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LETTER

Variability in marsh migration potential determined by topographic rather than anthropogenic constraints in the Chesapeake Bay region

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Scientific Significance Statement

Tidal marsh migration into displaced inland ecosystems could potentially allow marshes to survive sea level rise, but it remains unknown how spatial gradients in land use and topography will limit ecosystem migration. We use high-resolution mapping to demonstrate that future marsh migration area will greatly exceed historical observations and likely compensate for near complete tidal marsh area loss in the Chesapeake Bay region, USA. However, in contrast to previous work that emphasizes anthropogenic constraints, our work suggests that topography rather than land use drives spatial heterogeneity in local coastal responses along the predominantly rural U.S. coast. Future global marsh extent likely depends on migration into rural (forested, agricultural) portions of North American coasts as more developed coasts elsewhere limit marsh resilience.

Abstract

Sea level rise (SLR) and saltwater intrusion are driving inland shifts in coastal ecosystems. Here, we make high-resolution (1 m) predictions of land conversion under future SLR scenarios in 81 watersheds surrounding Chesapeake Bay, United States, a hotspot for accelerated SLR and saltwater intrusion. We find that 1050–3748 km^2 of marsh could be created by 2100, largely at the expense of forested wetlands. Predicted marsh migration exceeds total current tidal marsh area and is $\sim 4\times$ greater than historical observations. Anthropogenic land use in marsh migration areas is concentrated within a few watersheds and minimally impacts calculated metrics of marsh resilience. Despite regional marsh area maintenance, local ecosystem service replacement within vulnerable watersheds remains uncertain. However, our work suggests that topography rather than land use drives spatial variability in wetland vulnerability regionally, and that rural land conversion is needed to compensate for extensive areal losses on heavily developed coasts globally.

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

Global climate change is leading to permanent, directional shifts in ecotones along abiotic gradients (Osland et al. 2013; Smith and Goetz 2021). Salt marshes, tidal forests, and mangroves, are all migrating landward at increasing rates, driven largely by sea level rise (SLR) and associated increases in salinity (White and Kaplan 2017; Yao and Liu 2017). However, it remains uncertain whether this migration can occur fast enough for ecosystems to persist in the face of climate change, and whether transgression can occur as ecosystems migrate into developed portions of the coast (Haasnoot et al. 2021).

The predicted response of coastal wetlands to SLR is hotly debated (Törnqvist et al. 2021). Geologic reconstructions suggest a tipping point in SLR rates, after which extensive drowning will occur (Horton et al. 2018; Saintilan et al. 2020). Yet, numerical models suggest wetlands could expand with accelerated SLR by migrating inland (Kirwan et al. 2016; Schuerch et al. 2018). Saltwater intrusion inhibits germination and kills saplings of wetland tree species which have low salinity tolerance, allowing for tidal marsh replacement as mature trees die during extreme events (Williams et al. 1999). Forest mortality and marsh migration are well documented along the North American Atlantic and Gulf coasts (Smith 2013; Kirwan and Gedan 2019; White et al. 2021), compensating for loss of existing tidal marsh in several regions (Raabe and Stumpf 2016; Schieder et al. 2018).

However, the ability of marshes to migrate into adjacent upland and freshwater ecosystems may be limited by steep uplands and anthropogenic barriers, resulting in "coastal squeeze" (Enwright et al. 2016; Flester and Blum 2020). Less than 10% of low-lying areas on the U.S. Atlantic coast have been set aside for conservation (Titus et al. 2009); and future urbanization may further limit migration as available uplands become developed (Enwright et al. 2016). Yet, low-lying, salinized agricultural land is already being abandoned (Gedan and Fernández-Pascual 2019). Therefore, it remains uncertain whether marsh migration can compensate for predicted marsh loss, and how natural and anthropogenic barriers may limit transgression. Our work combines marsh-forest boundary delineations (Molino et al. 2021) with regional land use at a higher resolution than previous studies (Holmquist et al. 2021) to uniquely predict that salinization of uplands can maintain marsh area regionally, although functional compensation remains uncertain.

Methods

Study region

We quantified potential marsh migration area (i.e., sea-level driven conversion of upland to marsh) in the low elevation region surrounding Chesapeake Bay and its tributary rivers. The Chesapeake Bay is the largest estuary in the United States, and its mixture of forested, agricultural, and developed land uses are broadly representative of the North American coastal plain. Like the U.S. coast as a whole, the upland land types most at risk from SLR are nontidal wetlands, including palustrine emergent, forested, and scrub/shrub wetlands (Epanchin-Niell et al. 2017; Holmquist et al. 2021). Urban-dominated watersheds comprise a small fraction of the U.S. coast vulnerable to SLR (Holmquist et al. 2021). Nevertheless, the largely rural Chesapeake region includes substantial pockets of dense development (i.e., Hampton Roads, Virginia), and the regional population at risk from SLR ranks 5th in the United States (Hauer et al. 2016).

