The metric correlates with volumetric sediment fluxes, accounts for both vertical accretion and lateral erosion processes, and can be used to predict the lifespan of existing marshes (**Figure 9**). UVVR has been used across the continental U.S. (including Blackwater) and demonstrates that marshes are far more vulnerable than conventional metrics would indicate (Ganju et al., 2017). Second, Holmquist et al. (2021) propose a vertical resilience index and a lateral resilience index (**Figure 10**). The vertical resilience index calculates the threshold rate of sea level rise beyond which marshes will accrete more slowly than the rate of sea level rise, as a function of tidal range. Interestingly, this equation does not depend on sediment supply, so could be useful to predicting potential vertical accretion of migrating marshes where sediment supply data does not exist. Holmquist et al.'s (2021) lateral resilience index calculates the vulnerability of marshes as the ratio between the current area of wetlands and the area of land suitable for wetland migration for a given amount of sea level rise. The index assumes that developed and cultivated land is not available for marsh migration, and highlights that large marshes with small migration areas would be most vulnerable.

Both spatially integrated metrics seem to be relevant to understanding marsh vulnerability in the context of inland migration. The Holmquist et al. (2021) metrics could be used to identify where marshes are most vulnerable (i.e. low tide range environments with large marshes and limited migration space) and therefore where management intervention should be prioritized. UVVR, in turn, is sensitive to ponding, which we argue above is the key metric of current marsh health. Because UVVR scales with volumetric sediment fluxes, it can also be used to calculate the lifespan of existing marshes (Ganju et al., 2017), offering an absolute rather than relative predictive indicator of vulnerability. However, neither metric explicitly addresses ecological function, or the prevalence of invasive species.

***Landscape characteristics associated with healthy marsh migration***

Marsh migration research has thus far focused on understanding the processes that influence the rate and extent of marsh migration, rather than their ecological implications (Kirwan and Gedan, 2019; Fagherazzi et al., 2019). Landscape characteristics, such as topographic slope, anthropogenic land use, and exposure to storm events, are viewed in the context of quantifying rates of coastal transgression and/or maximizing potential marsh area (Holmquist et al., 2010; Kirwan et al., 2016; Schurech et al., 2018; Enwright et al., 2016; Mitchell et al., 2020). However, our review suggests that the ecological function and long-term sustainability of migrating marshes are also important metrics of success, and that poor drainage and invasive species are among the key threats to healthy marsh migration.

Although a thorough analysis of the landscape characteristics that allow for healthy marsh migration has not been conducted, several common landscape characteristics are emerging as potential facilitators of successful marsh migration. First, larger tidal ranges are generally associated with faster sediment deposition rates, more resilient marshes in the vertical dimension, and more extensive channel networks (Friedrichs and Perry, 2001; Kirwan et al., 2010; Kearney and Turner, 2016). Second, high soil salinities limit the growth of *P. australis* (Hellings and Gallagher et al., 1992; Chambers et al., 2008), such that the proportion of native marsh increases with decreasing distance from the mouth of an estuary (Smith, 2013). Finally, the role of upland land use and topographic slope are less clear. Agricultural and residential uplands may facilitate native marsh species relative to invasive *P. australis* due to more abundant light conditions (Gedan et al., 2019; Shaw et al., 2021). However, wetland migration is viewed negatively by landowners (Field et al., 2017; Van Dolah et al., 2020), and more valuable land uses may be more likely to have anthropogenic barriers that prevent marsh migration at all (**Figure 6**) (Enwright et al., 2016; Hall et al., in review). Gentle slopes lead to more rapid migration and larger marsh extents (Schieder et al., 2018; Flester and Blum, 2020). However, larger marshes require a greater volume of sediment to survive sea level rise (Tornqvist et al., 2020), which can only be accommodated by more extensive tidal channels. Rapid marsh migration outpaces the elongation of channel networks, so that the largest marshes are likely the most disconnected from tides, and therefore the most vulnerable to ponding and sea level rise.

The next iteration of this project will focus on identifying a current example of a healthy mosaic of coastal habitat, as defined by ecological function and sustainability in the face of sea level rise. However, the current literature review points to hydrological connectivity as the key landscape characteristic governing successful marsh migration. As discussed above, tidal range and proximity to tidal channels and marine environments are key characteristics determining hydrological connectivity. Locations with larger tidal ranges and connections to marine environments (e.g. seaside of the Maryland eastern shore) may have better drainage, more productive vegetation, and salinities that limit *P. australis* growth. At the same time, more regular tides and connectivity to marine sediment sources tend to increase sediment deposition rates, organic matter accretion, and marsh resilience. Other landscape characteristics may include exposure to storms and particular land uses, although these have not yet been evaluated. Finally, gently sloping uplands almost certainly facilitate the most rapid migration and the largest marshes. However, those same conditions likely lead to marshes that are disconnected from the marine environment, are heavily ponded, and dominated by invasive *P. australis*. Therefore, there are likely tradeoffs between landscape characteristics that promote large marshes, and those that promote healthy marshes.

**Figure 1.** Drone photographs of marsh migration around the Chesapeake Bay. In each case, the marsh shown formed from sea-level driven migration into retreating uplands, and is likely less than 100 years old. Clockwise from top left: Moneystump Swamp (MD), Monie Bay (MD), Phillips Creek (VA), and Goodwin Island (VA). Note that the marshes near the forested uplands are ponded, and in most cases dominated by Phragmites australis. Photo sources: Tyler Messerschmidt, VIMS.

