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Key Points:

- Soil cores reveal a clear biogeochemical gradient from lowland marsh to adjacent upland forest and farms
- Marshes had 4–50 times more soil carbon than their adjacent upland endmembers
- In some areas, the migrating marsh is thin and is underlain by aerobic soil

Supporting Information:

Supporting Information may be found in the online version of this article.

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Marsh Migration Into Forests and Farms: Effects on Soil Biogeochemistry Along the Salinity Gradients

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Abstract

Sea level rise (SLR) and increased storm intensity are causing landward expansion of intertidal zones in the low-lying Delmarva Peninsula, allowing marsh migration into forests and agricultural fields. Transitional zones along the marsh-upland transects are visible aboveground as ghost forests and crop die-off, respectively. While the aboveground impacts of marsh migration are clear, the effects on belowground biogeochemistry are understudied. To characterize the impacts of marsh migration on soil biogeochemistry, we collected soil cores from marsh-upland transects at 3 agricultural and 3 forested sites along the Delmarva Peninsula. Soil cores were analyzed for both porewater chemistry and solid-phase characterization. Marsh end members support sulfate reduction; transitional zones support iron reduction; and upland end members support aerobic metabolisms at the surface, with iron reduction occurring at depth. In addition, the quality and quantity of dissolved organic matter changed across the transects, indicating differences in carbon source and cycling dynamics. Furthermore, our results show that soil carbon concentration varies drastically from lowland marsh to uplands, with marshes having 4–50 times more soil carbon than their upland endmembers. We also observed site-specific differences, where at the site with the lowest slope, the migrating marsh layer was relatively thin and was underlain by low-carbon aerobic soil that was coarser-textured. These findings have important implications for better understanding the incremental and belowground effects of SLR on coastal forests and agricultural lands.

Plain Language Summary

Rising seas and stronger storms are pushing marshes inland into surrounding forests and crop lands. Above-ground impacts such as dying trees and salt-affected crops are obvious, but less is known about what is happening below-ground. We studied the soil below-ground and found large changes in soil chemistry, resulting in differences in carbon storage along this transition zone. These data are important cues for how coastal ecosystems are shifting and will shift in the future.

1. Introduction

Coastal wetlands are migrating upland into forests (Langston et al., 2017, 2022; Raabe & Stumpf, 2016) and agricultural fields (Gedan & Fernández-Pascual, 2019; Guimond & Michael, 2021) due to a combination of fast processes associated with increased storm surges (Fagherazzi et al., 2019; Kearney et al., 2019) and slow processes associated with sea level rise (SLR) (Schieder et al., 2018) that are driving saltwater intrusion (Tully et al., 2019). The inundation with saltwater and subsequent transition of upland terrestrial areas to more marine-like marsh habitat is controlled by key factors such as local rates of relative SLR (Schieder & Kirwan, 2019), topographic slope (Kirwan et al., 2016), sedimentation rates (Kirwan et al., 2010), salinity (Smith, 2013), ecosystem disturbance (Walters et al., 2021), vegetation structure, and land use (Gedan et al., 2020; Jobe & Gedan, 2021). A visible gradient in the extent of saltwater intrusion is evident in the health of aboveground vegetation. In coastal forests, these manifest as decreasing tree foliage and sapling growth as trees become increasingly salt-stressed toward the migrating marsh front (Smith & Kirwan, 2021). The same salinity gradient exists in coastal agricultural areas as crop yield progressively declines with increased salt stress (Guimond & Michael, 2021; Tully et al., 2019). Transitional zones are a way to visualize the extent of inundation, saltwater intrusion, and subsequent ecosystem transition (Smith, 2013). While salinization processes are altering aboveground vegetation in coastal forests and farms, their effects on belowground biogeochemistry along these salinity gradients are not well characterized.

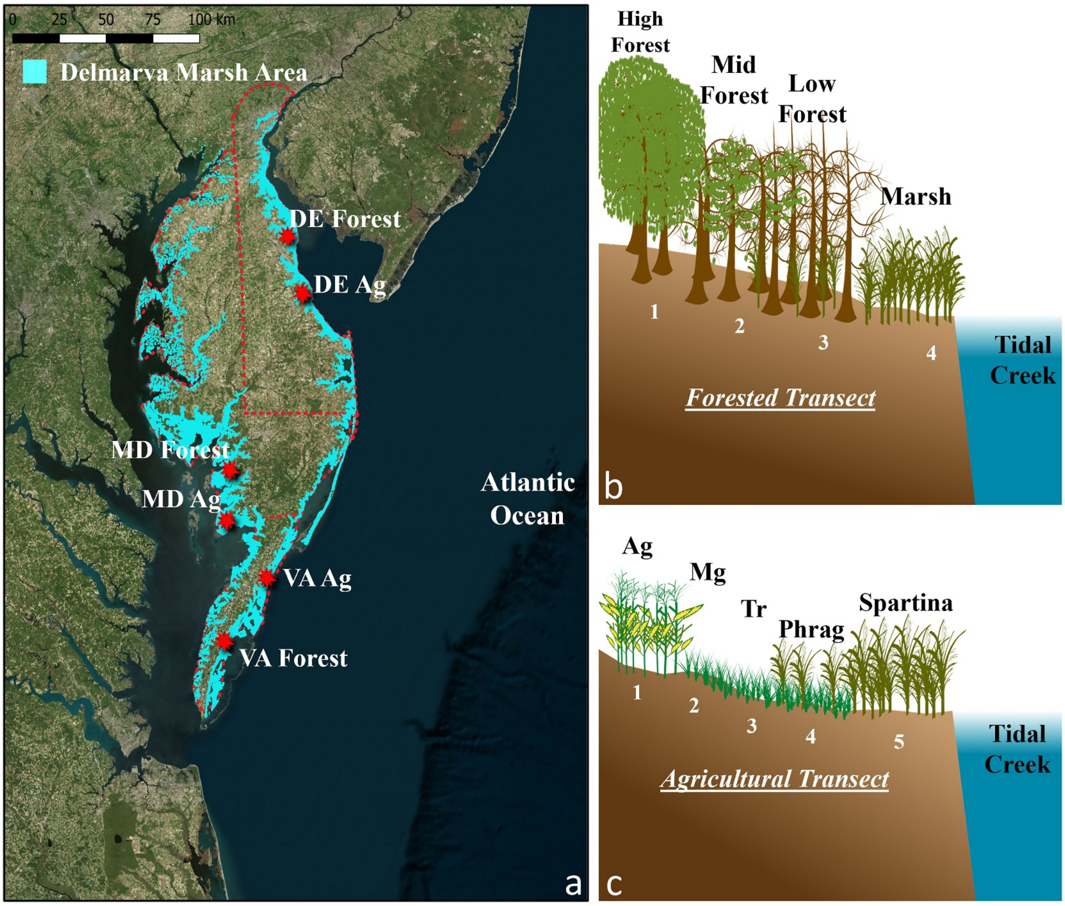

Figure 1. (a) Map of the Delmarva Peninsula and locations of the marsh-upland agricultural and forested transect sites in each of the three Delmarva states (DE, MD, VA), as well as a conceptual diagram showing the transect points for both (b) Forested ($n = 4$) and (c) Agricultural ($n = 5$) transects. Ag = Healthy Agriculture, Mg = Margin, Tr = Transition, and Phrag = Phragmites.

