Using Geospatial Analysis to Guide Marsh Restoration in Chesapeake Bay and Beyond

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Abstract

Coastal managers are facing imminent decisions regarding the fate of coastal wetlands, given ongoing threats to their persistence. There is a need for objective methods to identify which wetland parcels are candidates for restoration, monitoring, protection, or acquisition due to limited resources and restoration techniques. Here, we describe a new spatially comprehensive data set for Chesapeake Bay salt marshes, which includes the unvegetated-vegetated marsh ratio, elevation metrics, and sediment-based lifespan. Spatial aggregation across regions of the Bay shows a trend of increasing deterioration with proximity to the seaward boundary, coherent with conceptual models of coastal landscape response to sea-level rise. On a smaller scale, the signature of deterioration is highly variable within subsections of the Bay: fringing, peninsular, and tidal river marsh complexes each exhibit different spatial patterns with regards to proximity to the seaward edge. We then demonstrate objective methods to use these data for mapping potential management options on to the landscape, and then provide methods to estimate lifespan and potential changes in lifespan in response to restoration actions as well as future sea level rise. We account for actions that aim to increase sediment inventories, revegetate barren areas, restore hydrology, and facilitate salt marsh migration into upland areas. The distillation of robust geospatial data into simple decision-making metrics, as well as the use of those metrics to map decisions on the landscape, represents an important step towards science-based coastal management.

Introduction

Coastal wetlands, and salt marshes in particular, are biogeomorphic features that respond to coupled biophysical processes (Gourgue et al. 2022). The interplay between anthropogenic, atmospheric, oceanographic, and biogeochemical forcing leads to complex responses that modulate ecological communities, geomorphic evolution, and ecosystem services (Temmink et al. 2022). Measuring these responses is difficult, especially across large spatial scales at meaningful resolution.

Nonetheless, coastal managers and restoration practitioners require robust data and tools to make informed decisions on where to direct limited resources, and which restoration techniques will be most effective. For example, a new approach for considering natural resource management is the Resist-Accept-Direct Framework (RAD), which recasts decisions as distinct choices in response to climate change (Schuurman et al. 2022). For example, in the context of salt marsh management, restoring a degraded, low-elevation marsh parcel to its earlier state would be a "resist" action, while allowing the marsh parcel to convert entirely to open water would be an "accept" action. Allowing for conversion to open-water while restoring subtidal habitat within the parcel (e.g., oyster reef) could be considered a "direct action." Implicit in the RAD framework is the spatiotemporal context of decision-making: a certain choice may be appropriate in one location on the landscape, at a particular time, but inappropriate at another location in the present or future. Therefore, also implicit in this framework, is the need for spatially comprehensive data that represent timescales.

The inventory of salt marsh indicators and data products is vast, especially in well-studied systems such as Chesapeake Bay. Point-based estimates of vertical trajectory, such as those

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provided by surface elevation tables provide insight into historical vertical response over limited spatial scales (Cahoon et al. 2020). Other geospatial data aim to predict the spatially variable response of vegetative communities to sea-level rise (Marcy et al. 2011). While these data sources provide insight into specific responses to forcing, they are often not in a form that enables consistent, objective decision-making across a large landscape. For example, a model that does not represent sediment budgets is not optimal for identifying areas for sediment addition techniques (Ganju 2019); similarly, elevation trajectory trends will not indicate the likelihood of interior ponds converting to open water, which is a process of horizontal deterioration.

Restoration practitioners have a limited set of techniques available for restoring, protecting, and expanding salt marshes. At the seaward end, shoreline stabilization ("green" or "gray") may provide limited protection depending on sediment supply (Ganju 2019), but in the short-term will maintain the seaward marsh extent. Within the marsh complex, sediment-based techniques include seaward sediment placement (Schulz et al. 2021), ditch remediation (Burdick et al. 2020), and thin-layer placement (Thorne et al. 2019). Hydrologic techniques include removal of tidal restrictions (Eagle et al. 2022), creation of runnels (Besterman et al. 2022), and restoration of riverine sediment supply (Elsey-Quirk et al. 2019). Lastly, direct revegetation of the marsh plain can be used in isolation or in combination with other techniques to increase vegetative cover and eventually increase elevation capital through autochthonous and allochthonous material trapping (Duggan-Edwards et al. 2020). Ultimately, the target for these techniques is an increase in elevation capital and/or vegetative cover. These two metrics are both indicators of wetland vulnerability, but also scale with the ecosystem services provided by salt marshes. Increased vegetative cover and elevation provide greater wave attenuation (Castagno et al. 2022), carbon sequestration (Woltz et al. 2023), and potentially habitat for nesting avian species (Kocek et al. 2022).