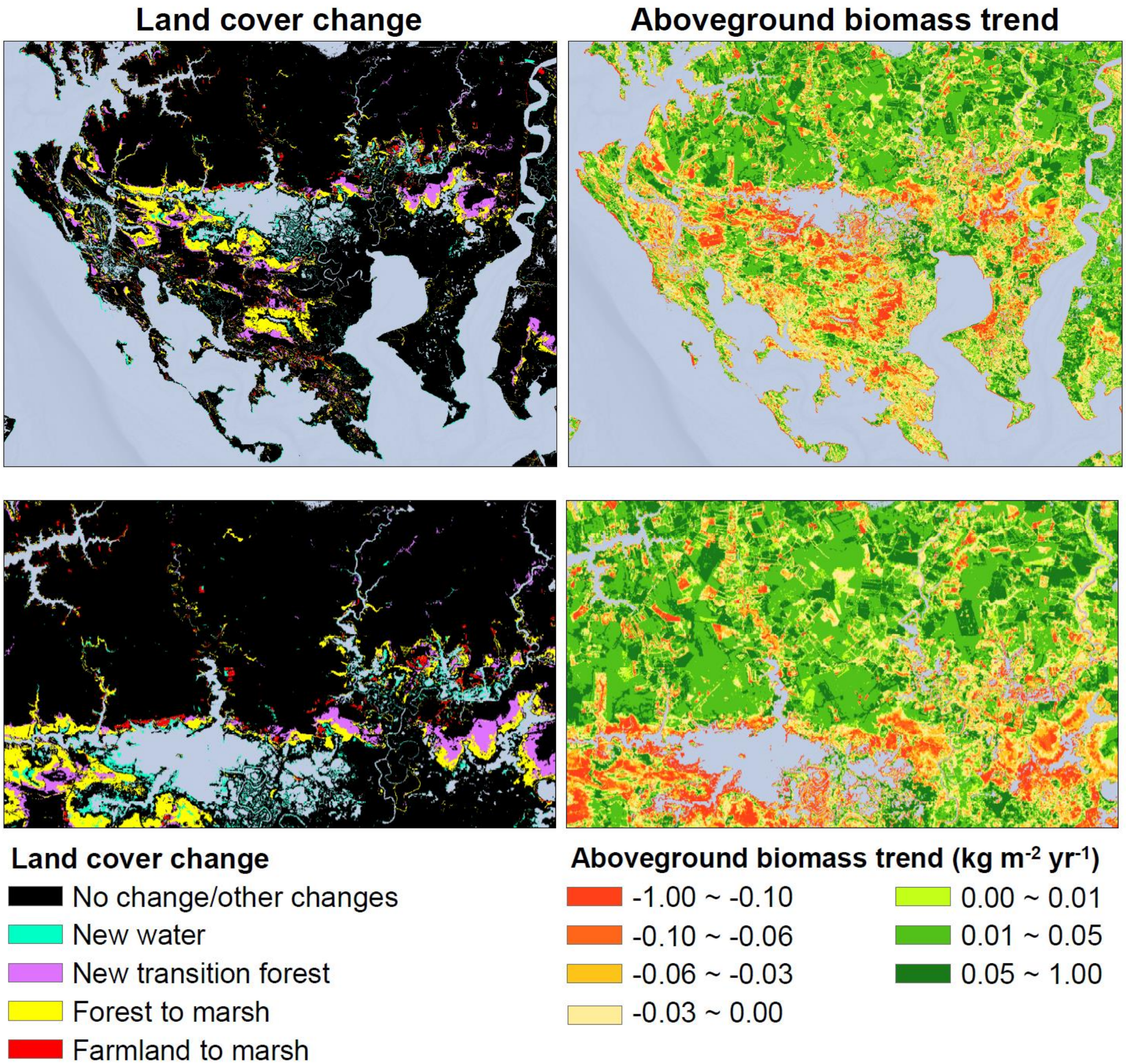



**Figure 2.** Changes in landcover and aboveground biomass surrounding the Blackwater National Wildlife Refuge (MD). Bottom panels are zoomed in on the priority area North of the refuge, and show significant conversion of farmland to marsh. Land cover classifications and above ground biomass trends calculated from Landsat imagery classification and NDVI change between 1984 and 2020.

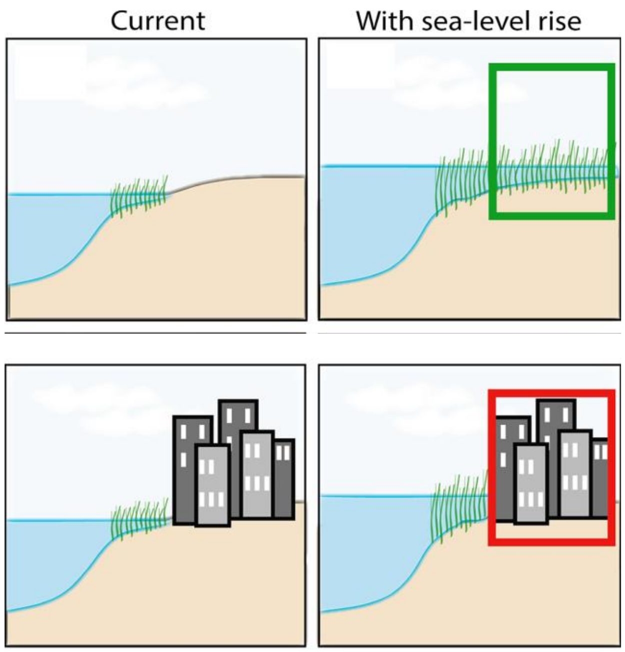



**Figure 3**. Schematic showing the effects of “coastal squeeze” on marsh response to sea level rise (Enwright et al., 2016). In the top panels, marshes expand with sea level rise by migrating inland. In the bottom panels, marshes are vulnerable to erosion because they are inhibited from migrating inland by coastal development that is frequently accompanied by flood control structures.

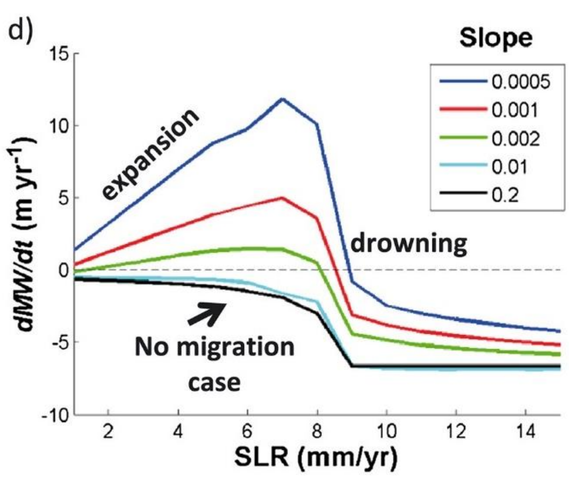



**Figure 4.** Modeled change in marsh width (dMW/dt) as a function of sea level rise (SLR) for marshes adjacent to uplands of various slopes (Kirwan et al., 2016). For gently sloping uplands, marshes initially expand in response to faster sea level rise rates, and rates of expansion increase with decreasing upland slope. However, sea level rise leads to inevitable marsh contraction for marshes bounded by steeply sloping uplands or anthropogenic barriers (i.e. “no migration case”).