The intrusion of saltwater and more inundation into upland freshwater ecosystems can have a variety of effects on belowground soil biogeochemistry, which ultimately affects aboveground vegetation and ecosystem function. Soil salinization causes increased ionic strength, alkalinization, and sulfidation, all of which negatively affect vegetation that is not adapted for saline conditions (Tully et al., 2019). In particular, the primary productivity of freshwater vegetation is expected to decrease due to increased salt stress (McKee & Mendelssohn, 1989; Willis & Hester, 2004), likely changing the quality and quantity of fresh dissolved organic carbon (DOC) inputs into the soil. The optical properties of chromophoric dissolved organic matter (CDOM) may give an indication of DOC quality, and at the marine-terrestrial interface, it may discern marine-like from terrestrial-like DOC (Osburn et al., 2015; Tzortziou et al., 2008). In addition, microbial activity and communities may shift with increased inundation and soil salinity (Canavan et al., 2006; Weston et al., 2006) due to changes in redox potential (E_H), electrical conductivity (EC), pH, and the availability of alternative electron acceptors such as Fe oxides (i.e., Fe reduction) and sulfate (i.e., sulfur reduction). Taken together, these soil processes could illuminate a biogeochemical fingerprint of the incremental effects of below-ground inundation with saltwater.

Marsh migration is also expected to increase soil C concentration because marshes sequester soil C orders of magnitude higher than terrestrial systems. Blue C ecosystems (i.e., salt marshes, seagrasses, mangroves) have received much attention recently, as their protection and restoration have been considered important mitigators of climate change due to rapid soil C sequestration (Alongi, 2018; Chmura et al., 2003; Duarte et al., 2013; Macreadie et al., 2021; Mcleod et al., 2016). While this is the case for mature and established blue carbon ecosystems, newly migrated marsh into upland forests have been shown to decrease overall C storage in the short term, namely due to a loss of aboveground C stocks in trees and shrubs (Smith & Kirwan, 2021). Agricultural fields experiencing saltwater intrusion will likely increase their C storage (De La Reguera & Tully, 2021) due to very low soil C inherent in US farm fields (Martens et al., 2004), but the negative impact on food production should not be overlooked.

To more fully understand how marsh migration into forests and farms affects belowground soil biogeochemistry and coastal ecosystem soil C, we analyzed the solid-phase soil and porewater from marsh-upland at three forested and three agricultural areas where marsh migration is occurring along the coastline of the Delmarva Peninsula. We hypothesized that as marshes migrate upland, soil C concentration increases due to lower E_H and slower microbial decomposition. We further hypothesized that points along the upland to lowland transects have a unique biogeochemical fingerprint (i.e., Fe reduction vs. sulfate reduction), indicative of the extent of saltwater inundation. Our findings have implications for better understanding coastal ecosystem resilience under a changing climate.

Table 1
Two-Way MANOVA Results at the Three Agricultural Sites Combined

Variable	Transect point	Depth	Transect point*depth
Log Soil C	*<0.0001*	*0.005*	0.81
Log Soil S	*<0.0001*	0.28	0.99
Log Soil N	*<0.0001*	*0.0004*	0.44
Log Soil C:N	*0.03*	*0.02*	0.39
Soil Fe	*0.006*	0.85	0.98
Soil K	0.73	0.59	0.99
Soil Mg	0.72	*0.01*	*0.01*
Soil Ca	0.06	0.92	0.99
Soil Mn	0.94	0.93	0.99
Soil Zn	0.95	0.45	0.99
Sand:Silt	0.35	0.17	0.47
Clay %	0.15	*0.002*	0.08

Note. The values indicate *p*-values with significance ($p < 0.05$) indicated by italics. Model output is presented for each soil chemical variable, separated by transect point, depth, and their interaction.

2. Methods and Materials

2.1. Field Sites

The 6 marsh-upland transects are located along the Delmarva Peninsula and include 3 agricultural transects (hereafter referred to DE-agricultural, MD-agricultural, and VA-agricultural) and 3 forested transects (hereafter referred to as DE-forest, MD-forest, and VA-forest) (Figure 1a). Approximate elevations of each site above sea level are 1.1 m, 0.5 m, 1.3 m, 2.1 m, 0.6 m, 0.9 m (Pratt, McQuiggan, et al., 2025, Pratt, Guimond, et al., 2025). For the forested transects, four points along the upland to lowland were identified based on aboveground features and sampled and are hereafter referred to as "High Forest," "Mid Forest," "Low Forest," and "Marsh" following previous identification and naming conventions (Smith & Kirwan, 2021) (Figure 1b). For the agricultural transects, five points along the upland to lowland transect were identified and sampled are hereafter referred to as "Healthy Agriculture," "Margin," "Transition," "Phragmites," and "Spartina" (Figure 1c). We clarify that Spartina is a well-established (i.e., older) marsh, while Phragmites is a more recently formed marsh.

2.2. Soil Sampling and Analysis

Soil cores were collected at the 6 field sites at each of the transect points (Figure 1), resulting in 27 total soil cores. Cores were collected at all sites in the growing season of 2021, except for the VA-agricultural transect which was collected in the 2022 growing season. Soil cores (84 × 6 cm) were taken at each transect point using a gouge auger, which minimizes compaction (Smeaton et al., 2020). In the field, the cores were quickly sectioned into 12 cm increments (i.e., 7 increments per soil core), placed in 250 mL HDPE bottles, and sealed inside gas-gas-impermeable bags with oxygen scrubbers (AneroPack-Anero, Mitsubishi) for anoxic preservation during transport to the lab according to previously established methods (Fettrow et al., 2024). Once in the lab, the 12 cm soil sections were immediately placed inside an anoxic glove bag containing 95% nitrogen and 5% hydrogen. A subsample of each soil section was left to dry inside the glove bag for elemental analysis. Once dried, the subsample was sieved (2 mm), ground, and powdered for analysis of total C, H, N and S (Vario EL Cube, Elementar). Furthermore, to determine total soil elemental concentrations of Fe, Ca, Mg, K, Mn, and Zn, powdered soil samples were analyzed using X-ray fluorescence (Bruker S1 Titan 600). For this, each sample was analyzed using the Oxide3Phase method with a scan time of 360 s (120 s/phase). Two standard reference materials (NIST Montana 2710a, NIST San Joaquin 2709a) were used to test instrument accuracy with an average percent recovery for Ca, Fe, K, Mg, Mn, and Zn of 102%, 99%, 87%, 124%, 110% and 91%, respectively. The remaining field-moist soil was left inside the 250 mL HDPE vial, capped inside the glove bag, and centrifuged for extraction of porewater according to the following section.

