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Key Points:

- Combining geospatial analysis and hydrodynamic modeling reveals spatial variability in marsh degradation-elevation relationship
- Variability depends on hydrological setting and salinity regime, with hydrology exerting the stronger influence
- At a given elevation, marsh degradation generally decreases across hydrological regions and salinity regimes from offshore to inland

Supporting Information:

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

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Spatial Heterogeneity of Salt Marsh Vulnerability to Sea-Level Rise: Dual Controls of Hydrological Setting and Salinity Regime

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Abstract Salt marsh vulnerability to sea-level rise (SLR) is typically assessed using point measurements of vertical accretion, neglecting three-dimensionality of geomorphic evolution and spatial variability. Recent studies suggest links between vertical and horizontal vulnerability, with differences between oligohaline and polyhaline marshes, yet these relationships remain untested in estuary-marsh systems. Here we combine geospatial analysis with hydrodynamic modeling to evaluate how unvegetated/vegetated marsh ratio (UVVR), a metric of marsh degradation, relates to elevation across hydrological regions and salinity regimes in the Albemarle-Pamlico Estuarine System, the largest lagoonal estuary in U.S. We show that at given normalized elevation, UVVR decreases across hydrological regions and salinity regimes from offshore to inland. UVVR-elevation relationship varies systematically with both hydrological setting and salinity regime, with hydrology exerting stronger influence. These findings challenge the assumption of a universal marsh deterioration trajectory and underscore the need to account for spatial heterogeneity when predicting responses to SLR.

Plain Language Summary Salt marshes are vital coastal ecosystems that protect shorelines, reduce flooding, and support wildlife, but they are vulnerable to sea-level rise (SLR). Most assessments of marsh vulnerability focus on how quickly they build upward, but this approach overlooks horizontal loss and how vulnerability differs across landscapes. Recent studies suggest that marshes exposed to waters of different salinity may respond differently to SLR, yet this has not been tested in a large estuary spanning broad salinity gradients. We address this gap in the Albemarle-Pamlico Estuarine System, the largest coastal lagoon in the United States. Using computer models and satellite imagery, we study how marsh vulnerability changes across regions with different salinity and dynamic conditions. We find that marshes do not respond uniformly: even at the same normalized elevation, those closer to inlets are more vulnerable to SLR than those farther inland. This finding highlights the need to consider spatial variability when predicting marsh conditions.

1. Introduction

Salt marshes provide important ecosystem services, including flood mitigation, carbon sequestration, and nutrient transformation, but they are vulnerable to rising sea levels (FitzGerald et al., 2008; Ganju et al., 2017; Kirwan & Megonigal, 2013; Valentine et al., 2023). For decades, research on marsh vulnerability has focused on vertical accretion, asking whether marshes can build elevation faster than sea-level rise (SLR). Vertical accretion depends on both inorganic sediment deposition and organic matter production, processes strongly tied to elevation (Fagherazzi et al., 2012). This marsh-elevation relationship (e.g., Morris et al., 2002; Silvestri et al., 2005) reveals mechanisms of biophysical interactions between marsh ecology and geomorphology, and forms the basis of ecogeomorphic models (e.g., D'Alpaos et al., 2007; Fagherazzi et al., 2012; Kirwan & Murray, 2007; Mariotti, 2018). However, much of this understanding is derived from individual systems under a single hydrological setting and salinity regime (e.g., Belliard et al., 2017; Morris et al., 2002). Subsequent applications have often assumed universal applicability across salinity gradients and hydrological settings (e.g., Belliard et al., 2015; Mariotti & Fagherazzi, 2010). Yet both ecological dynamics and geomorphic development are strongly conditioned by hydrology and salinity (Bird, 1994; D'Alpaos, 2011; Lauzon et al., 2018; Odum, 1988). Thus, it is reasonable to expect that the marsh-elevation relationship is not universal, but context-dependent.

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Assessing marshes solely through vertical accretion provides limited insight into their three-dimensional condition (Ganju et al., 2020). For example, marshes may continue to build vertically while undergoing lateral erosion and internal open-water expansion (Stagg et al., 2024). Work by Ganju et al. (2017, 2020) and Ganju, Ackerman, and Defne (2024) demonstrated that the unvegetated-vegetated marsh ratio (UVVR), a measure of marsh horizontal degradation, is related to marsh vertical vulnerability. UVVR is linked to marsh sediment budgets and can infer sediment-based trajectories of microtidal marshes (Ganju et al., 2017). Moreover, UVVR serves as a proxy for potential runaway open-water expansion, which can be incurred by rapid SLR and/or sediment deficits (Mariotti, 2020). Thus, UVVR can serve as an index for evaluating marsh vulnerability from a three-dimensional perspective. However, Ganju, Defne, et al. (2024) noted variability in the UVVR-elevation relationship based on salinity regime: for the same normalized elevation, oligohaline marshes across the southeast U.S. have markedly less internal deterioration, indicating the potential influence of salinity on marsh vulnerability in addition to elevation. However, that analysis relied on generalized characterizations of tidal elevation and salinity to compare sites, and the potential mechanisms for the variability were not identified.