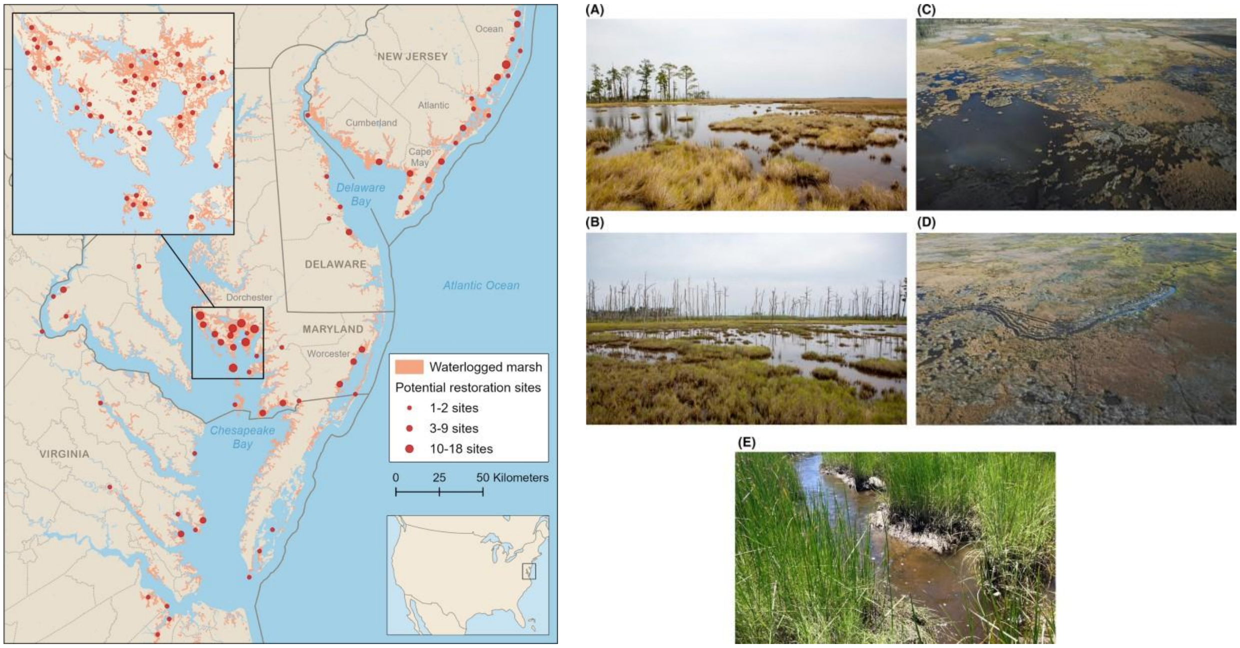



**Figure 5**. Map and photographs of waterlogged soils at the upland-marsh transition boundary from Taylor et al., 2020. Left side: map of potential restoration sites to relieve waterlogged soils. Right side: Photographs of Farm Creek Marsh, MD showing water logged soils (**a**–**c**) and the ditch constructed to drain these soils (**d**, **e**). Photo credits: **a**, **b** Camilla Cerea/Audubon, **c**, **d** Maryland Department of Natural Resources, **e** David Curson.

**Figure 6.** Photograph of marshland occupying former agricultural fields in Gloucester County, VA. Photograph was taken during a king tide (October 11, 2021) and shows the mixed effects of historical levees that reduce flooding on some marshes, and reduce drainage on others (photo source: Tyler Messerschmidt, VIMS).

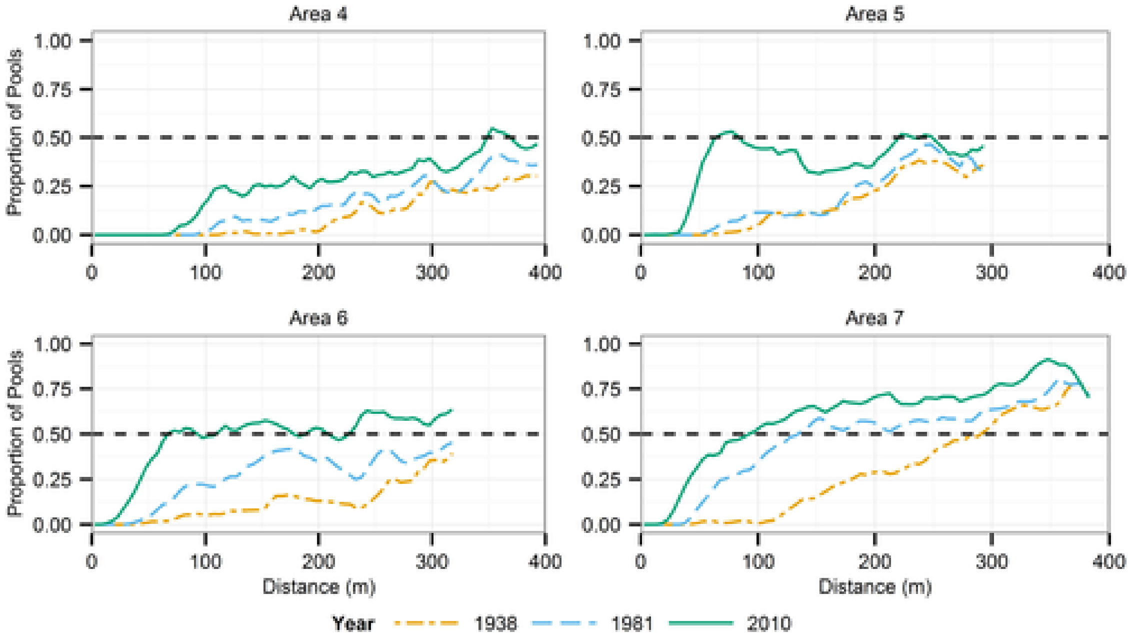



**Figure 7.** Proportion of marsh area occupied by ponds in four regions surrounding the Blackwater River, MD (Schepers et al., 2017). Distance from the Blackwater River is plotted on the x-axis to illustrate that ponding is most extensive in the interior of marshes, far from channels. Colors show increasing pond area through time (i.e. runaway marsh loss) that begins far from the Blackwater River and expands outward. This process is perhaps analogous to pond formation and expansion at marsh-upland boundaries, which are similarly disconnected from tidal channels.

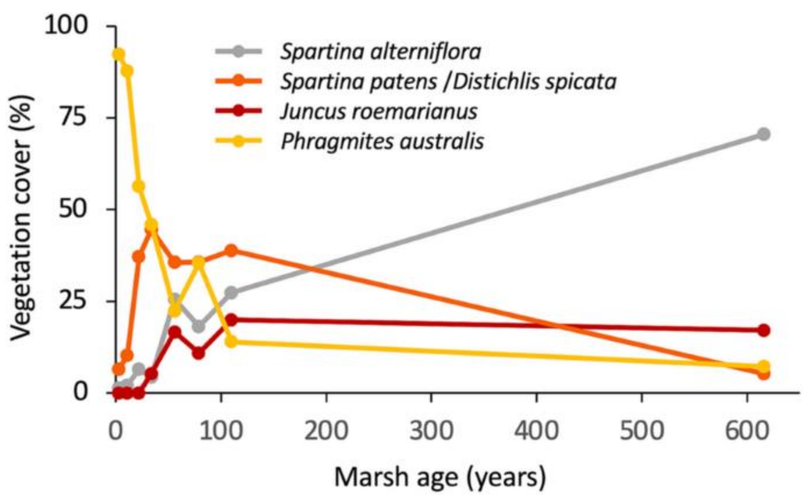



**Figure 8.** Relative percent cover of plant species occupying marsh of various ages on Goodwin Island, VA (Langston et al., 2021). Young marsh forming at the marsh-upland boundary is dominated by invasive *Phragmites australis*, whereas older marshes are dominated by *Spartina alterniflora*. Intermediate aged marshes that formed as a result of marsh migration up to a century ago have the most diverse vegetation composition.