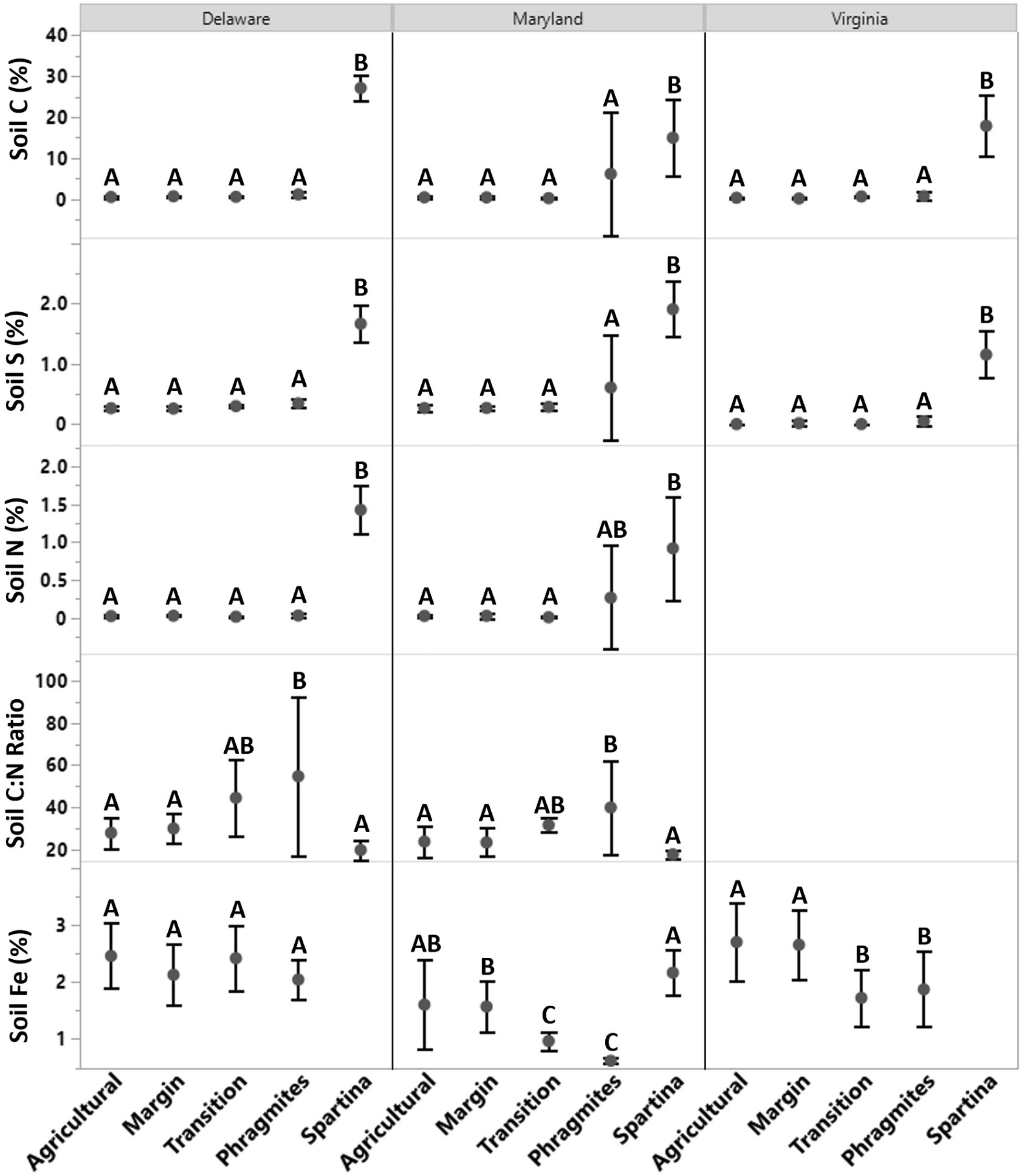

Figure 2. Depth-averaged (±standard error) of measured soil parameters and their corresponding post-hoc ANOVA analysis at the three agricultural transects. Values with the same letter within the same state are not significantly different. Full depth profiles are reported in Figure S1 in Supporting Information S1.

2.3. Porewater Extraction and Analysis

Porewater was extracted from the individual 12 cm soil increments by centrifugation. Capped, anoxically preserved HDPE bottles containing field-moist soil sections were placed inside the centrifuge and spun at 2,000 g for 10 min. A fraction of the porewater was filtered with 0.45 μm PTFE syringe filters while the remaining fraction was vacuum filtered using glass fiber filters (0.7 μm). The 0.45 μm filtered porewater was analyzed for Fe^{2+} using the ferrozine colorimetric method (Stookey, 1970), S^{2-} using the methylene blue method (Cline, 1969), pH, E_H (relative to the standard hydrogen electrode), and EC using calibrated electrodes (Orion Ross Ultra pH/ATC Triode, Orion 9179E Triode, Orion DuraProbe Conductivity Cell), and total elements with ICP-MS (Thermo iCAP TQ ICP MS) after acidification to 2% HNO_3 solution. The porewater filtered with 0.7 μm glass fiber was analyzed for DOC, dissolved inorganic carbon (DIC), and total nitrogen (Vario TOC Analyzer, Elementar).

Table 2
Two-Way MANOVA Results at the Three Forest Sites Combined

Variable	Transect point	Depth	Transect point*depth
Log Soil C	*0.002*	*<0.0001*	0.20
Log Soil S	*<0.0001*	0.34	0.43
Log Soil N	*0.001*	*<0.0001*	0.54
Log Soil C:N	0.32	0.80	0.98
Soil Fe	0.29	*0.007*	0.27
Soil K	0.39	0.25	0.96
Soil Mg	0.22	0.13	0.68
Soil Ca	*0.002*	*0.04*	0.39
Soil Mn	0.15	0.56	0.99
Soil Zn	*0.0001*	0.17	*0.02*
Sand:Silt	0.99	0.60	0.99
Clay %	0.99	0.26	0.99

Note. The values indicate p-values with significance ($p < 0.05$) indicated by italics. Model output is presented for each soil chemical variable, separated by transect point, depth, and their interaction.

Optical properties of CDOM were further characterized with ultraviolet-visible analysis (UV-VIS spectrometer, Aligent). Measurements were taken over the wavelengths of 200–730 nm with 2 nm steps. The instrument was calibrated and background checked using double deionized (DDI) water blanks. Absorbance indices (Abs_{254}, $SUVA_{254}$, S_r, E_2:E_3) were calculated using previously established equations (Hansen et al., 2016).

2.4. Statistical Analysis

Soil and porewater biogeochemical variables were simultaneously assessed for variability across three independent variable groups: transect point, depth, and their interaction. This was done using two-way multivariate analysis of variance (MANOVA) with follow-up one-way ANOVAs and post hoc Tukey HSD analysis ($\alpha = 0.05$) specifically for transect point. Therefore, four MANOVAs were run: one for the three agricultural transects and one for the three forested transects for solid-phase variables, and one for the three agricultural trasnsects and one for the three forested transects for the porewater variables. The follow-up ANOVAs and post-hoc tests were run primarily to determine specific differences in soil and porewater variables across the marsh-upland gradient at individual field sites. Individual ANOVA results are presented in Supporting Information S1. Data normality was assessed using QQ plots, and homogeneity of variance was assessed with Levene's Test prior to running ANOVAs. Certain soil variables (Soil C, S, and N) and all porewater variables were log-transformed to satisfy statistical assumptions for analysis of variance. In addition, relationships among biogeochemical variables were analyzed using principal components analysis (PCA). Finally, a normal mixture cluster analysis was conducted to identify groupings of data based on statistically significant biogeochemical variables. All statistical analyses were done using JMP (Version 16.2).

3. Results

3.1. Solid-Phase Analyses

3.1.1. Agricultural Transects

Solid-phase analysis revealed significant variability in soil chemical and physical properties at the agricultural transects from MANOVA analysis (Table 1; Table S1 in Supporting Information S1); some of these variables were affected by transect point, depth, or both. There was minimal significant interaction between transect point and depth. Soil C and N exhibited significant variation mainly across transect points but also with depth, which is also evident from depth profiles (Figure S1 in Supporting Information S1). Transect point, rather than depth, appeared to drive most of the variability across measurements. Therefore, we conducted follow-up one-way ANOVAs with Tukey HSD analyses on depth-averaged data to determine differences among transect points (Figure 2; Tables S2–S4 in Supporting Information S1). Depth-averaged data revealed that Spartina contained significantly more C and N than all other transect points at all three agricultural transects. The C:N ratio also varied across transect point and depth, though Phragmites tended to have the highest C:N ratio compared to the other transect points and consistent trends with depth were less apparent. Soil S significantly varied with transect point but not with depth. Similar to C and N, soil S was generally significantly higher at Spartina than all other transect locations. There were no differences between soil K, Mn, or Zn, but soil Fe varied by transect point with Healthy Agriculture tending to have the highest soil Fe, while Transition generally having the lowest. There was a significant interaction between depth and transect point for soil Mg; most sites had consistently similar soil Mg with depth except for the Spartina transect point at the MD site where Mg was 2-fold higher at ∼42 cm depth (Figure S1 in Supporting Information S1). The soil clay content varied significantly by depth (Table 1). Clay content tended to increase initially with depth, then decrease toward the bottom of the soil profile (Figure S1 in Supporting Information S1).