In this study, we combine a remote sensing data set of UVVR and elevation with process-based hydrodynamic modeling to evaluate marsh vulnerability in the Albemarle-Pamlico Estuarine System, U.S. (APES). Our goal is to understand the spatial heterogeneity of marsh vulnerability and its controlling factors. We use UVVR as a metric of horizontal degradation and an index of vulnerability. We hypothesize that (a) UVVR is related to not only elevation, but also hydrological setting and salinity regime and (b) UVVR-elevation relationships vary across hydrological settings and salinity regimes. We test these hypotheses by analyzing UVVR and UVVR-elevation relationships across different hydrological regions and salinity regimes in the APES.

2. Methods

2.1. Site Descriptions

The APES is located on the northeast coast of North Carolina, U.S. (Figure 1a). With a surface area of 7,800 km², it is the largest coastal lagoon in the U.S. Separated from the Atlantic Ocean by a chain of barrier islands, estuary–ocean exchange occurs primarily through Ocracoke, Hatteras, and Oregon Inlets. Except near the inlets, tidal range in the APES is less than 0.1 m (Wells & Kim, 1989). The APES includes two major sub-sounds: Albemarle Sound and Pamlico Sound, with the Pamlico and Neuse Estuaries located upstream of Pamlico Sound.

We focus on five hydrological regions with distinct hydrologic and hydrodynamic contexts: Tributary Estuary, Sound Peninsula, Barrier Island, Currituck Sound, and Core Sound (Figures 1b and 1d). Hydrological regions were delineated following the coastal watershed concept, considering both terrestrial hydrologic characteristics (e.g., topography, land surface, soils) and marine hydrodynamic influences (e.g., tidal forcing, wave exposure, coastal circulation; Text S1 and Figure S1 in Supporting Information S1). In addition, the APES exhibits a pronounced horizontal salinity gradient (Figure 1c). Following Odum (1988), marshes were classified as oligohaline (<5 psu), mesohaline (5–18 psu), or polyhaline (>18 psu) based on adjacent water salinity.

2.2. Geospatial Analysis

A combination of the National Wetland Inventory (NWI) classification of estuarine intertidal wetlands and hydrologic delineation from the high-resolution National Hydrography Data set (NHDPlus HR) was used to define marsh units (Figure S2 in Supporting Information S1). Specifically, estuarine type wetlands from the NWI were first selected to establish the outer bounds of wetlands, and NHDPlus HR catchments located within these bounds were identified. From these, we retained only catchments adjacent to NWI polygons classified as deepwater or unconsolidated shoreline. Contiguous catchments were then dissolved to form single marsh units. Following Ganju et al. (2020), our analysis was limited to units larger than 5,000 m². This resulted in a total of 3,804 marsh units in the APES, subdivided as 463, 786, 286, 649, and 1,620 units in Core Sound, Currituck Sound, Sound Peninsula, Barrier Island, and Tributary Estuary, respectively. Following Defne et al. (2020), marsh units were then used to aggregate grid-based elevation and vegetation data sets to derive marsh unit elevation and UVVR. Elevation from the CoNED DEM (Thatcher et al., 2016) was downsampled to 30 m and averaged within each unit. Vegetation fraction (percentage of vegetated area, Figure S3 in Supporting Information S1) was derived from the 2022 Landsat-based data set (Couvillion et al., 2024) at 30 m resolution. UVVR was then calculated from vegetated fraction following Equation S1 in Supporting Information S1.