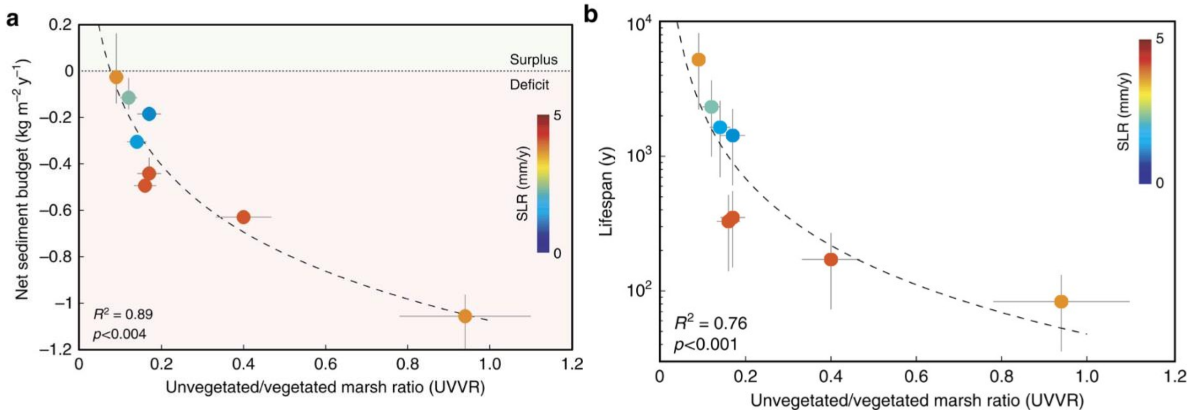



**Figure 9.** Characteristics of the unvegetated to vegetated marsh ratio (UVVR) of 8 microtidal marshes in the U.S., highlighting the vulnerability of Blackwater River, MD marshes (Ganju et al., 2017). (**a**) UVVR corresponds to the sediment budget needed to offset SLR. (**b**) Sediment-budget-based lifespan of the marsh complex as a function of UVVR. In both panels, the Blackwater River marshes have the highest UVVR (>0.9), corresponding to strongly erosive sediment budgets, and the shortest lifespan of all studied marshes.

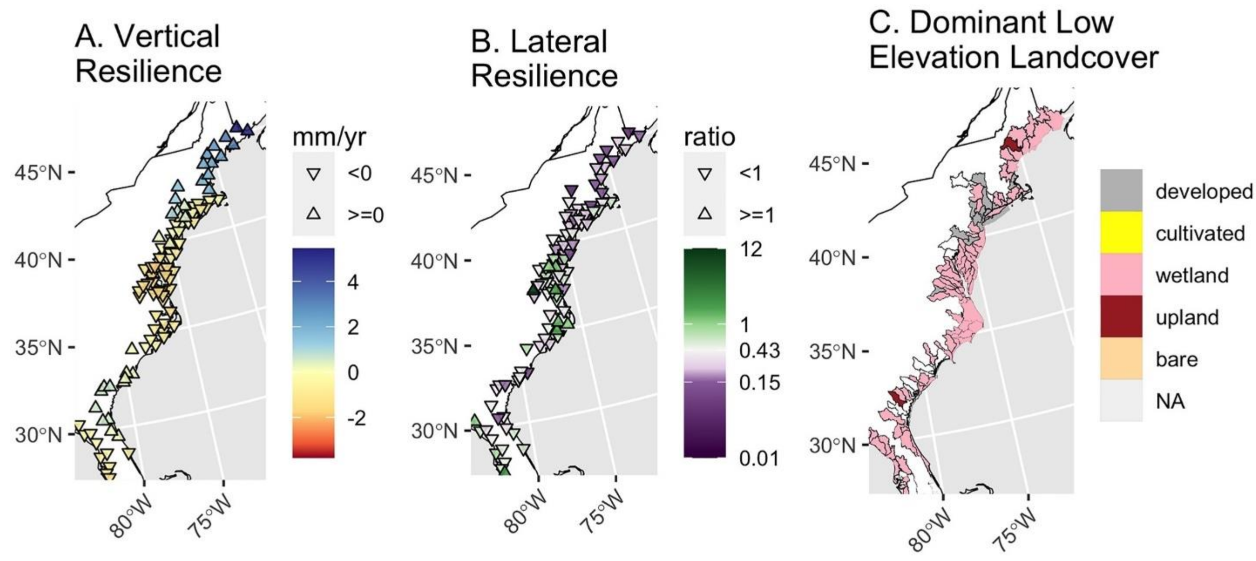



**Figure 10.** Vertical and lateral resilience metrics for marshes on the U.S. Atlantic Coast (Holmquist et al., 2021). Marshes in mid-Atlantic and Chesapeake Bay watersheds are predicted to have accretion deficits under future sea level rise (low vertical resilience) (a), but have relatively high lateral resilience (b) because adjacent uplands are gently sloping and/or undeveloped (c).

**Table 1.** List of common indicators of marsh health and resilience to sea level rise.

| Category | Ecological Attribute | Metric | Reference |
|---|---|---|---|
| Vegetation | Biomass | Aboveground (g/m2) | Craft 1999 |
| | | Aboveground biomass trend (g/m2/yr) | This study (Figure 2) |
| Soil | Nutrient Cycling | % C, N, and P | Craft 1999 |
| | | C:N | Craft 1999 |
| | | C, N, and P accumulation rate | Langston et al., 2021 |
| | Erodibility | Shear strength (kPa) | Himmelstein et al., 2021 |
| | | Penetration depth (m) | Cole Ekberg et al., 2017 |
| | | Loading response | Cole Ekberg et al., 2017 |
| Hydro/Biogeochem | Connectivity (anaerobic soils) | Porewater sulfide concentration [$H_2S$] | Himmelstein et al., 2021 |
| | | Porewater ammonium concentration [$NH_4$+] | Himmelstein et al., 2021 |
| Trophic diversity | Benthic infauna | Density | Craft 1999 |
| | | Species richness | Craft 1999 |
| Resilience: vertical | Accretion rate and associated factors | Elevation change rate (mm yr-1) | Raposa et al. 2016 |
| | | Accretion rate (mm yr-1) | Raposa et al. 2016 |
| | | Turbidity (mg/L) | Raposa et al. 2016 |
| | | Tidal range (m) | Raposa et al. 2016 |
| | | Vertical resilience index | Holmquist et al., 2021 |
| | Vegetation | Mean S. alterniflora height | Cole Ekberg et al., 2017 |
| | | % unvegetated | Cole Ekberg et al., 2017 |
| | | % Low marsh | Cole Ekberg et al., 2017 |
| | | % High marsh | Cole Ekberg et al., 2017 |
| | | % Transitional vegetation | Cole Ekberg et al., 2017 |
| | Marsh elevation distribution | % of marsh below MHW | Raposa et al. 2016 |
| | | Percent of marsh in lowest third of plant distribution | Raposa et al. 2016 |
| | | Skewness | Raposa et al. 2016 |
| | | Elevation NAVD 88 | Cole Ekberg et al., 2017 |
| | | Elevation above MHW | Cole Ekberg et al., 2017 |
| Resilience: lateral | Lateral resilience | Lateral resilience index | Holmquist et al., 2021 |
| Resilience: integrated | Vegetation | Codominant species mixtures | Schepers et al., 2020 |
| | Channelization/sediment fluxes | UVVR | Ganju et al. 2009 |