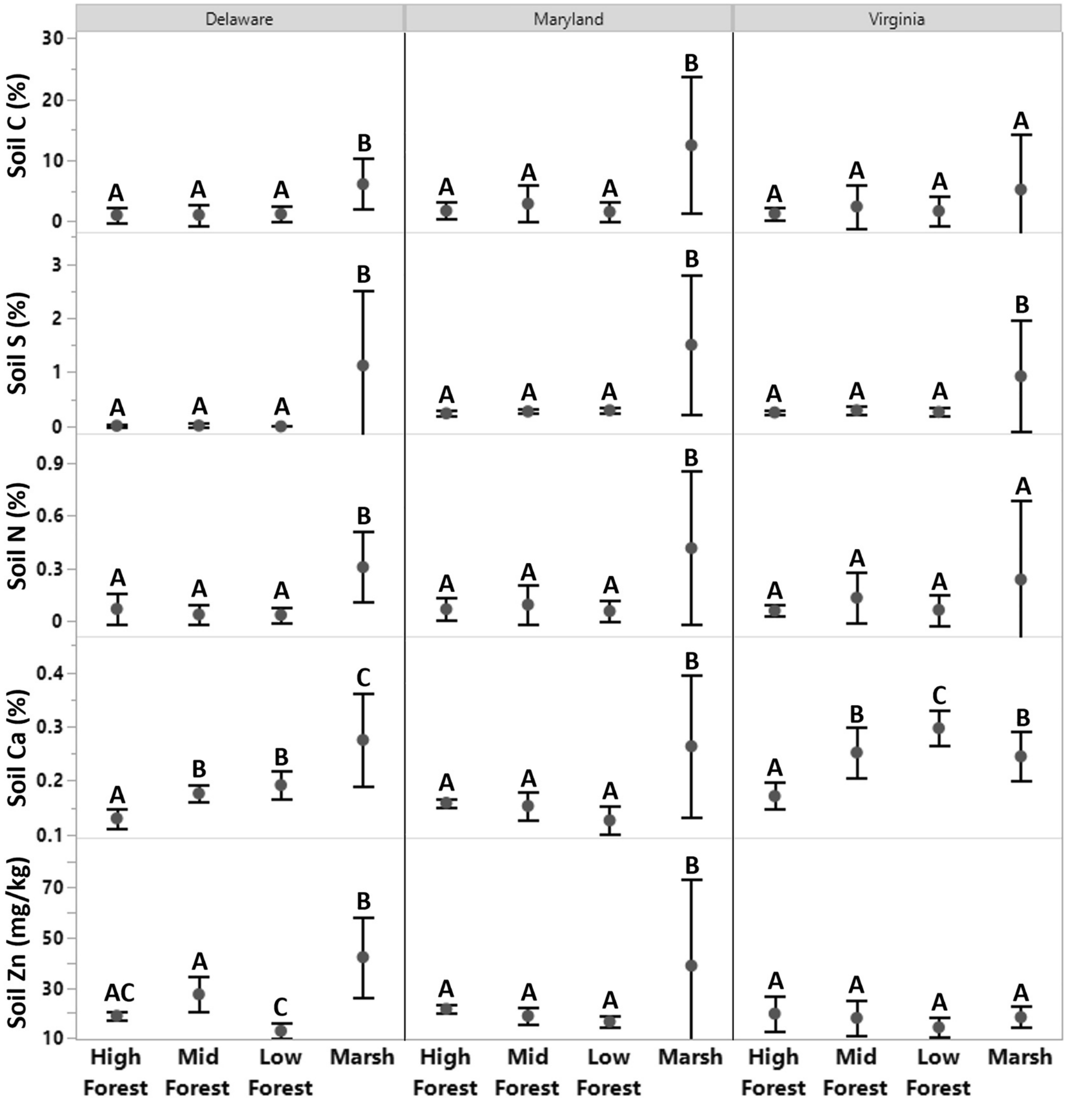

Figure 3. Depth-averaged (±standard error) of measured soil parameters and their corresponding post-hoc ANOVA analysis at the three forested transects. Values with the same letter within the same state are not significantly different. Full depth profiles are provided in Figure S2 in Supporting Information S1.

3.1.2. Forested Transects

Soil chemical and physical properties at the forested transects were also affected by transect point, depth, or both, with little interaction (Table 2; Table S5 in Supporting Information S1). Both soil C and N were significantly affected by depth and transect point, whereas soil S was only affected by transect point, and no interactions between transect point and depth were observed. These patterns are similar to the agricultural transects, in which the Spartina marsh end member contained significantly higher soil C, N, and S than all other transect locations, and soil C and N tended to decrease with depth (Figure S2 in Supporting Information S1). Follow-up one-way ANOVAs with Tukey HSD analyses further revealed differences among subsite transect points with depth-averaged data (Figure 3; Tables S6–S8 in Supporting Information S1), and these data show that Marsh end members had significantly higher soil C, N, and S than other transect locations across most sites. Soil Ca and Zn only varied with transect point with both increasing in concentration from upland to lowland. At the forested sites, there were no significant differences in % clay or soil Mn, K, or Mg.

Table 3
Two-Way MANOVA Results at the Three Agriculture Sites Combined

Variable	Transect point	Depth	Transect point*depth
DOC	0.22	0.87	0.43
DIC	*0.004*	0.38	0.65
TN	*<0.0001*	0.97	0.16
Sulfide	*0.01*	0.40	0.85
Fe^{2+}	*<0.0001*	0.65	0.49
E_H	*0.002*	0.66	0.82
pH	*<0.0001*	0.96	0.93
Salinity	*0.007*	0.99	0.99
SUVA$_{254}$	0.07	0.99	0.88
$E_2:E_3$	*0.002*	0.81	0.38
S_r	*0.04*	0.34	0.90

Note. The values indicate p-values with significance ($p < 0.05$) indicated by italics. Model output is presented for each soil chemical variable, separated by transect point, depth, and their interaction.

3.2. Porewater Analyses and Depth Profiles

3.2.1. Agricultural Transects

Transect point, rather than depth, were significant drivers of differences in porewater chemistry at the agricultural transects (Table 3; Table S9 in Supporting Information S1). Thus, we conducted follow-up ANOVAs with Tukey HSD analyses to determine specific differences among subsite transect locations (Figure 4; Tables S10–S12 in Supporting Information S1). The VA-agricultural transect was dry during sampling, and thus porewater could not be extracted; therefore, the marsh transect points (i.e., Phragmites and Spartina) are the only transect locations for the VAagricultural site. DIC, TN, pH, and sulfide tended to be higher at the marsh end member (i.e., Spartina) compared to all other transect locations, while salinity tended to increase from ~1 ppt at Healthy Agriculture to ~10 ppt at Spartina. Porewater E_H decreased from Healthy Agriculture to Spartina, whereas Fe^{2+} was generally highest in Transition. The carbon molecular weight tended to be higher (i.e., lower $E_2:E_3$ and S_r) at the marsh end members and lower in the upland locations. The full depth profiles are provided in Figure S3 in Supporting Information S1.