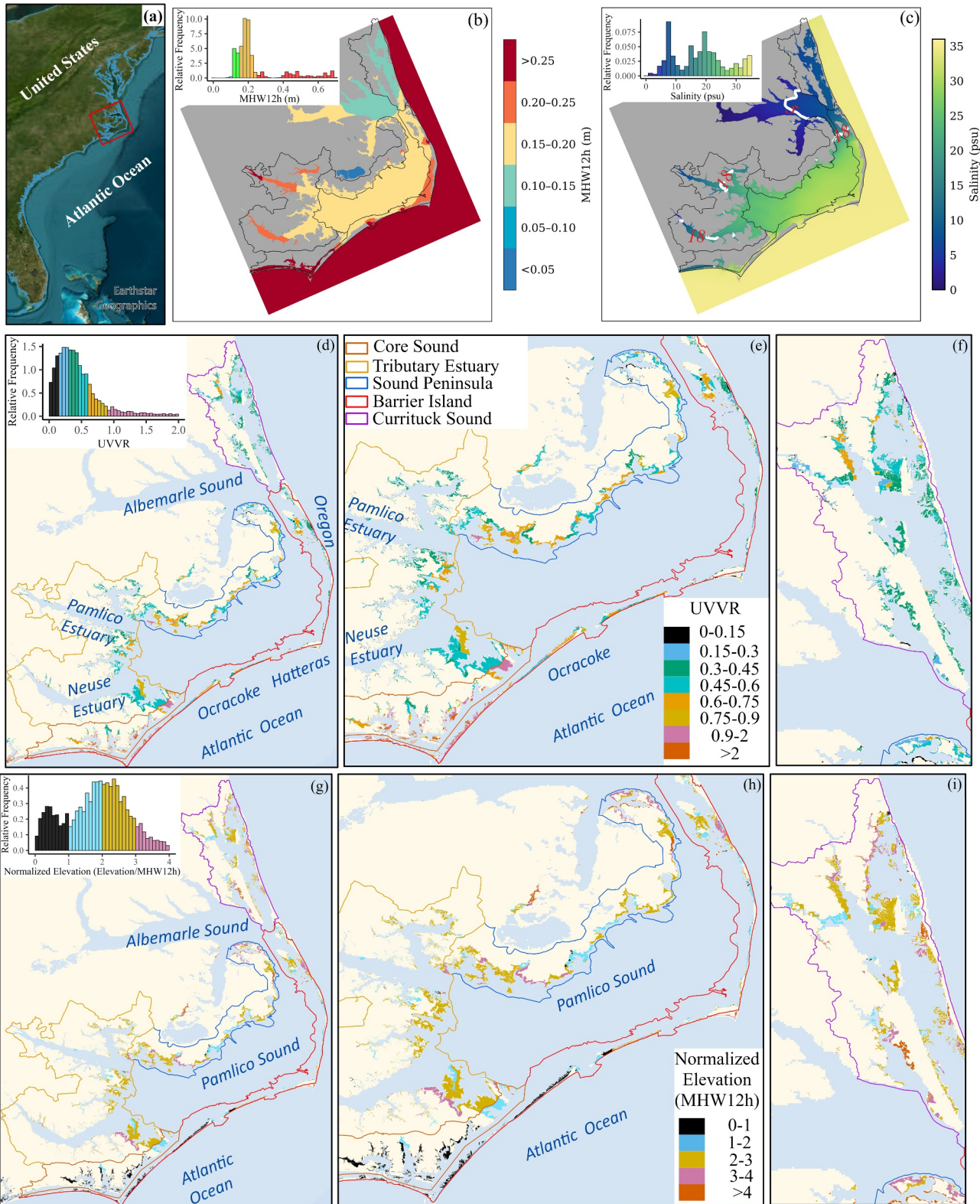


Figure 1. Albemarle-Pamlico Estuarine System (APES). (a) Location on the U.S. East Coast; red box indicates the numerical model domain. (b) Marsh unit annual mean MHW_{12h} (mean high water at the semidiurnal frequency); inset shows histogram. (c) Same as (b), but for annual mean salinity. (d–f) Marsh unit unvegetated-vegetated marsh ratio (UVVR) across the APES and zoomed into selected regions for improved visibility; inset shows histogram. (g–i) Same as (d–f), but for normalized elevation (elevation/MHW_{12h}). Hydrological regions are indicated by colored outlines in panels (d–i) and shown in black in panels (b–c) for improved visualization.

2.3. Numerical Model

To obtain spatially explicit salinity and water-level fields, we used a previously developed and calibrated Regional Ocean Modeling System for the APES (Yin, Ralston, et al., 2025), which realistically simulates estuarine hydrodynamics for 2022 with hourly output (Text S3 in Supporting Information S1). Model results were used to derive annual mean salinity and a characteristic high-water level across the APES to represent background salinity and inundation conditions relevant to long-term marsh exposure and vulnerability. The model was not used to examine short-term or event-scale processes in this study.

Using simulated hourly water levels, we calculated mean high water at the semidiurnal frequency (MHW_{12h} , Figure 1b) by averaging the maximum water level in successive 12-hr windows over the year. We adopted MHW_{12h} rather than tidal amplitude because the APES is weakly tidal and inundation is primarily driven by the dominant semidiurnal seiche, with additional contributions from wind and river discharge (Lagomasino et al., 2013; Luettich et al., 2002; Yin, Harris, & Warner, 2025). Marsh elevation was normalized by MHW_{12h} to quantify relative position within the semidiurnal inundation frame, which governs inundation frequency, duration, and sedimentation processes (Holmquist & Windham-Myers, 2022; Mariotti, 2020). For each marsh unit, MHW_{12h} and normalized elevation were assigned using a nearest-neighbor approach based on the model grid cell closest to the unit centroid.

Spatially explicit mean salinity was calculated from simulated hourly surface salinity (Figure 1c), and marsh unit salinity was assigned using the same nearest-neighbor approach. Previous studies in the APES indicate strong agreement between open-water salinity and marsh soil porewater salinity, supporting its use as a proxy for marsh salinity exposure (Horton & Culver, 2008; Kemp, Horton, Corbett, et al., 2009).

2.4. Statistical Analysis

We used generalized additive models (GAMs, Hastie, 2017) to evaluate whether UVVR depends on hydrological setting and salinity regime in addition to elevation, and to quantify their relative influence on the UVVR-elevation relationship.

To address the first objective, we fit four systemwide GAMs: elevation only ($\hat{f}(E)$), elevation plus hydrological region ($\hat{f}(E + H)$), elevation plus salinity regime ($\hat{f}(E + S)$), and elevation plus both factors ($\hat{f}(E + S + H)$), where E , H , and S denote normalized elevation, hydrological region, and salinity regime, respectively. Model performance was compared using Akaike's Information Criterion (AIC), with reductions in AIC indicating added explanatory power beyond elevation alone, and thus evidence for an influence of hydrological setting and/or salinity regime on UVVR.