***Examples of healthy and unhealthy marsh migration in Maryland***

The literature review suggested that ponding and phragmites invasion are the key threats to healthy marsh migration in the Chesapeake Bay, driven largely by the Bay's small tidal range, low sediment availability, fresh to brackish salinities, and gentle upland slopes. In response, we developed and/or applied a number of geospatial metrics of ponding and waterlogged soils, including the Normalized Difference Water Index (NDWI) and the Unvegetated Vegetated Ratio (UVVR). We found these conventional metrics were unsuitable in the marsh-forest transition zone. NDWI failed to resolve waterlogged soils and small ponds. The domain of existing UVVR datasets was limited to marsh outside the transition zone, and was limited to a single year, so that it could not capture progressive wetting or drying through time. In contrast, we found that temporal trends in the Normalized Difference Vegetation Index (NDVI; a proxy for aboveground biomass based on Landsat imagery- see literature review) adequately captured the effects of waterlogged soils, reflected as a browning of marsh vegetation. We examined phragmites distribution using the Tidal Marsh Vegetation Classification (3m) dataset for the Northeast U.S., which is based on the multispectral National Agriculture Imagery Program (NAIP) imagery and a Digital Elevation Model. Based on our literature review, we hypothesized that the healthiest marsh migration would occur near tidal channels, rivers, or large embayments where exposure to salt would limit phragmites, and more regular tidal inundation would enhance drainage. Moreover, we hypothesized that areas with steeper uplands may have healthier migration despite slower rates of migration because the poorly drained transition zone would be narrower. With these hypotheses in mind, we applied each of our metrics across the state of Maryland in an attempt to find an example of healthy marsh migration in Maryland, including both the bayside and seaside of the Delmarva peninsula.

The study area maps show the elevation of low-lying land (Figure 11a) and the average rate of historical forest retreat (1984-2020) (Figure 11b) for all areas within 0-5 m elevation in the upper Chesapeake Bay. We identified 6 sites across the bayside of the Maryland Delmarva reflecting a gradient in forest retreat rates, slope, and marsh health. Site 1 (Eastern Neck National Wildlife Refuge) is located in the steepest region with slowest migration rates and most exposure to the Chesapeake Bay. Sites 2 and 3 (Blackwater National Wildlife Refuge and vicinity) are located in the region with the most gentle slope, fastest migration rates, and least exposure to the Chesapeake Bay. Sites 4, 5, and 6 (Monie Bay region) are located in a region with intermediate slope, migration rates, and exposure to the Chesapeake Bay. As discussed below, marsh health generally followed these topographic gradients, where the healthiest marsh migration occurred in more steeply sloping, more exposed sites and the unhealthiest marsh migration occurred in the more gently sloping, less exposed sites with wide transition zones.

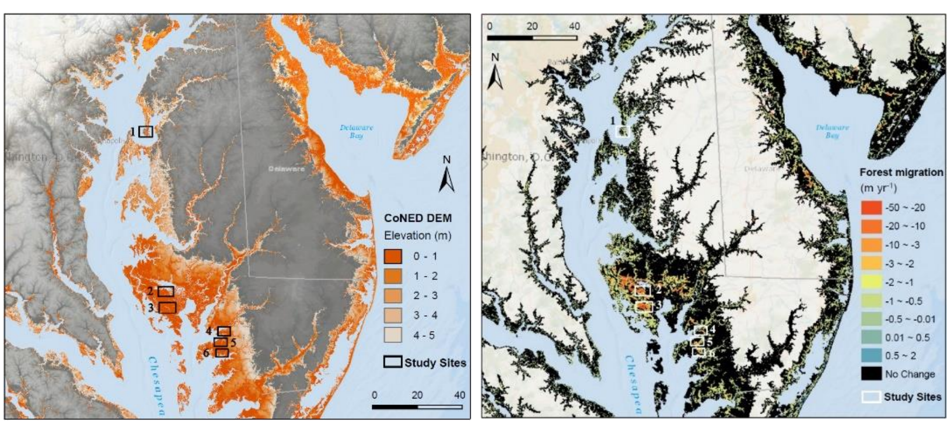



**Figure 11.** (a) Study area map indicating the elevation of the coastal zone from the USGS CoNED DEM. (b) Study area map indicating historical forest retreat rates (1984-2020). Sites 1-6 are ordered from North to South.

*Site 1: Eastern Neck National Wildlife Refuge. Healthy marsh.*

Our remote sensing analysis identified the northern portion of the Eastern Neck National Wildlife Refuge as a site with especially high marsh health. A relatively steep topography created small patches of forest loss (from 1984 to 2020, yellow polygons with stenciled interior) with narrow marshes. Additionally, its location as an island in the Chesapeake Bay with numerous embayments maximized its exposure to marine waters and regular inundation by tides. Calculated NDVI trends (1984-2020) were mostly positive (i.e. vegetation greening indicated by green colors), and were neutral to positive within and immediately adjacent to areas of forest loss. Negative NDVI trends (i.e. aboveground biomass loss/browning indicated by red colors) reflect erosion around the edge of embayments and the expansion of 2 interior ponds. Overall, the trend in marsh NDVI was clearly positive. The tidal marsh classification dataset does not include this site, but observations on the ground suggest that phragmites is the dominant plant species within the transition zone, and that native marsh is extensive in older marsh.

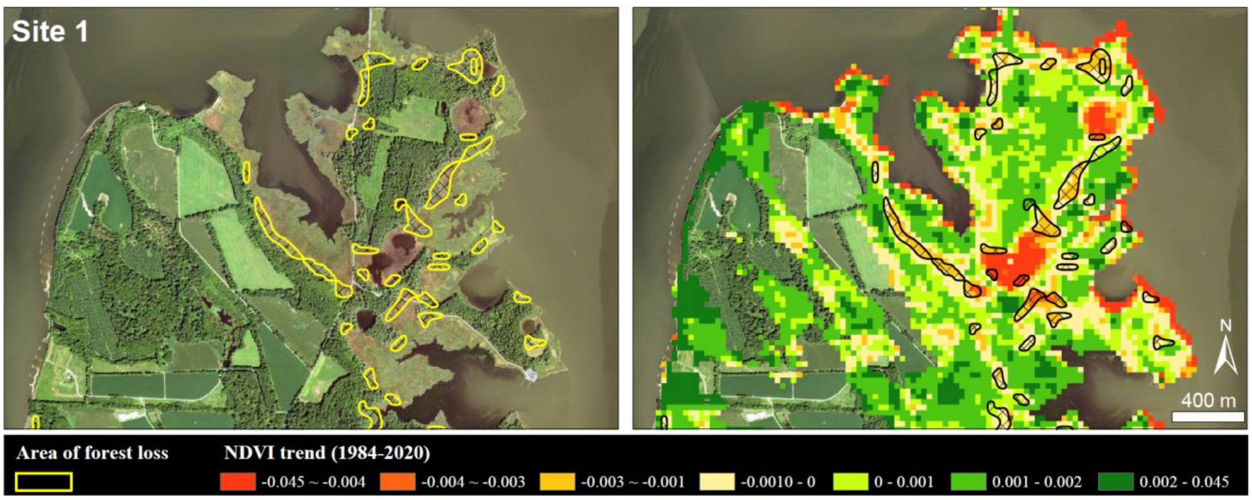



**Figure 12.** Map of Eastern Neck. Map on left shows areas of forest loss (yellow polygon) from 1984 to 2020. Map on right shows NDVI trend (1984-2020) for all areas within 0-5 m elevation where red and green colors represent decreases and increases in aboveground biomass, respectively. Decreased biomass within the forest loss polygons primarily represents replacement of forest vegetation with marsh vegetation. Though there are areas of marsh loss, the overall biomass trend is positive. NDVI source: Yaping Chen, VIMS.