Marsh migration is well documented in Chesapeake Bay (Hussein 2009; Gedan et al. 2020). Approximately 400 km^2 of uplands have converted to tidal marsh over the past 150 years (Schieder et al. 2018) and rates of marsh migration are accelerating (Schieder and Kirwan 2019), driven by inundation of the low-lying gently sloping coastal-plain by relative SLR 2–3$\times$ the global average (Engelhart et al. 2009). However, marshes in this region are vulnerable to drowning due to low sediment input, microtidal tides, and accelerating rates of SLR (Stevenson et al. 1985; Kearney et al. 2002; Schepers et al. 2017). As a result, migration is a primary mechanism of tidal marsh survival in Chesapeake Bay, making this region a model system to determine if upland conversion can compensate for loss.

Analytical methods

We quantified migration of the current tidal marsh-forest boundary with SLR to estimate potential marsh migration area for the entire Chesapeake Bay coastal plain, following a general approach established for the U.S. Gulf coast (Enwright et al. 2016). In ArcMap 10.7, we started with a previously delineated tidal marsh-forest boundary dataset of > 200,000 points at 30-m resolution (Molino et al. 2020, 2021). We then extracted the elevation of each point from the U.S. Geological Survey (USGS) Coastal National Elevation Database (CoNED) Topobathymetric Digital Elevation Model (Danielson and Tyler 2016). Inaccurate points were eliminated to minimize error associated with misrepresentation of the marsh-forest boundary and locations with poor elevation data (Supporting Information). We calculated the median elevation of the tidal marsh-forest transition boundary, hereafter referred to as the threshold elevation, for USGS HUC10 (Hydrologic Unit) watersheds (USGS 2020) to account for spatial variability in processes that likely influence threshold elevation (e.g., tidal range, salinity) and quantify marsh migration at the watershed scale (Supporting Information Fig. S1).

Increments of SLR were added to the transition threshold elevation of each watershed to quantify potential marsh migration area, using National Oceanic and Atmospheric Administration (NOAA) global Low (0.45 m), Intermediate (1.22 m), and High (2.66 m) scenarios adjusted for the Chesapeake Bay region (Sweet et al. 2017). Land between the threshold elevation and the threshold elevation plus the SLR scenario was considered to be potential marsh migration area. Following previous approaches, we neglect accretional and erosional processes that affect the longevity of converted tidal marsh area (Enwright et al. 2016; Borchert et al. 2018; Holmquist et al. 2021). Thus, our estimates of potential marsh migration area should not be considered predictions of long-term marsh extent, as future marsh extent would be vulnerable to losses at the seaward edge (Törnqvist et al. 2021).

We assume that transition threshold elevations determined from the marsh-forest boundary are representative of marsh-upland boundaries in general given that forested uplands comprise more than half of total upland land use, and that other upland land uses (e.g., agriculture), are typically separated from wetlands by a forested buffer. Preliminary observations suggest that threshold elevations for non-forested boundaries are similar to the elevations of the marsh-forest boundary (Supporting Information Table S1). However, more work is needed to refine this method for other land uses. We also assume that migration is not limited by hydrological connectivity (Poulter and Halpin 2008), or highly localized freshwater inputs that cannot be inferred at the scale of HUC10 watersheds. Future work that includes hydrodynamic modeling could resolve these predictions at even finer spatial scales.

Following Gesch (2012), we calculated uncertainty envelopes for area converted under the localized NOAA predictions by adding and subtracting the root mean square error (RMSE) of CoNED (20 cm) from the new marsh-upland elevation