To address the second objective, we applied a GAM-based curve-deviation (Δ) approach. A systemwide GAM $\hat{f}(E)$ was fit using all observations, and group-specific GAMs $\hat{g}_k(E)$ were fit for each hydrological region and salinity regime. Δ_k was calculated as the mean difference between $\hat{f}(E)$ and $\hat{g}_k(E)$ evaluated over n equally spaced normalized elevation values spanning the marsh concentration zone ($E \in [0, 4]$, Equations S2 and S3 in Supporting Information S1). Overall divergence (Δ) was defined as the mean Δ_k across groups (Equation S4 in Supporting Information S1), with larger values indicating stronger departures from the systemwide relationship, and thus greater control by the grouping factor (hydrological setting or salinity regime). Sensitivity analyses were performed by varying the number of evaluation points and the definition of the elevation domain. Full equations and implementation details are provided in Text S4 in Supporting Information S1.

3. Results

3.1. Marsh Unit MHW_{12h} , Salinity, and UVVR

Across the APES, MHW_{12h} (Figure 1b) is lowest in Currituck Sound, intermediate in the Sound Peninsula and Tributary Estuary, and highest in Core Sound, whereas marsh elevation (Figure S4 in Supporting Information S1) shows the opposite pattern. Consequently, normalized elevation (elevation/ MHW_{12h} , Figures 1g–1i) is lowest in Core Sound and inlet-adjacent parts of Barrier Island and increases landward, reflecting decreasing inundation duration with distance from inlets.

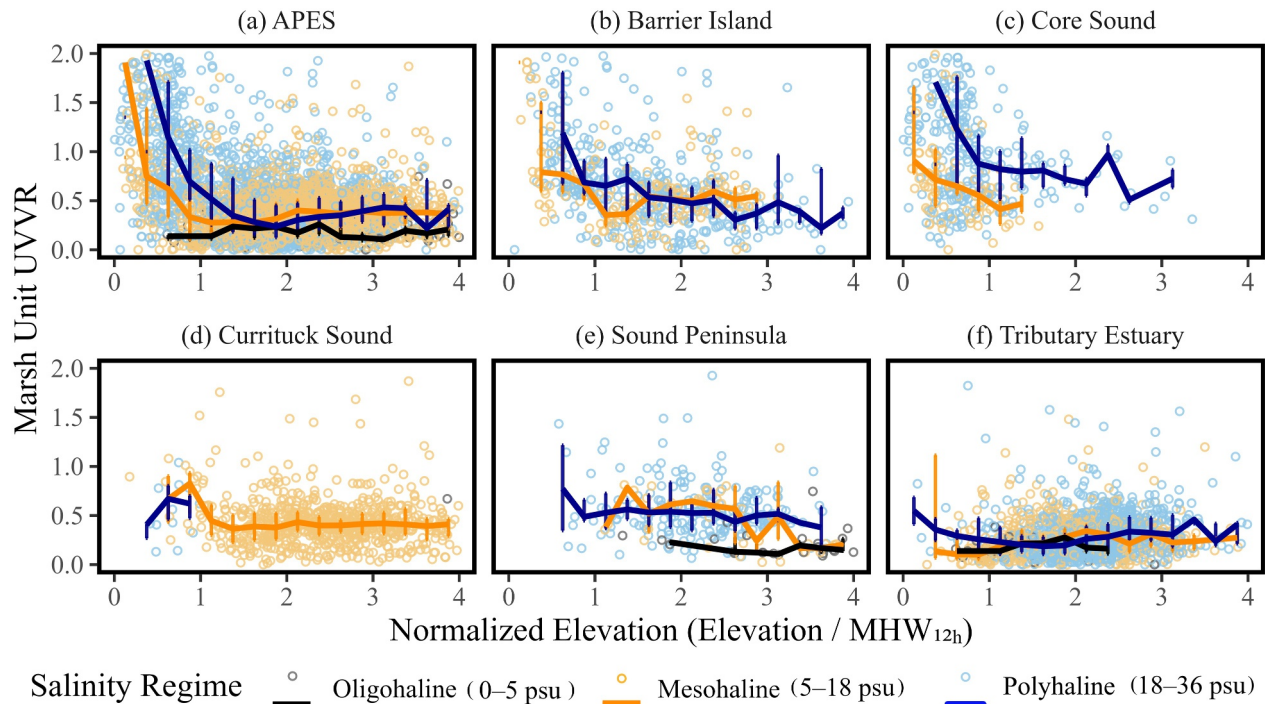


Figure 2. Relationship between unvegetated-vegetated marsh ratio (UVVR) and normalized elevation (Elevation/ MHW_{12h}). Panel (a) shows all marsh units across the Albemarle-Pamlico Estuarine System, while panels (b–f) show the same relationship for: (b) Barrier Island, (c) Core Sound, (d) Currituck Sound, (e) Sound Peninsula, and (f) Tributary Estuary. Each point represents UVVR and normalized elevation of an individual marsh unit, with color indicating the salinity regime in which it falls. In each panel, error bars show the 25th and 75th percentiles of UVVR within each elevation bin, and lines connect binned medians, with line color indicating the salinity regime. The boundaries of hydrological regions are shown in Figure 1d.