*Site 2: Blackwater National Wildlife Refuge. Unhealthy marsh.*

Site 2 represents the site with the least healthy marsh migration. Very gently sloping topography created large areas of forest loss (yellow polygons with stenciled interior) with large areas of marsh and ponds. Additionally, its location in the uppermost reaches of the Blackwater River minimized its exposure to tides (<25cm), sediment supply, and regular inundation-drainage cycles. Given very fast rates of forest retreat, we split our NDVI analysis into 2 time periods (1984-2002; 2003-2020). Green colors represent consistently positive NDVI trends or a switch from negative to positive trends (reflecting marsh migration into dying forest, or increased drainage and productivity of marsh through time). Red colors indicate consistently negative NDVI trends or a switch from positive to negative trends (reflecting marsh submergence, ponding). In contrast to Site 1, NDVI trends at Site 2 were mostly negative, reflecting ponding within the area of forest loss. Moreover, previous observations from the marsh outside the area of forest retreat area indicate rapid marsh degradation and conversion into open water ponds. The tidal marsh classification dataset suggests that the forest-marsh transition area is 50-75% phragmites and that the surrounding marshland is 25-50% phragmites. On the ground observations from nearby locations suggest that the transition zone is dominated by phragmites.

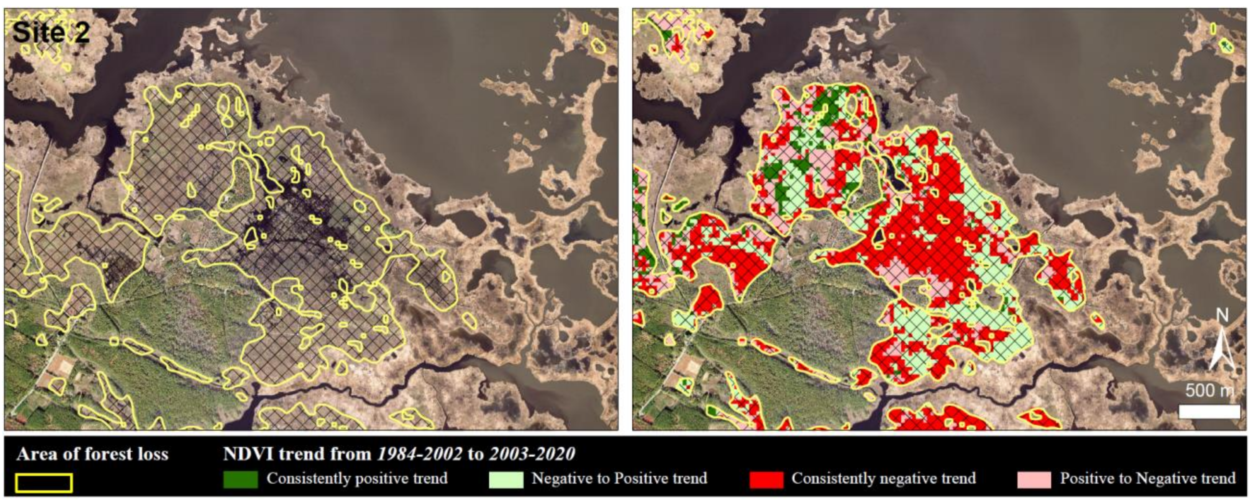



**Figure 13.** Map of forest migration area south of Lake Blackwater. Map on left shows large areas of forest loss (yellow polygon) from 1984 to 2020. Map on right shows change in NDVI trend from 1984-2002 to 2003-2020. In locations with rapid forest retreat and healthy marsh migration, NDVI trends would be expected to change from negative (i.e. forest loss) to positive (i.e. marsh migration), as indicated by light green coloring. At this site, however, biomass trends are consistently negative, which reflects the deterioration of even newly formed migrating marshes. NDVI source: Yaping Chen, VIMS.

*Site 3: Beachground Swamp. Mostly unhealthy marsh.*

Site 3 represents a site with unhealthy marsh migration, but illustrates an interesting gradient in marsh health that might be related to an eventual recovery of a ponded transition zone. As with Site 2 (Blackwater River), a very gently sloping topography created large areas of forest loss (yellow polygons with stenciled interior) and large areas of marsh and ponds. Also like Site 2, its location in the uppermost reaches of Farm Creek minimizes its exposure to tides, sediment supply, and regular inundation-drainage cycles. Prior remote sensing efforts identify this area as the most rapid forest loss in the Chesapeake Bay (~1000 m in ~40 years). NDVI trends at Site 3 were mostly negative reflecting ponding within the area of forest loss, and supported by drone photography identifying extensive unvegetated areas. However, more subtle observations indicate a gradient in marsh health and a potential recovery of ponded areas. For example, positive NDVI trends (green colors) were located in the marsh closest to Farm Creek, especially at the more downstream locations. Marsh greening could reflect better drainage closer to Farm Creek, or eventual recovery of marsh vegetation in the areas farthest from the modern forest-marsh boundary (i.e. in the oldest marsh). The tidal marsh classification dataset suggests that the forest-marsh transition area is 50-75% phragmites and that the surrounding marshland is >50% phragmites. Drone observations confirm that the transition zone is dominated by phragmites.