Land managers require spatially aggregated data for decision-making. For example, a high-resolution aerial image may clearly detail all facets of the landscape, but without classification and aggregation of selected features, the image itself does not distill information into actionable information. With regard to resolution, depending on the nature of the problem, some aggregation of data to a management spatial scale is necessary. A sub-1 m resolution map of mineral resources, for example, must be aggregated up to an actionable spatial unit to identify the lowest cost–benefit ratio for exploiting that resource. In terms of marsh vulnerability to sea-level rise, land managers have restoration techniques at their disposal that can be applied on spatial scales on the order of a few hectares (Thorne et al. 2019) to several hundred hectares (Ganju et al. 2022), though in the latter case, individual actions are dispersed across the landscape.

Ultimately, marsh horizontal and vertical status must be aggregated over the spatial scale of the appropriate restoration area-of-influence.

Several studies have identified the spatially aggregated unvegetated-vegetated marsh ratio (UVVR) as a horizontal, integrative indicator of marsh condition and future geomorphic trajectory (Ganju et al. 2017, 2020, 2023; Wasson et al. 2019). The UVVR, by design, is aggregated over some spatial scale depending on the application. For inventories across state and estuarine intertidal areas, Ganju et al. (2022) used a 30-m resolution, within-pixel UVVR estimate to quantify vegetated area and marsh deterioration. For parcel-scale management, the marsh-unit UVVR is more appropriate, as it delineates marsh complexes into topographically distinct units that are constrained by elevation, hydrology (e.g., ditches), or upland land use. Aggregating the UVVR, marsh plain elevation, and sediment-based lifespan (Ganju et al. 2020) over units enables a quantitative comparison of horizontal marsh deterioration and vertical status on actionable spatial scales.

In this paper, we describe application of existing methods (Defne et al. 2020; Ganju et al. 2020) to determine the marsh-unit based UVVR, elevation, and lifespan for guiding marsh restoration in Chesapeake Bay. We first detail the methodology for quantifying these spatial data, highlight general and regional trends, then demonstrate how the data may be used to identify restoration strategies using a simple decision matrix. Lastly, we describe how the lifespan calculation can be modified by restoration action and used to estimate relative gains in marsh lifespan given increases in sediment inventory and/or vegetative cover. All data used in this paper are published and publicly available (Ackerman et al. 2022; Defne et al. 2023).

Methods

Site Description

Chesapeake Bay (Fig. 1) is the largest estuary in the United States and contains over 1000 km^2 of vegetated tidal wetland (Ganju et al. 2022). The majority of tidal wetland area is emergent salt marsh, along the eastern edge of the Bay (Delmarva Peninsula) with the remainder distributed along the fringes of the tidal tributaries along the western edge of the Bay. Tidal freshwater wetlands comprise the remaining tidal wetland area, and though outside the scope of this study, are increasingly vulnerable to sea level rise and salinity intrusion (Noe et al. 2021). Salt marshes within Chesapeake Bay have experienced significant loss due to sea-level rise, sediment deficits, herbivory, and edge erosion (Kearney et al. 1988; Ganju et al. 2013; Stevenson et al. 2000; Sanford and Gao 2018). There have also been gains due to landward migration into coastal