Salinity (Figure 1c) exhibits a substantial horizontal gradient, decreasing from Pamlico Sound and Core Sound upstream toward the Tributary Estuary and Currituck Sound. In the APES, oligohaline marshes are largely restricted to the upper reaches of Tributary Estuary and the portion of Sound Peninsula within Albemarle Sound. Polyhaline marsh units are concentrated along Sound Peninsula within Pamlico Sound, in Core Sound, along Barrier Island, and in the most downstream sections of Tributary Estuary. Mesohaline marshes occupy the transitions between these zones.

Marsh unit UVVR (Figures 1d–1f) clusters mainly between 0 and 1.0, with a median of 0.39. About 86% of the marsh area has $UVVR < 1$, indicating that most marshes are more vegetated than unvegetated. Spatially, UVVR values are generally higher in marshes fringing Barrier Island, Sound Peninsula and Core Sound, and decrease moving landward into Tributary Estuary and Currituck Sound, indicating a gradient of deterioration from landward (most intact) to seaward (most degraded).

3.2. UVVR-Elevation Distribution Across the Hydrological Region and Salinity Regime

The UVVR-elevation distribution for the entire APES (Figure 2a) shows a general decline in UVVR with increasing elevation, leveling off above a threshold, consistent with previous studies (e.g., Ganju et al., 2020). However, region-specific analyses reveal distinct patterns that are masked in the systemwide distribution. Marshes along Barrier Island (Figure 2b) follow the overall trend, with UVVR decreasing and stabilizing above normalized elevation ≈ 1.3 , and extend landward to elevations up to four times the MHW_{12h} . In contrast, marshes in other regions cluster primarily within either the intertidal (normalized elevation < 1) or supratidal (normalized elevation > 1) zones. Core Sound marshes (Figure 2c) are mainly distributed within the intertidal zone, while marshes in Currituck Sound (Figure 2d), Sound Peninsula (Figure 2e), and Tributary Estuary (Figure 2f) are primarily found in the supratidal zone.

The dependence of the UVVR-elevation relationship on salinity regime across the APES is illustrated by elevation-binned median UVVR curves. In the intertidal zone, where oligohaline marsh is largely absent

(Figure 2a), the mesohaline curve consistently lies below the polyhaline curve. In the supratidal zone, mesohaline and polyhaline curves converge, while the oligohaline curve remains lower than both. These patterns indicate that lower-salinity marshes tend to be more horizontally intact (i.e., lower UVVR) than higher-salinity marshes, consistent with previous results (Ganju, Defne, et al., 2024), and generally persists within individual hydrological regions (Figures 2b–2f), indicating an additional control of salinity on the UVVR-elevation relationship beyond hydrological setting.

Regarding the dependence of UVVR on hydrological setting and salinity regime, systemwide GAM model comparison shows that normalized elevation alone ($\hat{f}(E)$) provided the weakest fit (AIC = $-1,731.5$). Adding hydrological region alone ($\hat{f}(E + H)$) greatly improves model performance (AIC = $-2,445.3$ and $\Delta\text{AIC} = -714$), while adding salinity alone ($\hat{f}(E + S)$) yields a smaller gain (AIC = $-1,805.1$ and $\Delta\text{AIC} = -74$). The best-fitting model included both hydrological region and salinity ($\hat{f}(E + S + H)$, AIC = $-2,514.9$), outperforming the hydrological region only model ($\hat{f}(E + H)$) by $\Delta\text{AIC} = -70$. These results indicate that UVVR is governed primarily by elevation, with hydrological setting exerting stronger secondary control and salinity providing additional, weaker influence.

The curve-deviation (Δ) values demonstrate stronger variation in the UVVR-elevation relationship across hydrological settings ($\Delta = 0.087$, Equation S4 in Supporting Information S1) than across salinity regimes ($\Delta = 0.076$). With the former approximately 15% larger than the latter, this result suggests the modestly stronger role of hydrological setting in shaping marsh vulnerability. Sensitivity tests using different numbers of evaluation points and alternative definitions of elevation domain consistently yielded larger Δ values when grouped by the hydrological setting than when grouped by salinity regimes, reinforcing this conclusion.

4. Discussion

4.1. Beyond the General Trend: Hydrological and Salinity Controls on UVVR-Elevation Patterns

Previous studies report a broadly consistent trend across systems in which UVVR decreases with increasing elevation (Ganju et al., 2020; Ganju, Ackerman, & Defne, 2024). However, those studies either addressed systems with less hydrological variability or relied on point-based measurements to characterize water levels and salinity. Here, we examine the UVVR-elevation relationship across distinct hydrological regions and use a hydrodynamic model to provide a spatially explicit representation of water level and salinity. Our results (Figure 2a) confirm the system-scale pattern: elevation exerts a first-order control on marsh horizontal degradation and marsh vulnerability, as quantified by UVVR. This relationship aligns with expected evolution of marshes in a transgressive landscape (FitzGerald et al., 2008), which is typical of many coastal lagoons along the southern and eastern U.S. coasts (Bird, 1994).