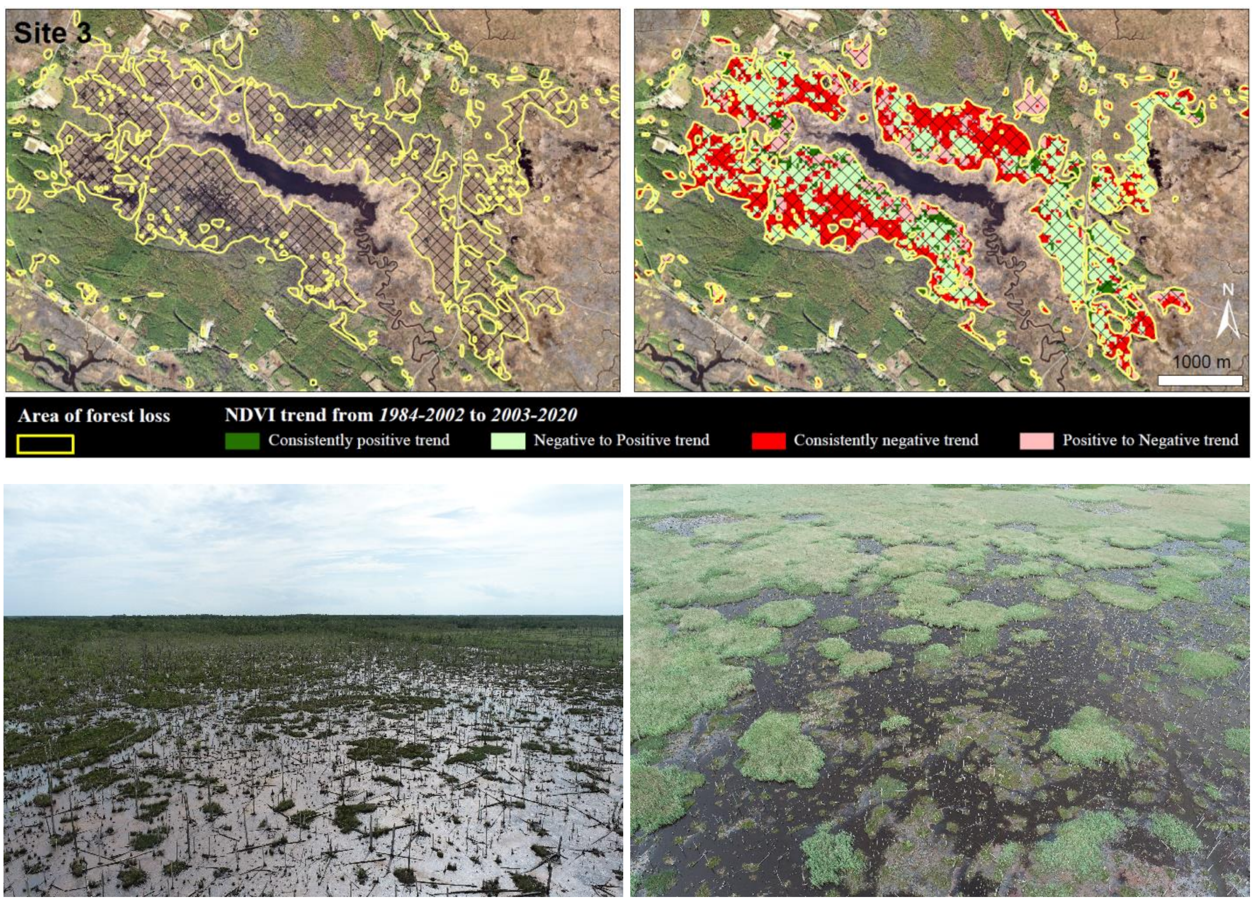
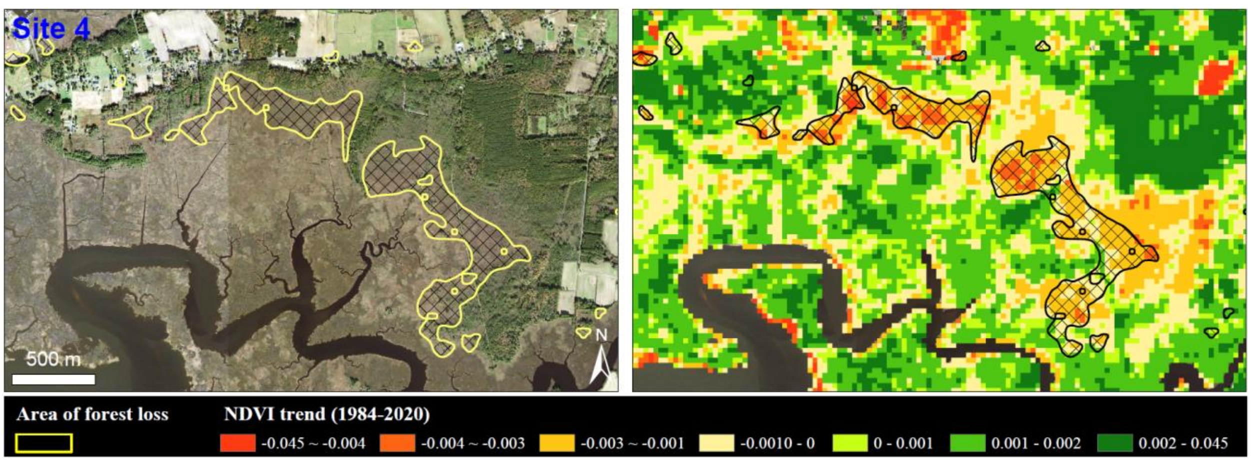
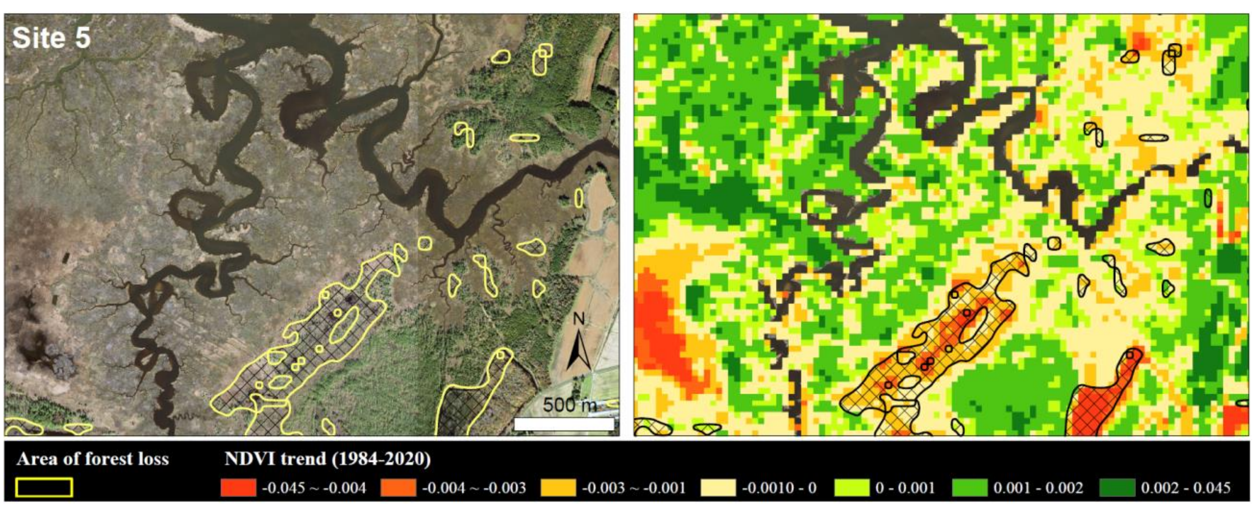



**Figure 14.** Maps and photographs of Beachground Swamp. Photographs illustrate large areas of open water where marsh migration has not accompanied forest retreat. Photograph on right shows dominance of phragmites australis (light green) in the areas where marsh vegetation has migrated. NDVI source: Yaping Chen, VIMS. Photo source: Tyler Messerschmidt, VIMS.

*Sites 4-6: Monie Bay region. Healthy marsh.*

Our remote sensing analysis identified a region of relatively healthy marsh migration along the peninsulas surrounding Deal Island/Monie Bay. This region has intermediate upland slopes (less than Site 1, but more than Sites 2 and 3), that created intermediate sized patches of forest loss (yellow polygons with stenciled interior). The selected examples of healthy marsh migration were located near tidal channels and embayments, so that the marshes were relatively narrow, and more exposed to tides and sediment than Sites 2 and 3. Additionally, anthropogenic ditches potentially increase the drainage of the marsh at Sites 4 and 6. NDVI trends at Sites 4 and 5 are negative within the area of forest loss (reflecting tree mortality) but overwhelmingly positive in the marsh itself. Negative NDVI trends are largely restricted to a single area of marsh erosion at the head of an embayment in Site 4, and an area of ponding in Site 5. Site 6 had faster rates of forest retreat so we split the NDVI trends into 2 time periods (1984-2002; 2003-2020) to capture forest loss and subsequent potential marsh migration. NDVI trends within the area of forest loss at Site 6 were mostly positive, and reflected a switch from a negative NDVI trend in the earlier time period (forest loss) to a positive NDVI trend in the most recent time period (marsh migration without ponding). The tidal marsh classification dataset suggests that the forest-marsh transition area at these sites is 50-75% phragmites and that the surrounding marshland is <25% phragmites. On the ground observations at Site 5 suggest that Phragmites is by far the dominant plant species within the transition zone but that native high marsh vegetation occurs in older marsh.