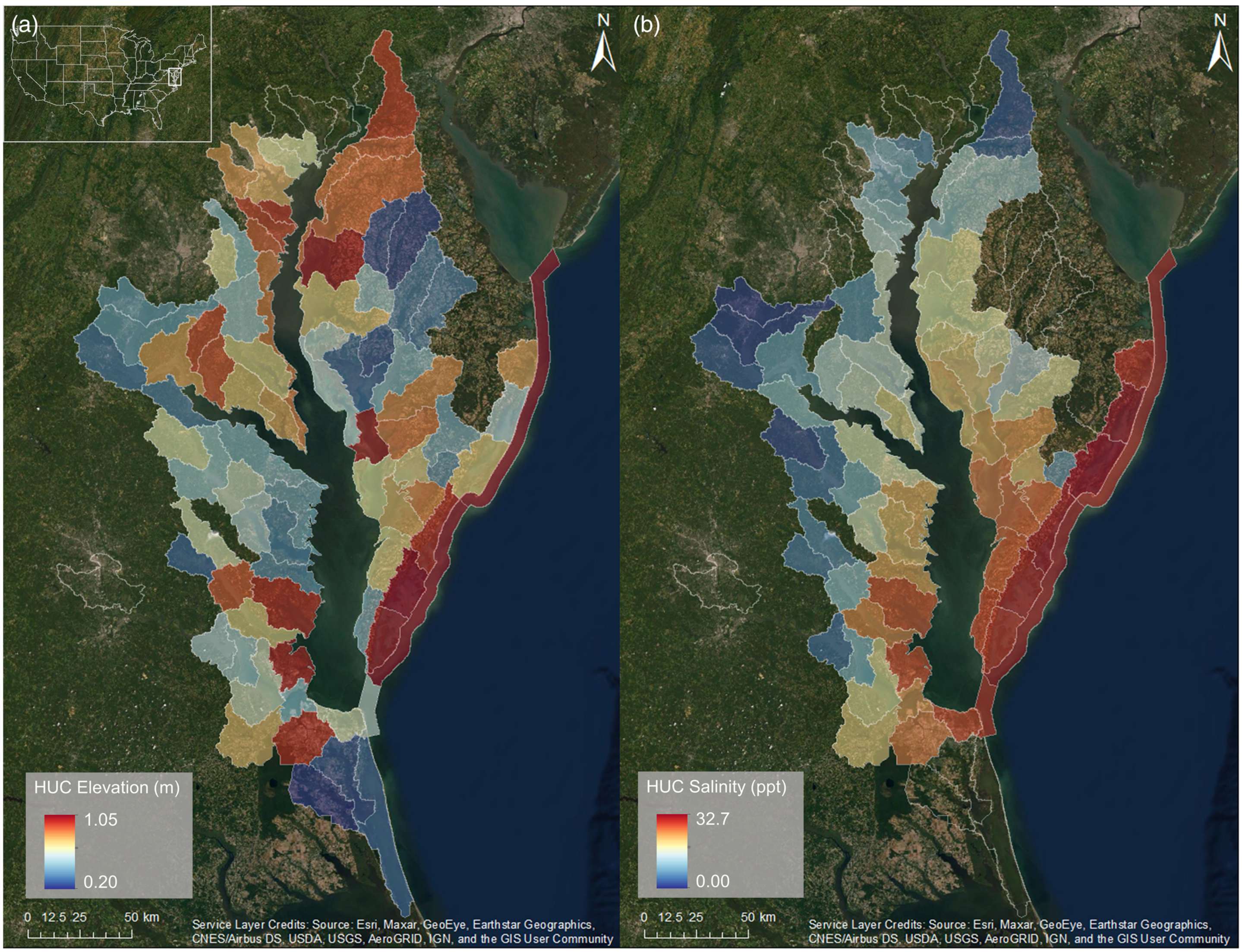

Fig. 1. (**A**) Median elevation (m NAVD88) of marsh-forest boundaries for 81 HUC10 units; 5 additional units have no color as there were discrepancies in the underlying elevation data or there were insufficient points in that unit. Median elevation was taken from all points within each HUC unit. For specific median elevation values of each HUC, see Supporting Information Table S3. (**B**) Median salinity for 68 watersheds which had sufficient salinity data based on model output provided by St-Laurent et al. (2020). Threshold elevation and salinity are positively correlated ($R^2 = 0.3$, $p = 0.03$). Salinity data were not used in our analyses other than to interpret possible sources of variability in threshold elevations. Data used to generate this figure are available in the metadata (Molino et al. 2022).