3.2.2. Forested Transects

Similar to the agricultural transects, porewater chemical differences at the forested transects were mainly driven by transect point and not depth (Table 4; Table S13 in Supporting Information S1). Thus, we conducted follow-up ANOVAs with Tukey HSD analyses to determine specific differences among subsite transect points (Figure 5; Tables S14–S16 in Supporting Information S1). Similar to the agricultural transects, the marsh end member (i.e., Marsh) generally had the highest levels of sulfide. Porewater E_H, pH, and salinity followed similar trends to the agricultural transects, where pH and salinity increased toward the marsh end member, while E_H decreased. Fe^{2+} followed similar trends to the agricultural transects, where transitional locations (Mid Forest and Low Forest) tended to have higher concentrations. Trends with depth were less apparent (Figure S4 in Supporting Information S1).

3.3. Relationships Between Variables

Principal components analysis (PCA) was used to simultaneously visualize relationships between variables at all 6 transects combined (Figure 6). These results indicated several variables that trend well together across the solid-phase soil and porewater data sets. An obvious grouping of variables includes DIC, sulfide, soil C, soil S, Ca, salinity, and pH. Because these variables trend in a similar direction, they have an overall positive relationship with one another. Porewater E_H trended in the opposite direction, indicating that E_H generally trends negatively with DIC, sulfide, soil C, soil S. Fe^{2+} and total Fe trend positively together which is likely related to most of the Fe in the porewater being in the reduced form. The sand:silt ratio trends in the opposite direction of the Fe variables, as does Si. DOC and Abs$_{254}$ trend in the same direction because DOC absorbs light ~254 nm. S_r trends in the opposite direction of Abs$_{254}$. This was likely because Abs$_{254}$ tends to increase with aromatic CDOM while S_r increases with aliphatic CDOM.

3.4. Normal Mixture Clusters Analysis

Cluster analysis using the normal mixtures approach was conducted and informed based on the MANOVA, ANOVA and PCA results. After finding the best-fitting model (i.e., Bayesian Information Criterion value) using the least number of variables possible, there are three main clusters of data with several key variables (Figure 7). Transect point locations are also indicated by different shapes within clusters. The three main clusters seem to generally represent lowlands (Cluster 1), upland forested sites (Cluster 2), and upland agricultural sites (Cluster 3), but Cluster 2 and 3 overlap where each is undergoing a transition to marsh (Figure 7). Associated mean cluster values for variables (Table 5) reveals thatCluster 1 contains the highest EC, pH, sulfide, soil C, soil S and lowest E_H and $E_2:E_3$ (inverse to molecular weight), which are characteristics of reducing marsh soils. This was confirmed because most Cluster 1 data points are associated with the Marsh (forest transects) and Spartina (agricultural transects) points. Cluster 2 has lower EC, pH, sulfide, soil C, soil S, a higher E_H and $E_2:E_3$ and the highest DOC

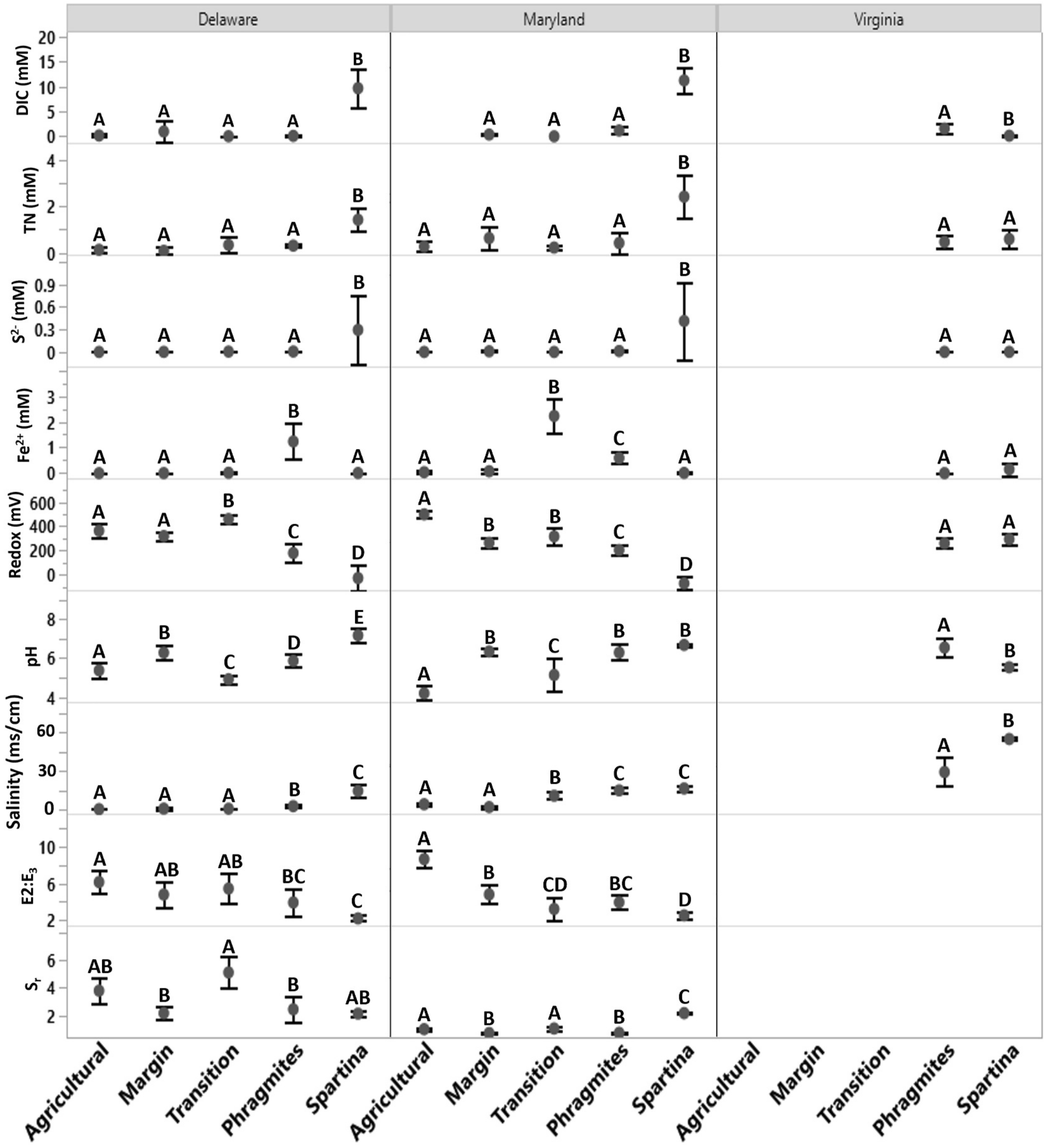

Figure 4. Depth-averaged (±standard error) of measured porewater parameters and their corresponding post-hoc ANOVA analysis at the three agricultural transects. Values within each state with the same letter are not significantly different. The full depth profiles are reported in Figure S3 in Supporting Information S1.

and Fe^{2+} which was characteristic of forested transect points. Cluster 3 has the lowest EC, sulfide, pH, soil C, soil S and the highest E_H and E_2:E_3 was characteristic of upland Agricultural transect points.