Fig. 1 Chesapeake Bay and analysis subdomain boundaries. Base map graphic courtesy of Integrated Applications Network (http://ian.umces.edu)
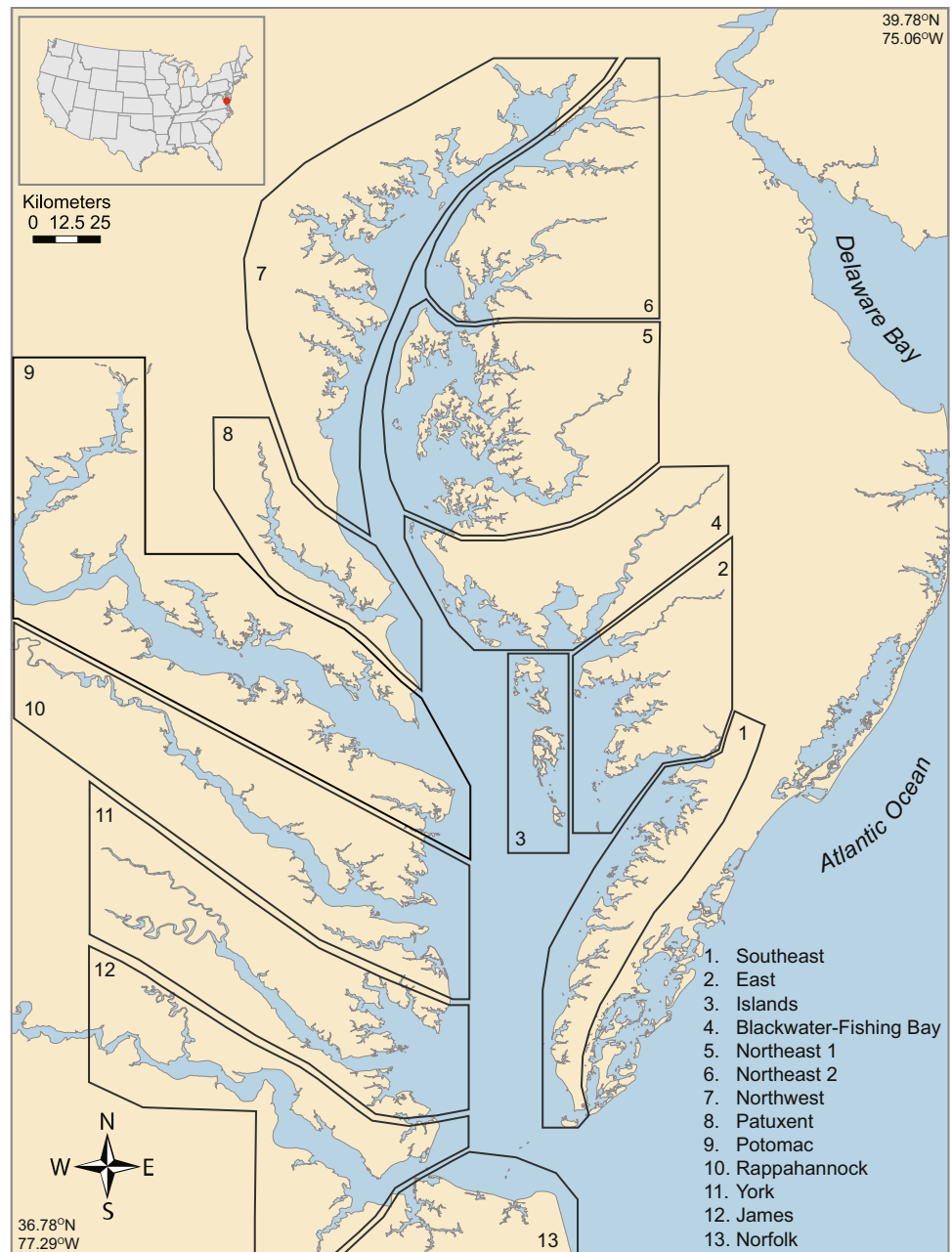
forest (Schieder et al. 2018) and restoration actions (Cornwell et al. 2020).

Elevation and Marsh Unit Delineation

The methods for using elevation to delineate marsh units are covered in detail by Ganju et al. (2020), and we briefly note the data sources and processing here. Elevation was extracted at 1-m horizontal resolution from the Coastal National Elevation Database (CoNED; Danielson et al. 2016). This dataset is limited by biases and errors related to the vegetation canopy (Buffington et al. 2016) but is essential for providing a consistent elevation product across regional scales. Elevation is reported relative to the NAVD88 datum and is also corrected to local mean tide level using VDatum (National Oceanic and Atmospheric Administration 2022) to enable cross-system comparison and lifespan calculations (below). The upland and open water boundaries were based on the National Wetland Inventory's (NWI) classification of estuarine intertidal wetlands (U.S. Fish and Wildlife Service 2019). The elevation data were used to delineate the marsh into hydrologically connected units using GIS analysis (Ganju et al. 2017).