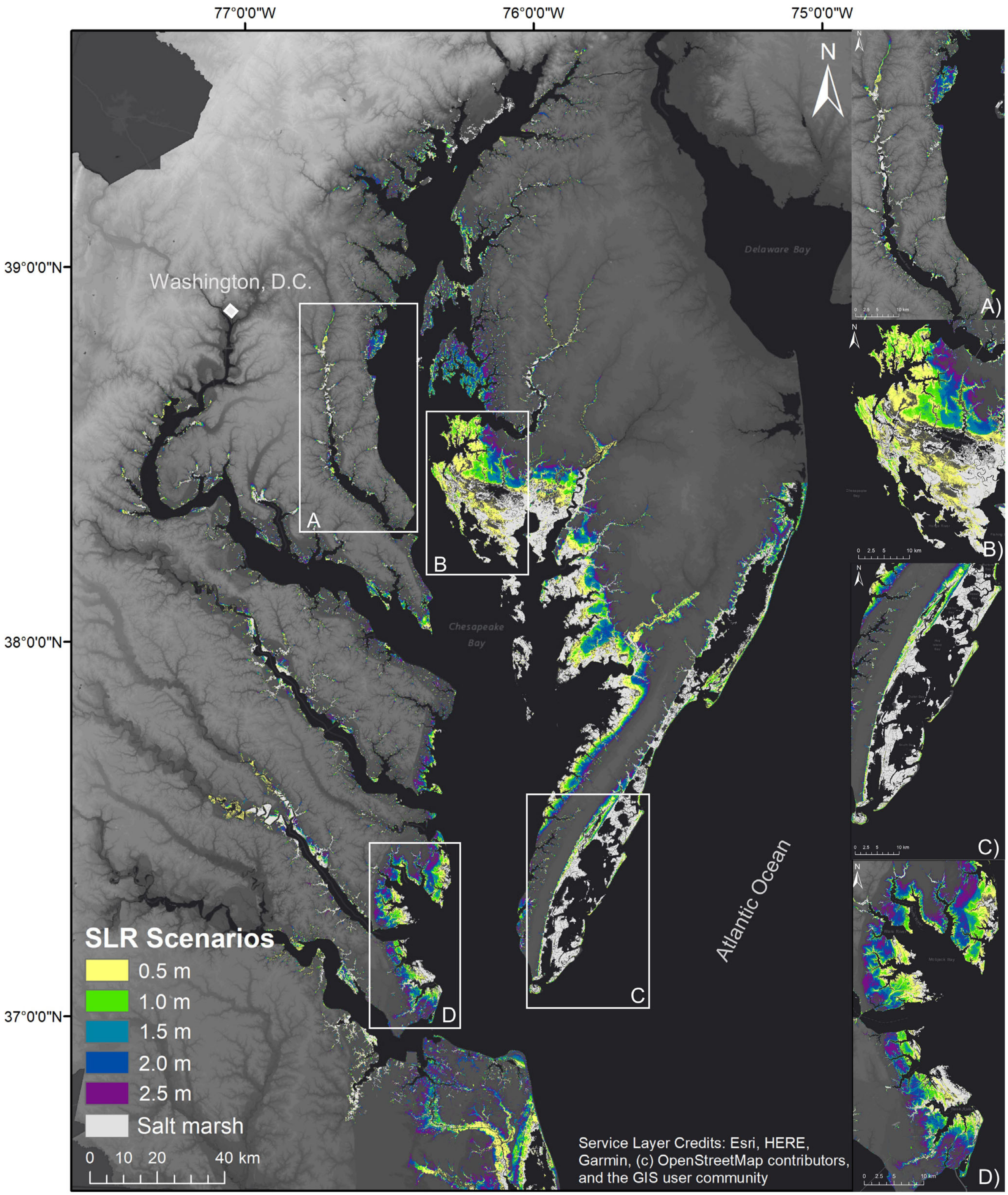

Fig. 2. Potential upland converted to marsh under five generalized sea level rise scenarios. Current tidal marsh area based on the NWI emergent wetland class is depicted in light gray. (**A**) Patuxent River, Maryland; (**B**) Blackwater, Maryland; (**C**) Atlantic coastal lagoons; (**D**) Mobjack Bay, Virginia. Data used to generate this figure are available in the metadata (Molino et al. 2022).

within each watershed (Danielson and Tyler 2016). Current marsh area was determined from the National Wetlands Inventory (NWI) (U.S. Fish and Wildlife Service 2018). The current land use of predicted marsh migration areas was assessed using the Chesapeake Conservancy High-Resolution Land Use and Land Cover datasets (Chesapeake Conservancy 2018a,b) for six categories: forest, forested wetlands, turf grass, agriculture, impervious, and other (Supporting Information Table S2). Forested wetlands were included separately from the forest category because their physiographic position results in a higher sensitivity to flooding and salinity stresses (Doyle et al. 2007). The "other" category includes mixed open and mixed impervious as well as marsh located at elevations above the median threshold value for each watershed.

Results

Median tidal marsh-forest boundary elevations were determined for 81 watersheds from a final dataset of 95,286 points. The median threshold elevation of transition from tidal marsh to forest around Chesapeake Bay is 0.54 m NAVD88. Median threshold elevations for HUC10 watersheds range from 0.20 m NAVD88 in the southernmost watersheds to 1.05 m NAVD88 along the Atlantic coastal lagoons (Fig. 1). Unique land conversion estimates for each watershed (Supporting Information Table S3) were combined to produce an estimate of potential upland conversion for the entire Chesapeake Bay coastal-plain (Fig. 2). Extensive areas of land conversion are predicted along the main stem of Chesapeake Bay (Fig. 2B,D), with limited migration along the western shore tributaries and in the Atlantic coastal lagoons at each SLR scenario (Fig. 2A,C) (Molino et al. 2022).

Marsh migration area increased through time and with the magnitude of SLR, ranging from 1050 km^2 (NOAA Low) to 3748 km^2 (NOAA High) by 2100 (Fig. 3A; Supporting Information Table S4), and is currently dominated by terrestrial and wetland forests. Developed land uses, including agriculture and impervious surfaces, generally occupy less than 10% of predicted migration areas in individual watersheds, despite more extensive development in watersheds overall (Fig. 3B; Supporting Information Table S6). For example, Elizabeth River surrounding Norfolk, VA is one of the most developed watersheds in the Chesapeake Bay and the United States, but impervious surfaces occupy only 16% of potential marsh migration area under 1 m of SLR, compared to 31% for the entire watershed (Supporting Information Table S6).

Discussion

Quantifying elevation thresholds

Predictions of coastal ecosystem migration typically depend on establishing threshold elevations, beyond which inundation drives state change (Enwright et al. 2016; Borchert et al. 2018; Mitchell et al. 2020). A single threshold elevation is often determined for large areas (e.g., county, estuary) despite potential spatial variation in the processes that control threshold elevation. For example, the elevation range of vegetated tidal marsh in Chesapeake Bay is thought to be controlled by tidal range, weather events, and salinity, where marshes exposed to greater water level fluctuations and higher salinities tend to have