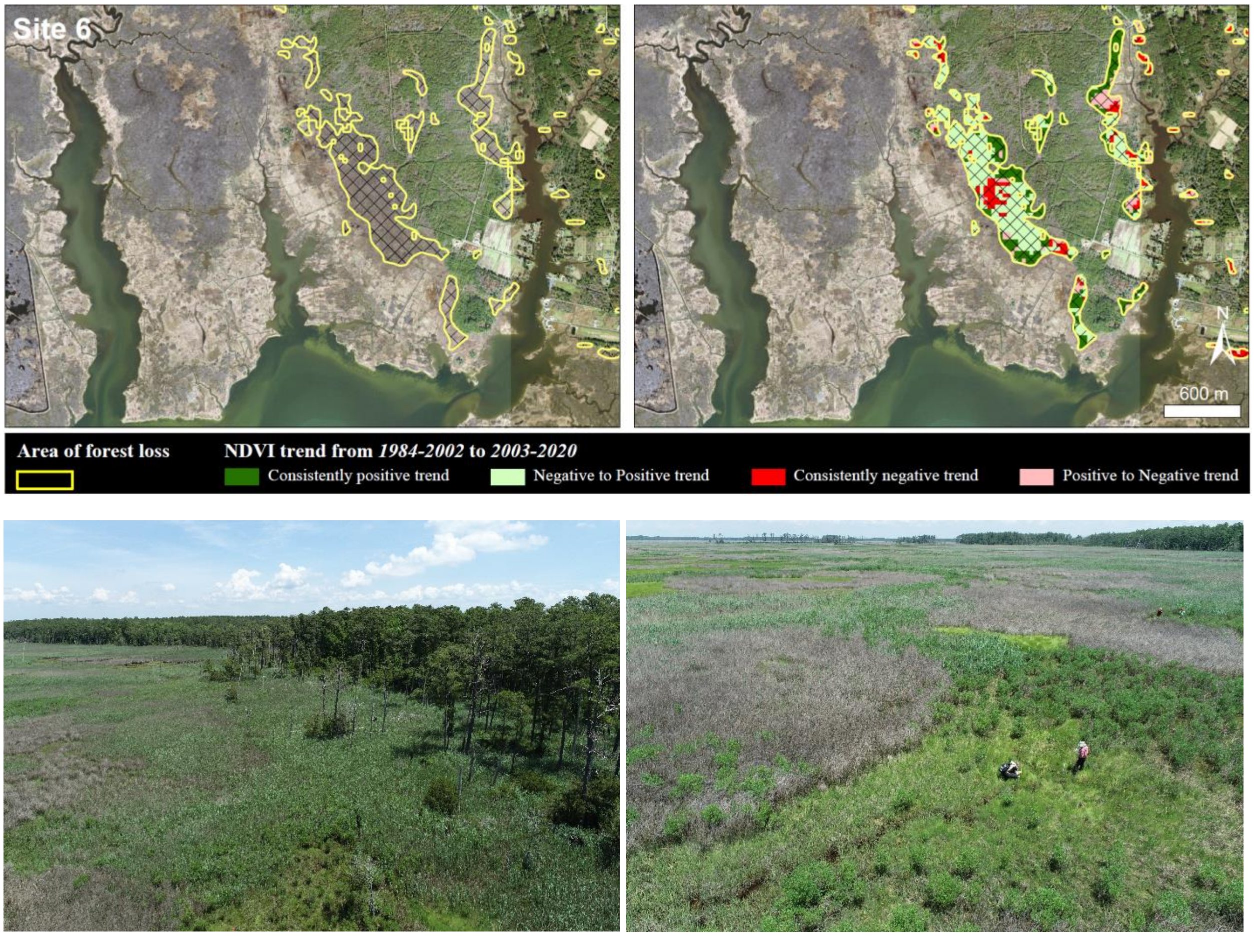



**Figure 15.** Maps and photographs of Monie Bay region. Sites 4 and 5 show negative NDVI trends (1984-2020) associated with forest conversion to marsh within the area of forest loss (yellow polygon) between 1984 to 2020, but positive NDVI trends in the marsh itself. Site 6 has more rapid forest loss, and illustrates a switch from a negative NDVI trend (1984-2002) to positive NDVI trend (2003-2020), consistent with healthy marsh migration. Photograph on left shows that the forest loss area is dominated by phragmites. Photograph on right shows that the older high marsh is dominated by native high marsh, including *Juncus romerianus* (gray), *Spartina patens* (light green), and *Iva frutescens* (dark green). NDVI source: Yaping Chen, VIMS. Photo source: Tyler Messerschmidt, VIMS.

### *Conclusions*

We utilized remote sensing analyses to identify gradients in marsh migration health throughout the Chesapeake Bay region of Maryland. Marsh health was defined by NDVI trends reflecting the health of aboveground vegetation between 1984 and 2020. Other criteria, e.g. accretion rates, were not included. Phragmites distribution was assessed using an existing remote sensing product with unknown accuracy, and informal surveys at a few of the example sites. However, as discussed in the literature review, it is not clear whether Phragmites should be considered as a metric of marsh health, as its effect on ecosystem services other than habitat are largely positive.

Marsh health generally followed topographic gradients, where steeply sloping, more exposed sites (Sites 1, 4-6) had vegetation with more positive NDVI trends reflecting marsh migration without extensive ponding. The unhealthiest marsh migration occurred in the most gently sloping and least exposed sites, that had the widest transition zones (Sites 2-3 near the Blackwater River National Wildlife Refuge). These observations suggest that the extent and quality of marsh migration may be at odds, where the fastest and most extensive marsh migration tends to result in wide, poorly drained marshes that are prone to ponding. However, very preliminary observations from Site 3 (Beachground Swamp) suggest that large areas of poorly drained transitional marsh may eventually recover as tidal channels erode and eventually drain the rapidly evolving landscape.

We were surprised to not find an example of healthy marsh migration on the seaside of the Delmarva peninsula, given its generally steeper slopes, exposure to seawater, and narrow marshes with extensive ditching. The effects of ditching- a management action designed to increase drainage in the transition zone identified in the literature review- were mixed. Extensive ditching on the seaside of the Delmarva Peninsula did not seem to have a positive effect, and in many cases was associated with strongly negative NDVI trends. On the other hand, healthy sites 4 and 6 were generally associated with ditching that may have increased drainage and resulted in positive NDVI trends.

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