UVVR Imagery Analysis

The UVVR was determined using variable resolution (0.6 or 1.0 m) aerial imagery from the National Agriculture Imagery Program (NAIP) (U.S. Department of Agriculture 2016, 2017, 2018) and Coastal National Elevation Database (CoNED), with the Marsh Edge from Image Processing (MEIP) method (Farris et al. 2019). The four bands from NAIP imagery and the elevation dataset were grouped into 32 classes with unsupervised classification, performed across several subregions of the estuary. This classified data was then reclassified to vegetated and unvegetated areas by visual comparison with the visible spectrum NAIP imagery (red, green, blue bands). The unvegetated and vegetated pixels were then aggregated across marsh units to provide areas; the UVVR is the ratio of unvegetated to vegetated area. Unvegetated areas typically consist of bare sediment, ponds, pannes, and channels. Note that Ganju et al. (2022) provide a Landsat-based UVVR at a coarser 30-m resolution for the conterminous United States; that product is ideal for aggregating data over regional scales (Ganju et al. 2023), while the NAIP-based product developed here is more appropriate for aggregation over individual marsh units. Further differences between the two methodologies are discussed by Ganju et al. (2022).

Lifespan Calculation

The sediment-based marsh lifespan (Ganju et al. 2017) quantifies a conceptual timescale by which the sediment mass in the vegetated plain, above mean sea level, can offset sediment deficits due to open-water conversion and sea-level rise. The method presented by Ganju et al. (2020) requires the UVVR, marsh plain elevation, sea-level rise, and substrate density across each marsh unit. The relationships used here were developed across eight microtidal marshes on both the Atlantic and Pacific US coasts (Ganju et al. 2017), and are considered generally applicable to microtidal marshes. First, the net sediment budget of a marsh system, Q_b (in kg m^{-2} y^{-1}), is assumed to be dependent on the UVVR based on the relationship presented by Ganju et al. (2017) as:

$$Q_b = -0.416 \, log \, UVVR - 1.075 \quad (1)$$

This sediment budget computed by Ganju et al. (2017) is based on measured sediment fluxes and historical or background sea-level rise rates; the future sediment budget, Q_{b_future} under increased sea-level rise rate, can then be computed as:

$$Q_{b\_future} = Q_b - _{\rho min} \times (SLR_{future} - SLR_{bgrnd}) \quad (2)$$

where r_{min} is the representative minimum dry bulk density required to keep up with sea-level rise (159 kg m^{-3}

following Morris et al. 2016; Ganju et al. 2017), SLR_{bgrnd} is the historical, local background sea-level rise rate (m y^{-1}), and SLR_{future} is the future sea-level rise rate (m y^{-1}). Note that at a UVVR ~ 0.08, the present-day sediment budget is predicted to be neutral; the sediment deficit caused by sea-level rise alone can be enforced by setting $Q_b = 0$. The total available sediment mass in the vegetated marsh plain, M_{sed}, is then approximated as:

$$M_{sed} = E_m \times A_{veg} \times \rho mean \quad (3)$$

where E_m is the mean elevation above mean sea level of the vegetated marsh plain within each marsh unit, A_{veg} is the vegetated area within the unit, and r_{mean} is a representative mean dry bulk density of the sediment stored within the marsh plain (373 kg m^{-3} following Morris et al. 2016; Ganju et al. 2017). Next, the sediment-based lifespan of the marsh system under historical sea-level rise rates, L_{sed}, is calculated as:

$$L_{sed} = -M_{sed}/(Q_b \times A) \quad (4)$$

where A is the total area of the marsh unit (i.e., sediment is assumed to be extracted from the entire system, not only the vegetated plain). The negative sign is required to convert the sediment export (negative) to a positive lifespan (units with a positive sediment import have an undefined lifespan). This calculation is performed for each marsh unit to yield a distribution of lifespans across each system. Site-specific bulk densities can be used if local data are available.