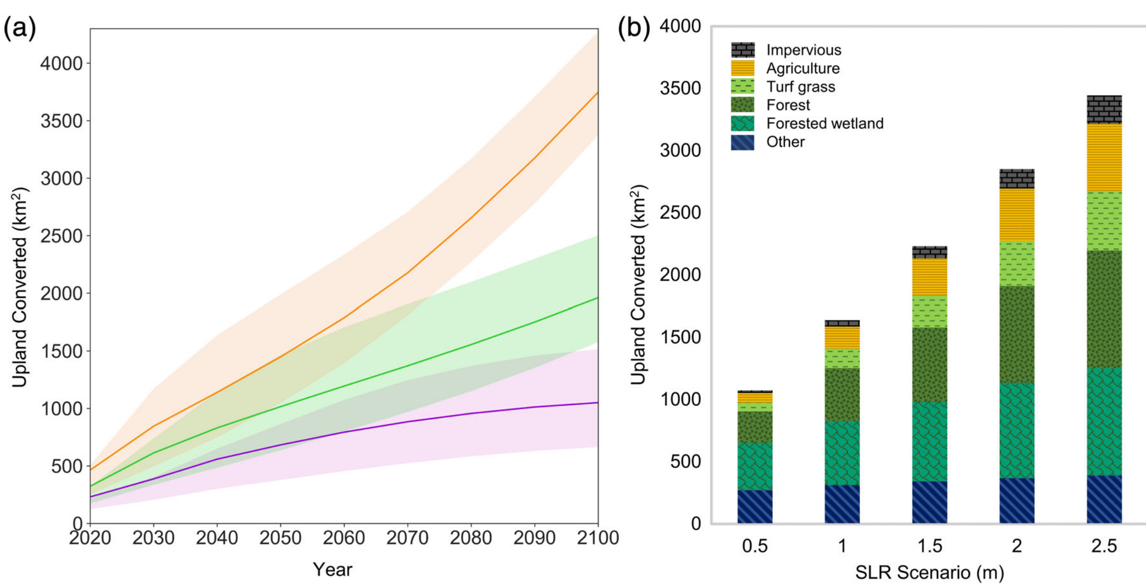

Fig. 3. (**A**) Potential upland area converted to marsh under three NOAA sea level rise scenarios. Sea level scenarios follow Sweet et al. (2017), where Low scenario (0.45 m) is in purple, Intermediate scenario (1.22 m) is in green, and High scenario (2.66 m) is in orange. Uncertainty envelopes account for RMSE of the underlying elevation data (Gesch 2012). (**B**) Land use type of potential upland converted to marsh under five generalized sea level rise scenarios. Categories based on merged classes from the Chesapeake Conservancy High-Resolution Land Use and Land Class datasets (Supporting Information Table S2).

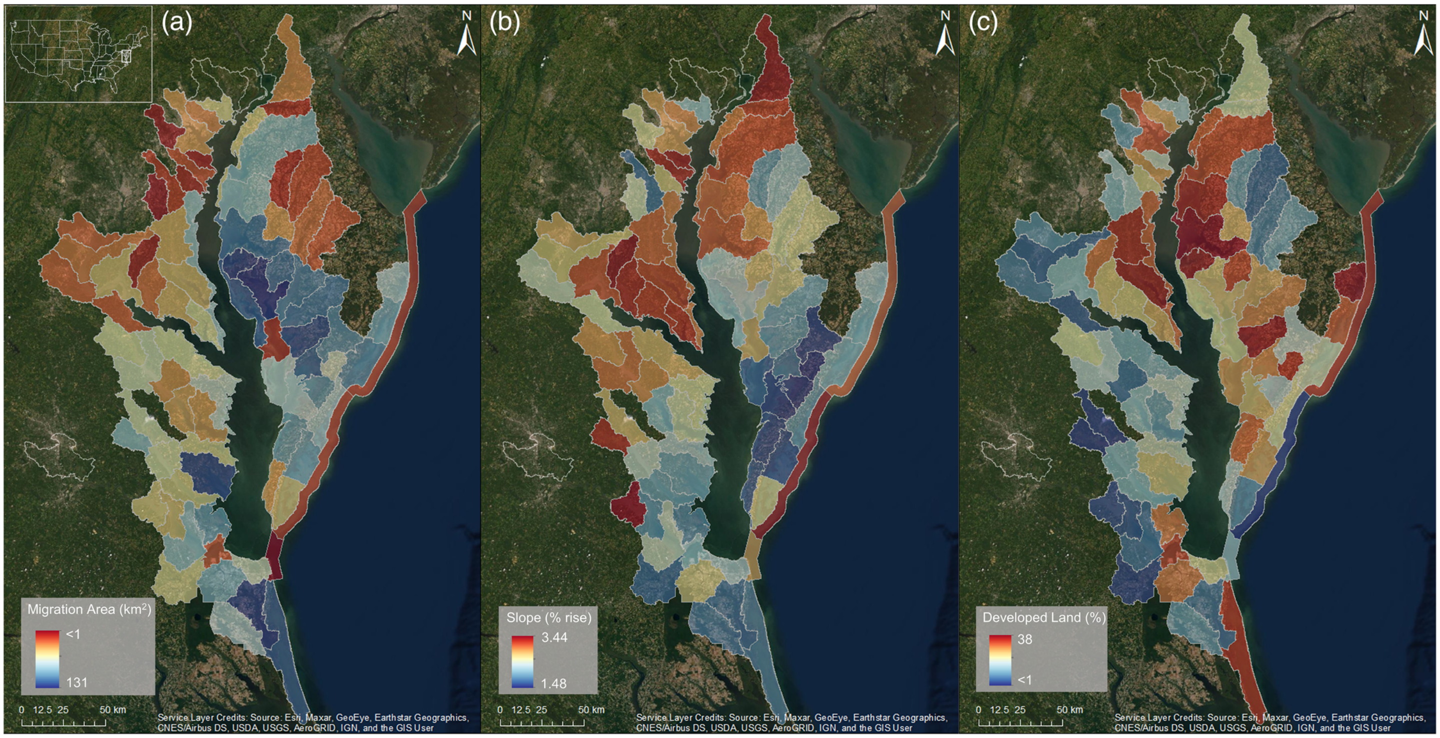

Fig. 4. (**A**) Estimates of marsh migration area under 1.0 m of SLR for each HUC10 watershed; (**B**) median slope for each HUC10 watershed calculated from slope values at the tidal marsh-forest boundary provided by Molino et al. (2021). (**C**) Percent developed land (impervious and agricultural) within the potential marsh migration area for 1.0 m of SLR. Land use classes based on the Chesapeake Conservancy High-Resolution Land Use and Land Cover projects (Chesapeake Conservancy 2018a,b).