However, this general trend conceals important variation. Our analysis further reveals that salt marshes across different hydrological settings exhibit distinct UVVR ranges, occupy different elevation ranges, and show varying distribution patterns with elevation (Figures 2b–2f). The marsh unit UVVR values in Barrier Island and Core Sound (Figures 2b and 2c) exhibit greater variation and are generally larger than those in other hydrological regions (Figures 2d–2f). This is likely due to the more dynamic water level conditions in Barrier Island and Core Sound, as indicated by the higher MHW_{12h} there (Figure 1g). Additionally, Core Sound is subject to sound-side inundation during extreme events (Over & Sherwood, 2025; Sherwood et al., 2023; Warner et al., 2025), which can cause direct salt marsh erosion and intensify soil salinization through saltwater flooding (Yu et al., 2016, 2021). Moreover, Core Sound and its adjacent regions are closer to inlets and thus also susceptible to coastal flooding and erosion. In contrast, Tributary Estuary, Sound Peninsula, and Currituck Sound are distant from inlets and are therefore less exposed to erosive forces from open ocean, resulting in generally lower UVVR values (Figures 2d–2f) that suggest greater overall stability.

In terms of occupied elevation range, salt marshes in Barrier Island (Figure 2b) tend to span a wide range—from the intertidal to the supratidal zone, reaching elevations greater than three times the MHW_{12h}. In contrast, salt marshes in Core Sound (Figure 2c) are generally confined to the intertidal zone, while marshes in the other hydrological regions (Figures 2d–2f) tend to cluster within the supratidal zone. These distinct patterns are consistent with previous studies in this region (e.g., Adams, 1963; Brinson, 1991; Kemp, Horton, & Culver, 2009) and reflect the adjustment of salt marshes in the APES to historical climate and sea-level change (Mallinson

et al., 2018). Since ~4,000 cal yr BP, the APES has experienced four periods of intense inlet activity and barrier island segmentation driven by climate change, SLR, and increased storm intensity, with the latest period occurring around 500–350 cal yr BP (Culver et al., 2007; Mallinson et al., 2011, 2018; Pre et al., 2011). During these periods, the APES was more influenced by the coastal ocean and had larger tidal ranges, stronger tidal currents, and higher sediment accumulation rates (Clunies et al., 2017; Hill et al., 2011; Mulligan et al., 2019; Zaremba et al., 2016).

Since ~350 cal yr BP, most inlets have closed, limiting the connection between the APES and the coastal ocean (Mallinson et al., 2018). As a result, tidal ranges in areas farthest from inlets, including Tributary Estuary, Sound Peninsula, and Currituck Sound, have largely diminished (Mulligan et al., 2019). This reduction in tidal energy decreased sediment supply to intertidal zones, creating conditions unfavorable for low-marsh development and leading to the general absence of salt marshes in these areas. At the same time, proximity to major freshwater inputs reduced salt stress in the less frequently flooded supratidal zone, promoting marsh development there (Belliard et al., 2017; Kim, 2012). Consequently, these regions are characterized by salt marshes clustered primarily in the supratidal zone (Figures 2d–2f). In contrast, inlet closure has not substantially altered dynamics in areas close to remaining inlets, such as Core Sound. There, the relatively high tidal range continues to deliver sediment from offshore via washover and former inlet erosion (Heron et al., 1984; Moslow & Heron, 1994), supporting salt-marsh development in the intertidal zone. However, the proximity of Core Sound to the coastal ocean and its susceptibility to sound-side inundation (Sherwood et al., 2023; Warner et al., 2025) also reduce marsh stability, resulting in the persistence of low marsh with substantial degradation (i.e., high UVVR, Figure 2c). In addition, frequent sound-side inundation (Cassalho et al., 2021; Peng et al., 2004; Sherwood et al., 2023) and limited freshwater input (Pruitt, 2008) intensify soil salinization, imposing salt stress that reduces vegetation productivity in the supratidal zone (Pratolongo et al., 2019; Xu et al., 2024; Yu et al., 2016, 2021). As a result, Core Sound is characterized by salt marshes largely confined to the intertidal zone. By comparison, Barrier Island supports marshes spanning both intertidal and supratidal zones, reflecting its broad spatial extent across diverse environments.

Beyond hydrological control, UVVR-elevation relationship also varies systematically with salinity, producing distinct patterns across salinity regimes. Ganju, Defne, et al. (2024) suggested that the UVVR-elevation relationship varies among estuarine systems as a function of basin-wide salinity. Our results build on this by showing that salinity also regulates the UVVR-elevation relationship within a single estuary, highlighting its role in shaping marsh vulnerability at finer spatial scales. For example, in the intertidal zone, marshes adjacent to lower-salinity waters (Figure 2a) tend to have lower UVVR values, indicating higher marsh stability, compared to marshes adjacent to higher-salinity waters. Likewise, marshes with similar UVVR values tend to occupy lower elevations when adjacent to low-salinity waters than when adjacent to high-salinity waters. These dual controls are evident across the entire system (Figure 2a) and within individual hydrological region (Figures 2b–2f). Note that in the model salinity is represented as an integrative, conservative tracer and does not resolve ionic composition. Accordingly, salinity should be interpreted as an integrative indicator of environmental conditions rather than a single causal driver, reflecting the influence of multiple salinity-associated processes on marsh stability (e.g., Ardón et al., 2013, 2016; Chambers et al., 2011; Deegan et al., 2012; Lamers et al., 2013; Neubauer, 2013; Rengasamy et al., 1984; Weston et al., 2006, 2010, 2011; Williams et al., 1999). Identifying specific mechanisms will require future studies that couple marsh stability with additional water-quality measurements or modeling.