Future lifespan under increases in sea-level rise rate, L_{sed_future}, is obtained by:

$$L_{sed\_future} = -M_{sed}/(Q_{b\_future} \times A) \quad (5)$$

All lifespan estimates produced here and by Defne et al. (2023) use the NOAA sea-level rise projections interpolated to each marsh unit. We implement the medium, 50th percentile scenario for global mean sea level (GMSL) rise rates of 0.3, 0.5, and 1.0 m by 2100. Note that local sea-level rise rates in Chesapeake Bay are significantly higher than global mean sea-level rise rates (Ezer 2023).

Results and Discussion

Geospatial data sets for the UVVR, elevation, lifespan, and associated parameters (Fig. 2) can presently be accessed via ScienceBase (Ackerman et al. 2022; Defne et al. 2023) as well as the USGS Coastal Wetland Synthesis Geonarrative (https://geonarrative.usgs.gov/uscoastalwetlandsynthesis/; "Synthesis Sites" tab). Users can visualize and investigate the data through a web browser or download the data into a geospatial software program for in-depth analysis. Below, we discuss general and regional patterns in the geospatial data.
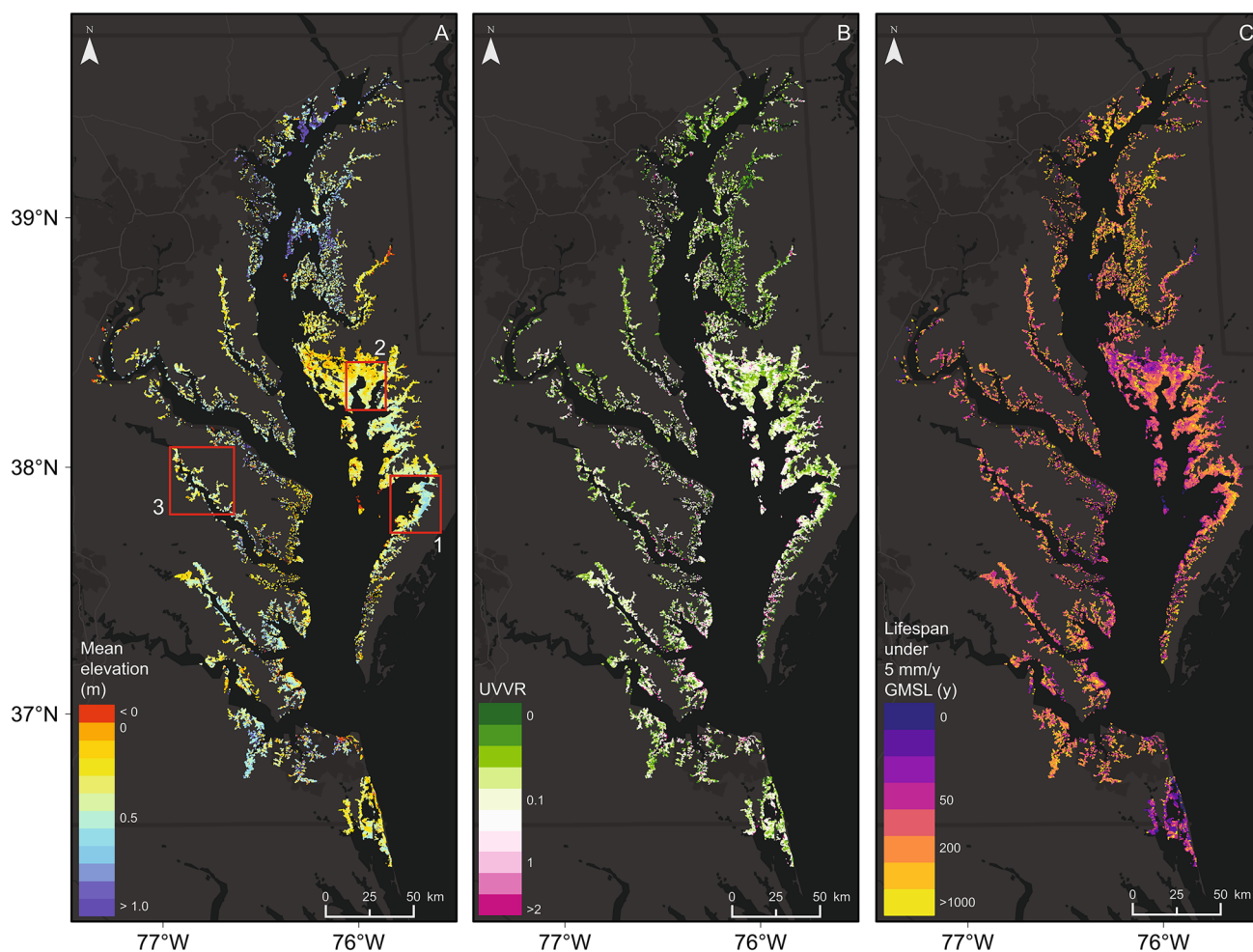
Fig. 2 Geospatial results for entire domain (Ackerman et al. 2022); **A** mean marsh unit elevation, **B** unvegetated-vegetated marsh ratio (UVVR), and **C** sediment-based lifespan under 5 mm/y global mean sea level (GMSL) rise scenario. Insets 1–3 on panel A indicate areas shown in Fig. 7. Area south of Norfolk subdomain was not included in this analysis but is included in the companion data release due to overlapping imagery coverage