higher threshold elevations (Boon et al. 1977). Alternatively, previous modeling and remote sensing studies of marsh vulnerability typically assume that the upper elevation limit of marsh corresponds to astronomical tidal datums alone (e.g., highest astronomical tide [HAT]) (Thorne et al. 2018; Mitchell et al. 2020; Holmquist et al. 2021). However, we demonstrate that salinity is also a driver of threshold elevation (Fig. 1B; Supporting Information Fig. S2). Our study relies on tidal marsh-forest boundaries determined independently from these metrics (Molino et al. 2021), allowing us to capture small-scale variability from both tidal range and salinity, despite a large study area. Our median threshold elevation (0.54 m) determined across the entire Chesapeake Bay from aerial imagery is largely in agreement with the threshold elevation determined from mean HAT in Virginia (0.61 m) (Mitchell et al. 2020). However, we find that threshold elevations vary more than fivefold across our study region, from 0.20 m NAVD88 in low-salinity watersheds to 1.05 m NAVD88 in exposed, high-salinity watersheds (Fig. 1; St-Laurent et al. 2020). These results suggest that using a single threshold elevation for large sections of the coast could result in significant underestimation or overestimation of future marsh migration area at smaller spatial scales and precludes attempts to account for spatial variability in wetland vulnerability.

Natural and anthropogenic barriers to marsh migration

Steep topography and anthropogenic land uses are well-known barriers to marsh migration (Torio and Chmura 2013; Enwright et al. 2016). We found extensive marsh migration predicted in the gently sloping watersheds of the Eastern Shore of Chesapeake Bay, and more limited marsh migration predicted in watersheds with steep topography along the western shore tributaries and Atlantic coast (Fig. 4B). These findings are consistent with observations of rapid forest retreat in other low slope portions of the Atlantic coastal plain (Smith 2013; Schieder and Kirwan 2019; Ury et al. 2021), and the conceptual understanding that topography constrains marsh migration (Kirwan et al. 2016; Mitchell et al. 2017). Moreover, these findings suggest that although marsh migration will be extensive in Chesapeake Bay, natural topographic variability will lead to substantial gradients in potential marsh migration and vulnerability to SLR.

Anthropogenic land uses also potentially limit upland conversion into marsh, especially in regions of the world with large urban centers and extensive agriculture (Schuerch et al. 2018). Like the U.S. coast as a whole, the Chesapeake Bay region is largely rural with pockets of intensive development (Holmquist et al. 2021). Our high-resolution, spatially explicit approach allows us to take advantage of that heterogeneity and evaluate specific land use limitations by examining responses in watersheds with major urban centers and