Overall in the APES, hydrological setting and salinity regime jointly control the UVVR-elevation relationship, with hydrology exerting the stronger influence. These controls shape the spatial extent of vegetation and the vertical distribution of marsh horizontal integrity (Figures 2b–2f). This is consistent with previous findings that vertical stability and horizontal integrity are coherent processes within a transgressive landscape (Ganju et al., 2020; Ganju, Defne, et al., 2024).

4.2. A Conceptual Model of Marsh Response to Sea-Level Rise and Coastal Transgression

In the APES, marsh unit UVVR generally decreases across hydrological regions from offshore to inland (Figure 3a). Salt marshes in hydrological regions nearer to open inlets are more strongly influenced by frequent extreme high water events, storm surge attack, and soil salinization, all of which enhance lateral deterioration at the same normalized elevation. This pattern is evident in the UVVR-elevation relationships for Core Sound and

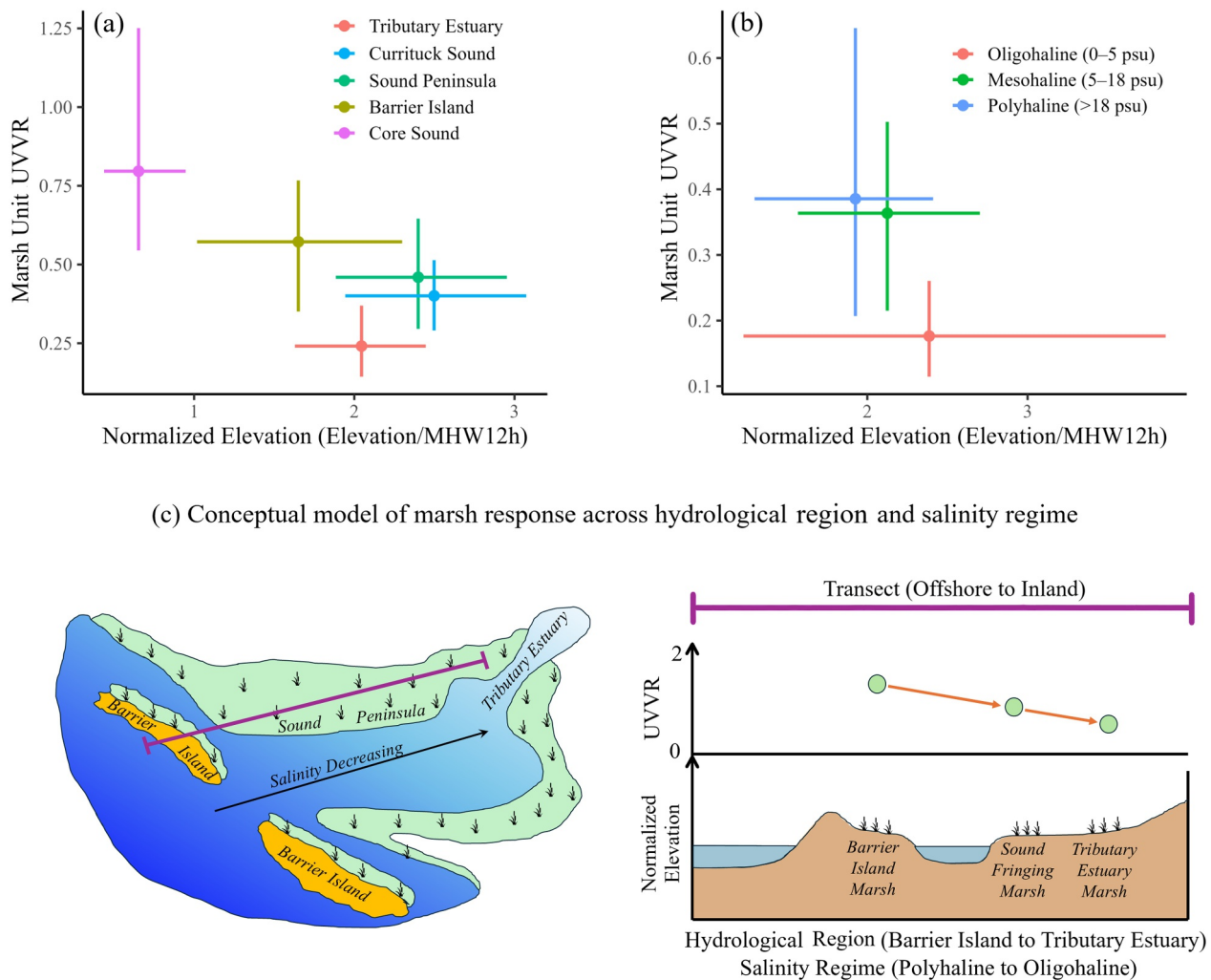


Figure 3. Relationships between normalized elevation ($Elevation/MHW_{12h}$) and unvegetated-vegetated marsh ratio (UVVR) by (a) hydrological setting and (b) salinity regime. Vertical and horizontal error bars denote the 25th and 75th percentiles of UVVR and normalized elevation, respectively. (c) Revised conceptual model of marsh decline in response to sea-level rise and coastal transgression that accounts for differential horizontal deterioration of marsh plain based on hydrological region and salinity regime. Conceptual transect illustrating how UVVR varies with salinity regime and hydrological region along an offshore-to-tributary gradient.