4. Discussion

4.1. Biogeochemical Fingerprint Along Salinity Gradient

We hypothesized that transect points would have a unique biogeochemical fingerprint, indicative of the extent of inundation with saltwater. Recent work at these sites observed differences in hydrology and elevation along the transects (Pratt, McQuiggan, et al., 2025, Pratt, Guimond, et al., 2025). We observed statistically significant differences in biogeochemistry across the transects, and the cluster analysis shows that, when all 6 sites are combined, three unique groupings of data exist. These three clusters seem to represent lowland (Cluster 1), upland forest (Cluster 2), and upland agricultural soils (Cluster 3) with Cluster 2 and 3 overlap consisting of many of the

Table 4
Two-Way MANOVA Results at the Three Forest Sites Combined

Variable	Transect point	Depth	Transect point*depth
DOC	*0.02*	0.40	0.50
TN	*0.01*	0.66	0.54
Sulfide	*<0.0001*	0.08	*0.03*
Fe^{2+}	*0.01*	0.99	0.99
E_H	*<0.0001*	0.35	0.62
pH	*<0.0001*	0.94	0.99
Salinity	*0.04*	0.99	0.99
SUVA254	0.66	0.99	0.56
E_2:E_3	0.24	0.82	0.63
S_r	0.59	0.55	0.82

Note. The values indicate p-values with significance ($p < 0.05$) indicated by italics. Model output is presented for each soil chemical variable, separated by transect point, depth, and their interaction.

transitional transect locations for both land uses. These findings support our first hypothesis and further suggest that as uplands transition to marsh, they become biogeochemically similar regardless of initial land use. Lowland (Cluster 1) soil chemistry was characterized as salty, anaerobic, and neutral pH with elevated levels of porewater sulfide and soil S, typical of marsh biogeochemistry (Fettrow et al., 2024; Seyfferth et al., 2020) and simulated SLR laboratory-based experiments (Capooci et al., 2019; Fettrow et al., 2023; Northrup et al., 2018). Low levels of Fe(II) are likely due to sulfide reacting with mobilized Fe(II) and forming FeS minerals, a mechanism which has been seen at other sites across the mid-Atlantic region (Seyfferth et al., 2020). Salty, low-oxygen, and sulfidic soils enable marsh grasses to outcompete upland species not adapted to these soil conditions (Berness et al., 1992). Low oxygen and a less energetically favorable metabolic pathway allow these types of lowland soils to accumulate higher amounts of soil C (Van de Broek et al., 2016).

Land use appeared to distinguish upland biogeochemistry. The upland forest sites (Cluster 2) were categorized as intermediately salty, with a higher soil E_H than the lowland areas. These upland forests had the highest porewater Fe^{2+}and mean porewater DOC concentrations, which were likely due to reduction of DOC-bearing Fe oxides dominating these transect point locations. Fe oxides are known to control the transport of DOC in coastal ecosystems, where increased inundation and Fe reduction leads to higher mobility and lateral export of DOC (Fettrow et al., 2023). In contrast to the upland forested sites, the upland agricultural sites (Cluster 3) were the least salty, had the highest E_H, and were the most acidic. This upland cluster had the lowest mean DOC concentration, likely linked to low porewater DOC in many agricultural fields, increased sorption from minerals such as Fe oxides, and higher microbial turnover rates due to higher soil E_H. Increased rates of upland DOC turnover were supported by a higher mean E_2:E_3, which indicates the upland cluster has lower molecular weight DOC. Differences in the E_2:E_3 and overall molecular weight of DOC can result from variable biodegradation (Allain et al., 2024) with lower molecular weights often broken down more quickly, particularly under aerobic conditions. In addition, mineral surfaces could have enriched low molecular weight DOC in the porewater due to preferential adsorption of high molecular weight compounds (Kalbitz et al., 2005). While many of the upland forest and upland agricultural sites are distinctly in cluster 2 and 3, respectively, they seem to converge where each is transitioning to lowland and graphically where clusters 2 and 3 overlap. This suggests that while land-use leads to distinct biogeochemistry, as these uplands transition to lowlands, they become biogeochemically similar and eventually indistinguishable (Cluster 1). We acknowledge that this sampling effort is a point-in-time snapshot and represents "baseline" conditions for these sites that future studies can compare to. Other concurrent monitoring efforts include groundwater dynamics (Pratt, McQuiggan, et al., 2025, Pratt, Guimond, et al., 2025), which are critical to assess how often inundation occurs and the pace of saltwater intrusion.

4.2. Site-Specific Dynamics in Biogeochemistry

We also hypothesized that as marshes migrate upland, soil C concentration increases due to lower E_H and slower microbial decomposition. While this is generally supported by our data, there were site-specific dynamics that must be highlighted. At the VA-forested site, we found evidence of a concept we refer to here as the "thin marsh layer" (Figure 8; Table 6). Soils in the top half of the Marsh core had higher soil C and porewater sulfide, lower E_H, and a lower sand:silt ratio than deeper in the profile, contrasting with the other marsh endmembers that were more uniformly rich in carbon and reducing with depth. Typically, soil C can build up in marsh soils due to slowed degradation caused by either high oxygen demand outpacing the supply (Lacroix et al., 2024) or/and a shift in the microbial community to anaerobic metabolisms that degrade carbon more slowly (Seyfferth et al., 2020). At the VA-forest Marsh, soil C drastically decreased from ∼26% near the surface to less than 1% at ∼48 cm. This coincided with an increase in porewater E_H from −70 near the surface to 157–203 mV at depth and a ∼5% increase in the proportion of sand (Table 6). These deeper soils at the VA forest marsh are more characteristic of the upland forest soils (i.e., low soil C, oxygenated, high sand:silt ratio) than the other marsh soils. We suspect that the marsh layer was thin near the migration front, while more established marshes farther from the forest-marsh