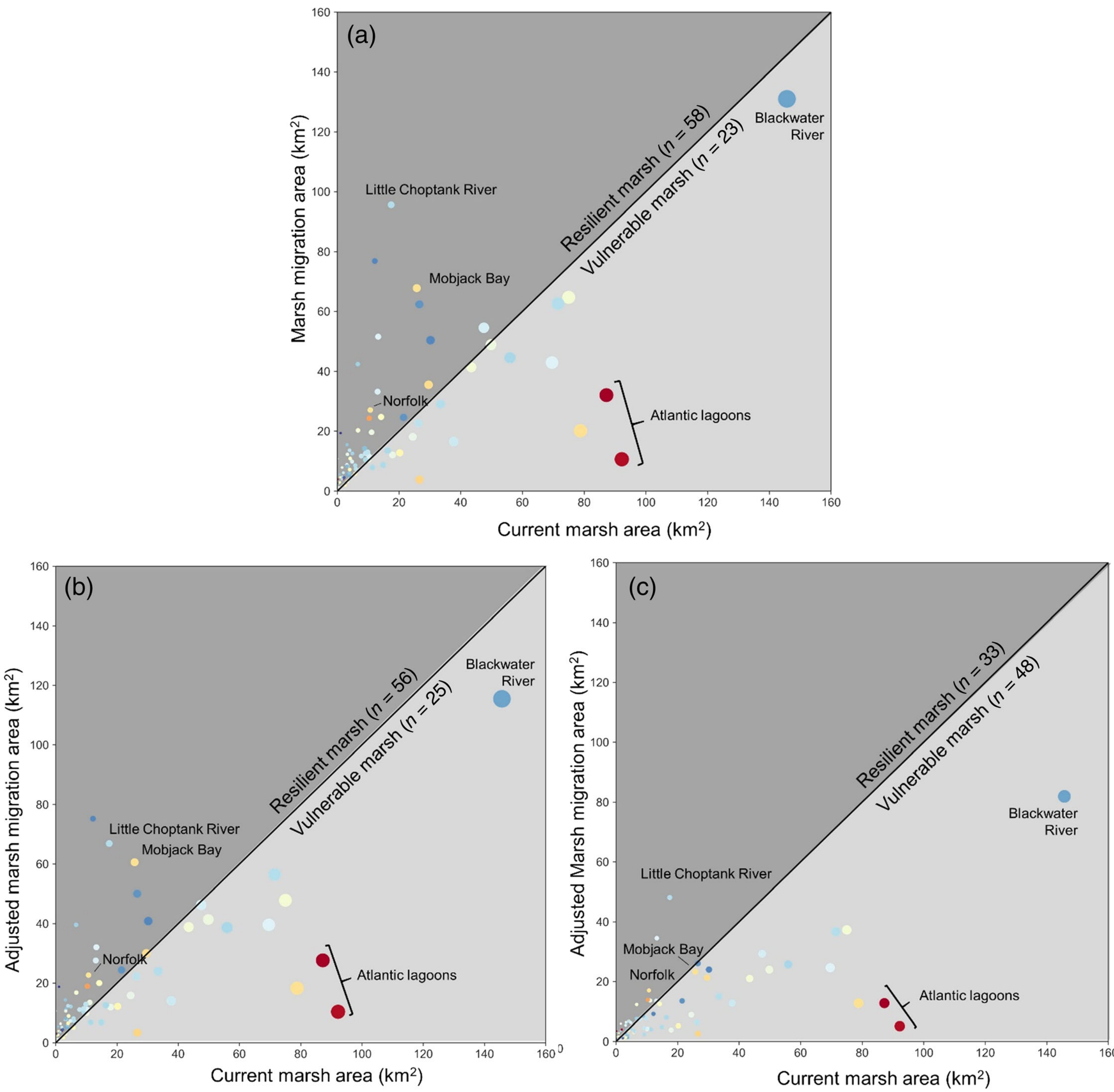

Fig. 5. (**A**) Estimates of marsh migration area under 1.0 m of sea level rise plotted against current marsh area (NWI) for each HUC10 watershed; (**B**) estimates of marsh migration area under 1.0 m of sea level rise with developed land (agriculture and impervious) removed plotted against current marsh area for each HUC10 watershed. (**C**) Estimates of marsh migration area under 1.0 m of sea level rise with terrestrial forest and forested wetlands removed plotted against current tidal marsh area for each HUC10 watershed. Dots are colored to represent the watershed threshold elevation value from Fig. 1A, where blue is low threshold elevation and red is high threshold elevation. Dot size corresponds to current marsh extent within the watershed. Data points above the black 1:1 line represent watersheds with resilient marsh, where marsh migration could compensate for even a complete loss of existing tidal marsh. Mobjack Bay (Virginia) and Blackwater River (Maryland) are examples of high marsh migration watersheds, while the Atlantic lagoons are representative of watersheds with low marsh migration potential. Norfolk (Elizabeth River watershed in Virginia) is an example of a watershed with high impervious cover, whereas Little Choptank River (Maryland) is representative of watersheds with high agricultural land use within the marsh migration area. Data used to generate this figure are available in the Metadata (Molino et al. 2022).

agricultural land use. We found that developed land use (impervious + agricultural) within low-elevation areas most vulnerable to marsh migration (i.e., land <1.0 m above current threshold elevations) was concentrated within a minority of watersheds and was usually dominated by one developed land use class (Fig. 4). Regionally, impervious land use in potential marsh migration areas was minimal through high SLR scenarios (Fig. 3B). For example, three of the five major urban centers in our study region (Hampton, VA; Annapolis, MD; Baltimore, MD) are located in watersheds with only small areas of potential marsh migration. Two urban centers (Norfolk and Newport News, VA) were located in watersheds with moderate marsh migration, but impervious cover only accounted for 14–16% of predicted marsh migration area despite extensive development inland. Despite the perception that major urban centers will heavily limit marsh migration, our high-resolution predictions suggest that the most vulnerable land in the Chesapeake Bay remains largely undeveloped, even in urban watersheds with extensive development.

Agricultural land use was more widespread in watersheds with extensive predicted marsh migration area and dominated developed land use. Agricultural land exceeded 10% of predicted marsh migration area in 23 watersheds whereas impervious land use exceeded 10% in only 9 watersheds (Supporting Information Table S6). Recent abandonment of agricultural fields with saltwater intrusion is being documented (Gedan et al. 2020). The majority of future marsh migration area under 1.0 m of SLR is predicted to come at the expense of freshwater forested ecosystems (870 km^2; Fig. 3B), which are more prevalent than developed land in low-lying areas in 78 of 81 watersheds (Supporting Information Table S7). Together, these observations suggest that highly variable land use across the broader Chesapeake region has relatively small influence on regional marsh migration, and that gradients in topography rather than anthropogenic land uses are the primary influence on spatial variability of marsh migration potential.