Barrier Island marsh units (Figure 3a). A similar trend is observed across salinity regimes (Figure 3b), with polyhaline and mesohaline marshes typically exhibiting higher UVVR values than oligohaline marshes at the same normalized elevation. Across the system (Figure 2a), at a normalized elevation of 1, the median UVVR is 0.14 for oligohaline marshes (dominated by Currituck Sound and Tributary Estuary units), 0.30 for mesohaline marshes, and 1.10 for polyhaline marshes. Because salinity also generally decreases from offshore to inland, these results indicate that, at similar relative elevations, horizontal deterioration is more pronounced in marsh units closer to oceanic forcing.

These findings align with existing models of coastal transgression. However, rather than a direct and universal submergence response to SLR controlled solely by vertical position, our results suggest that horizontal degradation is not entirely dependent on elevation but is also strongly influenced by hydrological setting and salinity regime. Such dependence is likely to hold across systems, given the well-established influence of physical and environmental conditions on marsh ecology and geomorphology. Additionally, in the APES, hydrological setting and salinity regime are linked to proximity to oceanic forcing, with increasing oceanic influence and salinity with decreasing distance from the inlet. A more complete conceptual model of marsh response to SLR and coastal transgression should therefore include differential deterioration of the marsh plain based on location within the transgressive framework (Figure 3c). Within a coastal lagoon system similar to the APES, wetland stability, as

represented by UVVR, is expected to decline across hydrological settings and salinity regimes with decreasing distance to oceanic forcing, even at the same normalized elevation. It should be noted, however, that this pattern may not apply uniformly across all estuarine settings, particularly in more tidally energetic systems (e.g., Delaware Bay), where tidal forcing can remain important throughout much of the system.

4.3. Implications for Marsh Evolution

The relationship between marsh plain integrity and normalized elevation is often assumed to be universal across an entire marsh system. As a result, previous understandings of marsh ecology and geomorphology interactions have overlooked their spatial heterogeneity across different hydrological settings and salinity regimes. Although the universal influence of salinity on salt marshes is well established (e.g., Adams, 1963; Ardón et al., 2013; Cronin et al., 2000; Kirwan et al., 2024), research on marsh evolution in response to SLR (e.g., D'Alpaos et al., 2007; Fagherazzi et al., 2012; Kirwan & Murray, 2007) has typically ignored the role of salinity in coupled geomorphic responses. The pronounced differences in UVVR-elevation distributions across salinity regimes suggest that maintaining a stable salinity regime is critical for sustaining wetland stability under rising sea levels. As shown in Figure 2, even if marsh surface elevation keeps pace with SLR and normalized elevation remains unchanged, an increase in salinity can lead to higher UVVR values. This reflects exposure to higher-salinity regimes or hydrological settings in closer proximity to oceanic forcing, which reduces horizontal integrity and makes marshes more vulnerable to conversion to open water (Ganju et al., 2017). In other words, even if a marsh system can keep up vertically with SLR, the associated salinity increase and change in hydrological setting may still render it more vulnerable and less resilient to future SLR (i.e., increased UVVR, Figure 3) due to an increase in external forcing from the oceanic end or reduced sediment delivery due to greater distance from riverine sources. This mechanism is consistent with general concepts of coastal transgression in response to SLR.

5. Conclusions

Salt marsh vulnerability to SLR is of widespread concern; however, previous understanding of salt marsh vulnerability has focused primarily on its vertical accretion relative to SLR, assuming a universal relationship between vegetation properties (e.g., biomass) and elevation. This perspective fails to account for the spatial heterogeneity of marsh evolution across different hydrological settings and salinity regimes. By combining hydrodynamic modeling with geospatial analysis, we find that within the context of a transgressive landscape, as is the case for many systems along the southern and eastern U.S. coasts, marshes are likely to experience distinct trajectories that are controlled by elevation to the first order, and at the regional scale, hydrological setting and salinity regime. While the importance of salinity for salt marsh health is well documented, its role in marsh evolution has been largely overlooked. Our results highlight the potential bias that can arise when the influence of salinity on the biophysical interactions between marsh ecology and geomorphology is ignored.

Conflict of Interest

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

Availability Statement

The geospatial data used in this study are publicly available data and include the UVVR data set (Couvillion et al., 2024), the Coastal National Elevation Database (CoNED) elevation data set (<https://www.usgs.gov/special-topics/coastal-national-elevation-database-applications-project>), National Wetlands Inventory (NWI) data downloaded by watershed using the NWI mapper (https://fwsprimary.wim.usgs.gov/wetlands/apps/wetlands_mapper/), and USGS high-resolution National Hydrography Data set (NHDPlus HR) catchments downloaded by hydrologic units via the USGS National Map Downloader (<https://apps.nationalmap.gov/downloader/>). Shapefiles of marsh units in the Albemarle–Pamlico Estuarine System used in this study are available online (Yin et al., 2026).

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