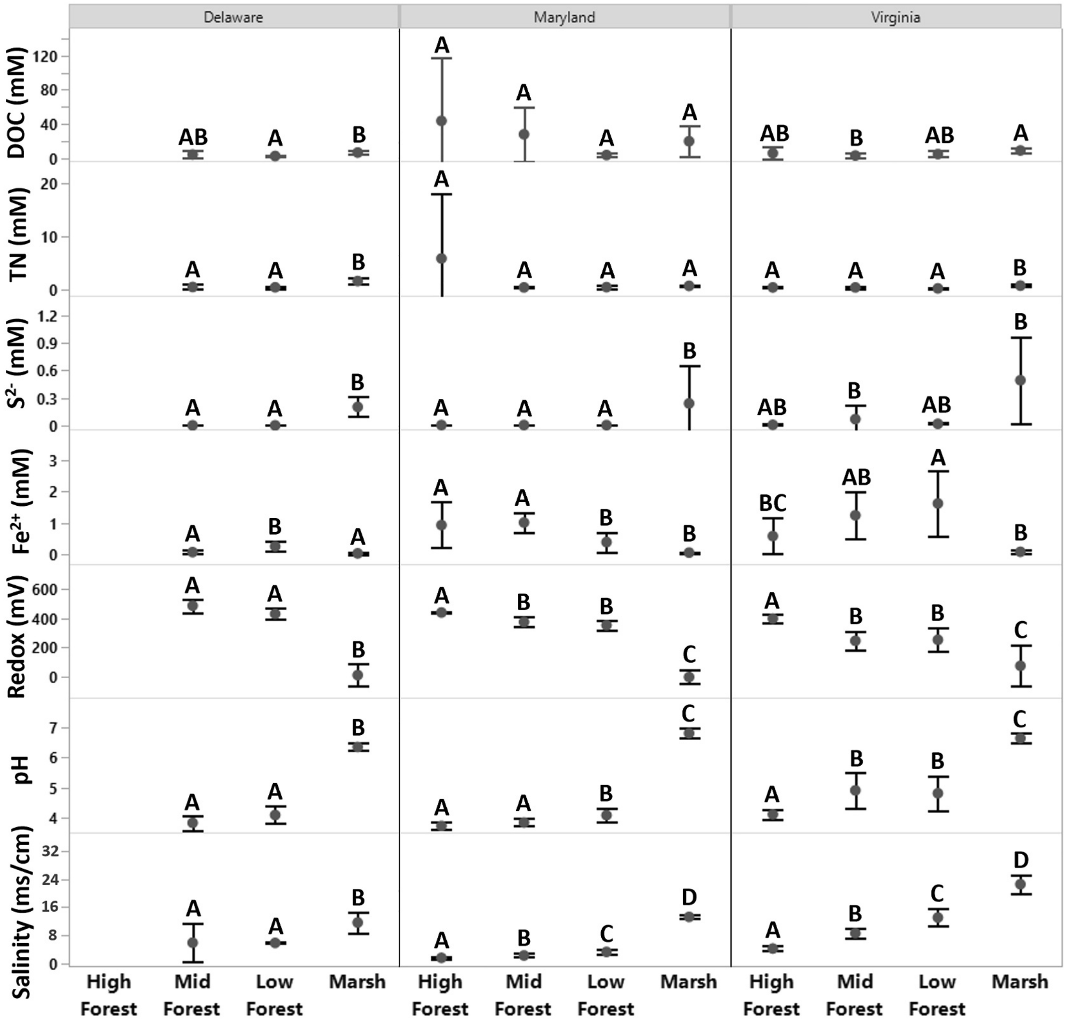

Figure 5. Depth-averaged (±standard error) of measured porewater parameters and their corresponding post-hoc ANOVA analysis at the three forested transects. Values within each state with the same letter are not significantly different. The full depth profiles are reported in Figure S4 in Supporting Information S1.

ecotone have thicker marsh soils. This site-specific dynamic may be caused by lower elevation and a low slope between lowland and upland observed at VA-forest (Pratt, McQuiggan, et al., 2025, Pratt, Guimond, et al., 2025). A wedge-shaped increasing thickness of marsh soils with increasing distance from the forest margin is consistent with stratigraphic cross-sections throughout the Chesapeake Bay and is typically interpreted as reflecting an increasing duration of marsh development (Smith & Kirwan, 2021; Van Allen et al., 2021). In addition, the spike in porewater E_H with depth may be a result of oxygenated upland groundwater flowing into deeper sandier and more porous sediments (Guimond and Michael, 2025), increasing C mineralization rates below the thin marsh layer, and decreasing soil C concentration at depth. It remains unknown what percentage of the surficial organic-rich material is inherited from the terrestrial soils (Smith & Kirwan, 2021). Having both marsh soils and buried forest soils in the same soil core has implications for C stock estimates in migrating marsh areas. If the entire 84 cm soil C at the VA-forest site is considered in the estimate, the average soil C would be 5.24%, but this would include the soil C that has been "diluted" by the buried sandier soil that had lower soil C and higher sand starting at ~36–48 cm depth If only the top half of the core is considered, this average soil C value increases to 8.6%, an increase of 65%. Therefore, long-term soil C estimates may be underestimated in recently migrated marsh if the buried upland soil underneath is included in the soil C estimate. Our recommendation would be to use layers of "marsh-like" soil, rather than include potential buried upland soils, in marsh accretion and migration C

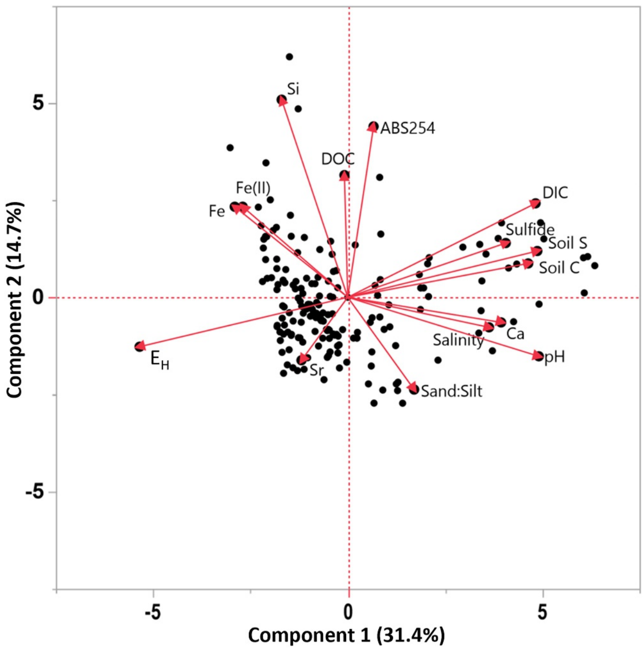

Figure 6. Principal components analysis results showing the relationships among select porewater and soil variables among all 6 sites combined.

accumulation estimates, with the understanding that marsh-like soils will increase in depth as the marsh ages. While the thin marsh layer will be important to consider when conducting blue C assessments near transitional forests and farms, we suspect this process to be less important in areas with a higher slope between upland and lowland and a slower marsh migration rate, such as our MD and DE sites, as we saw less clear evidence for a thin marsh layer at these locations. We therefore recommend that soil cores in newly developed marsh should be taken to a depth corresponding with typical marsh conditions (i.e., reducing conditions, high soil C, high silt and clay etc.).

We also found evidence for the removal of DOC due to variable E_H conditions, particularly as it relates to Fe oxide reduction and dissolution. For example, levels of both DOC and Fe^{2+} were much higher at MD-forest compared to DE-forest. At the Mid Forest transect point in the MDforest, DOC and Fe^{2+} formed a significant and positive correlation ($R^2 = 0.86$, $p = 0.01$), indicative of possible mobilization of DOC due to the reductive dissolution of C-bearing Fe oxides. This phenomenon was previously confirmed in coastal soils in a mesocosm experiment (Fettrow et al., 2023). This is also evident at VA-forest at the Low and Mid Forest transect points, where reducing conditions persist with depth, and DOC decreases, showing removal of DOC as sorbents such as Fe oxides are reduced and lose their binding affinity for C (Nierop et al., 2002; Riedel et al., 2013).

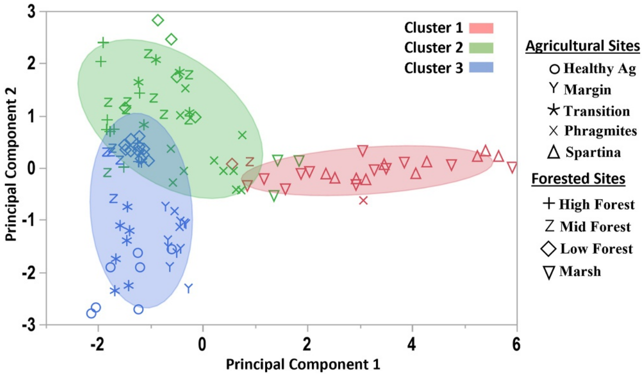

Figure 7. Normal mixture clusters analysis showing three main groupings of data.