Implications for marsh vulnerability

Coastal wetlands are threatened by global SLR and declining riverine sediment yields to the coast (Syvitski et al. 2005; Törnqvist et al. 2021). Predictions of wetland fate range from place-based estimates of loss (Crosby et al. 2016; Mitchell et al. 2020) to generalized models of expansion (Kirwan et al. 2016; Schuerch et al. 2018), depending largely on the ability of wetlands to migrate inland at rates faster than existing wetlands convert to open water. Our work shows unequivocally that future land conversion will be extensive in the Chesapeake Bay region. Across the entire Chesapeake Bay, we predict that 1050–3748 km^2 of new marshes will potentially be created by 2100 (Fig. 3A). Thus, predictions of potential marsh migration area over the next 80 years are approximately 2–9× greater than that inferred from historical maps over the last 150 years (400 km^2; Schieder et al. 2018). Moreover, predicted marsh migration area under Low to Intermediate SLR scenarios is similar to the current total area of marshes today (1454 km^2), and is more than twice the current tidal marsh area under faster scenarios (Fig. 3). These predictions of extensive land conversion suggest that, at the scale of the entire Chesapeake Bay, marsh migration could compensate for tidal marsh area loss under most SLR scenarios, even if all existing marshes drowned or were lost to erosion.

Marsh resilience is controlled by the interplay between vertical and lateral ecosystem vulnerabilities (Ganju et al. 2017; Fitzgerald and Hughes 2019). Following Holmquist et al. 2021, we estimate a marsh lateral resilience index as the ratio between marsh migration area under 1.0 m of SLR and current tidal marsh area for each watershed. Watersheds with ratios > 1 are considered resilient to SLR as inland migration could compensate for even a complete loss of existing marshes. Conversely, watersheds with ratios < 1 are considered potentially vulnerable. We found substantial spatial variability in lateral marsh resilience (Fig. 5) largely attributable to geomorphological differences throughout the region. For example, watersheds comprising the Atlantic coastal lagoons are vulnerable because extensive tidal marshes today are bounded by relatively steep adjacent topography (Fig. 5A). Watersheds along Mobjack Bay (Fig. 2D) are considered resilient as the low-lying area predicted to be inundated with 1.0 m of SLR is more than double current tidal marsh area (Fig. 5A). Interestingly, the watershed with the largest tidal marshes and most extensive marsh loss (i.e., Blackwater River) (Kearney et al. 2002; Schepers et al. 2017) is only moderately vulnerable to SLR because migration areas are large enough to compensate for a near complete loss of existing tidal marsh (ratio 0.90).

Landowners may perceive marsh migration negatively, and may attempt to defend developed land uses from SLR (Field et al. 2017; Van Dolah et al. 2020). Interestingly, we find that lateral tidal marsh vulnerability increased only slightly when anthropogenic land uses were completely removed from the marsh migration area (i.e., only two watersheds shift from resilient to vulnerable) (Fig. 5B). Six of the eight most developed watersheds have a resilience index greater than one, and the remaining two watersheds have a resilience index of less than one with or without including developed land in the migration area (Supporting Information Table S6; Fig. 5B). In contrast, tidal marsh vulnerability is very sensitive to the inclusion of freshwater forested ecosystem area (Supporting Information Table S7; Fig. 5C). Thus, our work points to extensive marsh migration regardless of land use, though tidal marsh resilience comes at the expense of forests and forested wetlands.

The large-scale conversion of forests and forested wetlands to tidal marsh has significant implications for ecosystem function. Salinization of forested wetlands could exacerbate coastal eutrophication (Noe et al. 2013) and loss of critical habitat for avian species (Brittain and Craft 2012). While marsh carbon burial rates surpass that of coastal forests, extensive time to replacement could limit carbon sequestration compensation (Smith and Kirwan 2021). Moreover, migrating marshes are typically dominated by invasive *Phragmites australis* rather than native wetland species (Smith 2013; Langston et al. 2021), making functional compensation uncertain despite areal maintenance. Future work could help to better distinguish between forest and forested wetlands in remotely sensed imagery, and to quantify potential loss of ecosystem services.

Previous work at a variety of scales emphasized the spatial heterogeneity of coastal responses to SLR and saltwater intrusion (Pendleton et al. 2010; Lentz et al. 2016). More specifically, tidal marshes along gently sloping, natural coastlines are considered more resilient to SLR than marshes along steep, anthropogenic-dominated coastlines (Kirwan and Megonigal 2013; Holmquist et al. 2021). Our approach to defining threshold elevations at the scale of individual watersheds allows for a more precise assessment of spatial variability and the influence of salinity. Our findings of wide variability in threshold elevations (0.20–1.05 m NAVD88), marsh migration areas (< 1–131 km^2), and lateral tidal marsh vulnerability indices (0.1–106.9) are consistent with the paradigm that spatial variability in topography and land use will lead to a heterogenous response. However, we uniquely find that low-lying areas are largely undeveloped, even in watersheds with substantial agriculture and urbanization. Therefore, we suggest that spatial gradients in forest mortality, sea-level driven land conversion, and marsh vulnerability are more fundamentally related to topography than anthropogenic land use in the Chesapeake Bay.

Strong spatial gradients in topography and land use imprinted on a largely rural landscape also define the land vulnerable to SLR on the U.S. coast as a whole (Borchert et al. 2018; Holmquist et al. 2021). This suggests that observations from the Chesapeake Bay may be more broadly applicable. However, our findings that marsh migration and resilience are not overly limited by anthropogenic land use does not apply to regions of the world with higher population densities and extensive hardened shorelines (e.g., Europe, Asia) (Kabat et al. 2005; Ma et al. 2014; CIESIN 2017). Therefore, spatial gradients at the scale of individual watersheds in the Chesapeake Bay may resemble larger-scale gradients, where global marsh extent will only be maintained if marsh loss in developed portions of the world is offset by migration into more rural regions.

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