Furthermore, there was a general trend of increasing salinity at both forested and agricultural transects in the order DE, MD, VA, a decreasing E_H in the order DE, MD, VA, and an increasing level of Fe^{2+} in the order DE, MD, VA. This is also the case for S_r, in which MD and VA forest have a significantly higher S_r (i.e., lower molecular weight DOC) across all transect points compared to DE with a lower S_r (i.e., higher molecular weight DOC). This indicates that as sites become saltier and more "marine-like" (i.e., Northern to Southern Delmarva Peninsula), DOC sources and processing changes. While higher molecular weight DOC is generally of terrestrial origin, lower molecular weight compounds could be from degraded terrestrial organic matter or directly from coastal aquatic inputs such as algae and microbial-derived DOC. In addition, soil C may become more susceptible to removal and transport via Fe reduction or destabilized (Fettrow et al., 2023; Pinsonneault

Table 5
Mean Values (± Standard Deviation) of the Variables Used to Construct Principal Components in Each Cluster

Cluster #	Salinity	Redox	pH	Fe (II)	Sulfide	DOC	Soil C	Soil S	E_2:E_3
1	9.5 (±4.3)	−1.6 (±79)	6.6 (±0.4)	0.05 (±0.05)	0.4 (±0.3)	7.5 (±3.4)	14.5 (±8.1)	1.6 (±0.7)	2.7 (±0.5)
2	5.4 (±5.7)	274.7 (±102)	5.0 (±0.9)	1.3 (±1.2)	0.01 (±0.01)	16.0 (±26.3)	1.3 (±1.4)	0.3 (±0.1)	2.9 (±0.9)
3	1.6 (±2.2)	375.6 (±4)	4.9 (±0.8)	0.12 (±0.1)	0.005 (±0.03)	2.7 (±3.2)	0.8 (±0.8)	0.2 (±0.1)	4.1 (±1.8)

et al., 2020). Differences in hydrology between sites likely drive these differences in soil chemistry seen across the Delmarva Peninsula (Pratt, McQuiggan, et al., 2025, Pratt, Guimond, et al., 2025).

4.3. Implications for Coastal Forests and Farms

The transition of coastal forests and farms into migrating marsh is a critical dynamic caused by SLR that has many future implications. New evidence suggests that while some marsh areas are lost to open water conversion, marsh expansion into forests has led to an overall increase in marsh area by 4% since 1984 in the mid-Atlantic region, where our study took place (Chen & Kirwan, 2023). Landward expansion of marshes allows coastal wetlands to escape drowning from SLR (Borchert et al., 2018), but marsh survival is at the expense of coastal forests and other types of coastal wetlands (Osland et al., 2022). Coastal forests provide many ecosystem services such as timber, recreation, and biodiverse habitat for coastal species (Burkhard et al., 2012). Marshes commonly migrate into freshwater forested wetlands, which provide many of the same services as marshes (Osland et al., 2022). As forests retreat and marshes migrate, forest ecosystem services would be replaced by coastal wetland ecosystem services. Coastal wetlands provide storm surge and flood protection to coastal communities, break down anthropogenic contaminants before reaching the ocean, provide habitat for coastal wildlife and fisheries (Barbier et al., 2011) and, as previously shown, store higher amounts of C in soils than forests.

Agricultural operations on the coast are highly susceptible to the negative impacts of SLR and storm surge. Most monocrops grown in the US cannot tolerate a soil salinity of higher than ~4 mS/cm (Tanji & Kielen, 2002). We measured salinities higher than 4 mS/cm at or nearby many of our agriculture sites. For example, at the MD-agricultural transect, the porewater salinity in the Healthy Agriculture transect point was on average 6 mS/cm across the 84 cm core. It has become common for land managers and farmers to abandon fields along the coast due to decreases in yield caused by the effects of salinization (White & Kaplan, 2017), allowing marshes to migrate into the abandoned fields (Gedan & Fernández-Pascual, 2019). While marsh migration can cause the loss of agricultural areas, bordering marsh can make farm fields more resilient to storm surge and SLR. This is because

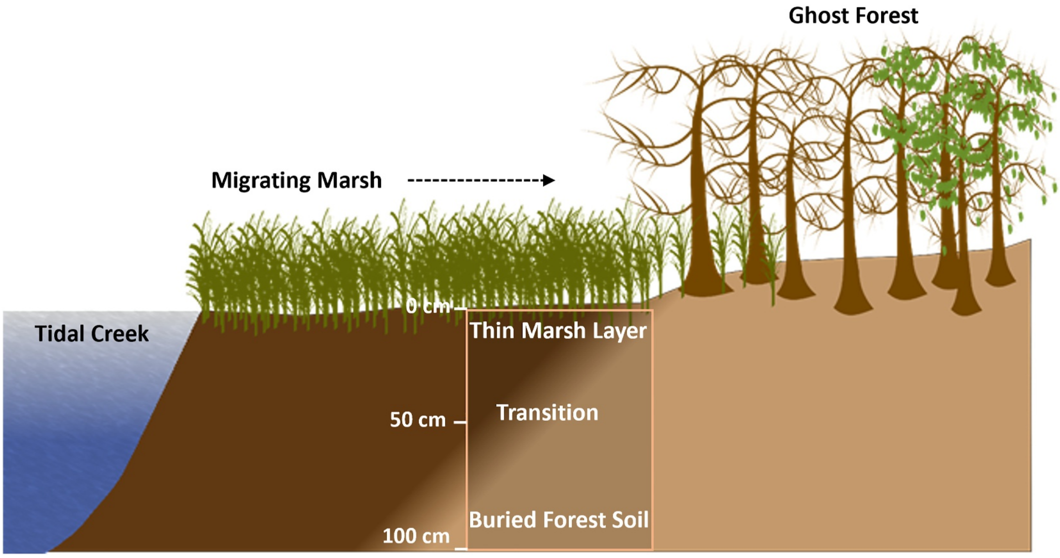

Figure 8. Conceptual diagram of the "thin marsh layer" concept.

marshes can slow the pace of the salt front in groundwater while also protecting fields against storm surge (Guimond & Michael, 2021). Preserving agricultural operations along the coast can be managed by protecting, restoring, and creating natural ecosystems that mitigate and buffer the negative effects of climate change.

Table 6
Marsh Soil Core Data at VA-Forest Site

Depth (cm)	Redox (mV)	Sand (%)	Silt (%)	Sand:Silt ratio	Soil C (%)
0–12	−80	N/A	N/A	N/A	26
12–24	−88	50	44	1.1	4
24–36	−70	49	44	1.1	3
36–48	157	52	40	1.3	2
48–60	191	55	38	1.5	1
60–72	202	54	39	1.4	1
72–84	203	55	39	1.4	1

Note. This data supports the observation of a “thin marsh layer.”

5. Conclusion

Our results indicate that marsh migration into forests and farms will significantly alter coastal soil C sequestration and biogeochemistry and subsequently change ecosystem functioning and dynamics. Marsh migration could significantly increase soil C concentrations in newly migrated marsh area by 4–50x compared to upland soils, particularly in agricultural fields that have low soil C. Migrating marsh areas can have a thin marsh layer with buried forest soil underneath, depending on the age of the marsh, as well as the slope gradient between upland and lowland. The thin marsh layer near transitional forests and farms will be important to consider when conducting C estimates with marsh migration because typical marsh soils (i.e., high soil C, low E_H) may only represent a fraction of the entire soil profile, with typical upland soils (i.e., low soil C, high E_H) underneath. If buried upland soils are incorporated into these C estimates, there may be a significant underestimation of marsh soil C storage. In addition, unique biogeochemistry exists in the upland, transition and lowland areas, indicative of the extent of inundation with saltwater. These findings have important implications for identifying rapidly changing ecosystem function along the coastline with a changing climate. Future studies should incorporate assessments of trace soil gas fluxes to understand the global warming or cooling potential of the migrating marsh.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Fettrow (2023). CZNCoastal_SoilCoreData.xlsx. figshare. Dataset. https://doi.org/10.6084/m9.figshare.22780112.v1.

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