Spatial Trends in Elevation, UVVR, and Lifespan

Spatial trends were first analyzed by grouping marsh units into 13 tributaries and/or regions (Fig. 1; Table 1). The largest region, by total wetland area, is the Blackwater-Fishing Bay subdomain (301 km^2), while the smallest is the Norfolk subdomain (16 km^2).
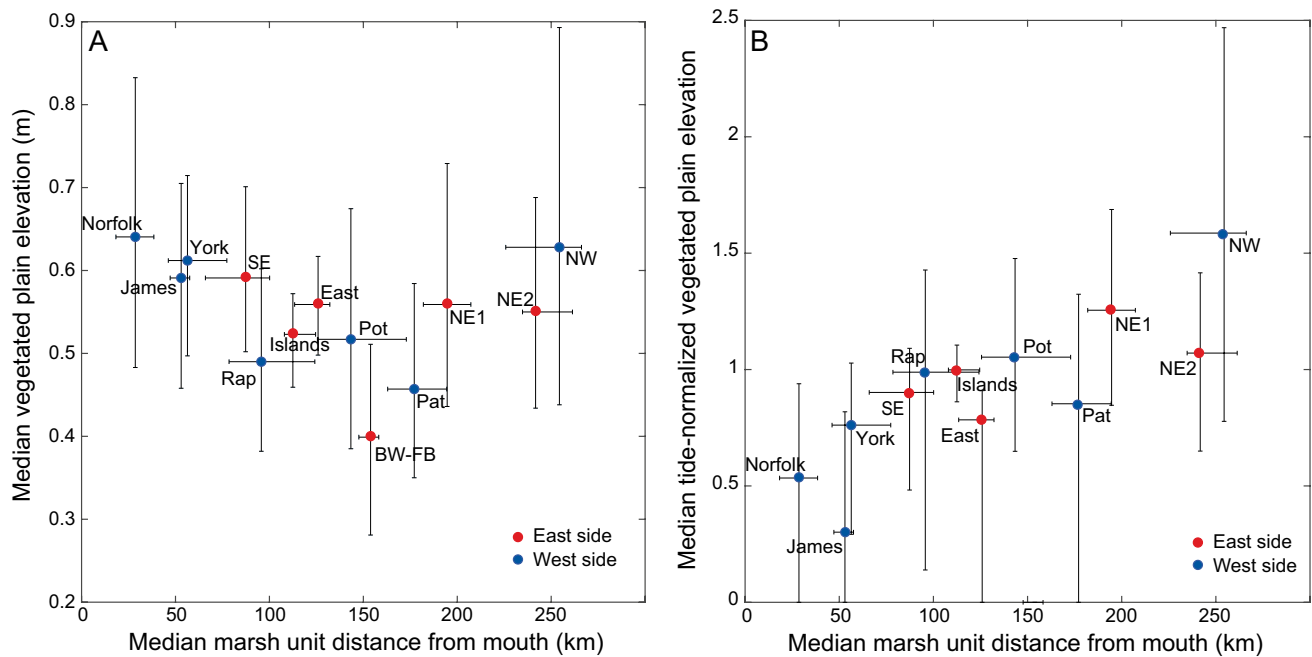
Median vegetated plain elevations were lowest in the Blackwater-Fishing Bay subdomain (Table 1), an area with substantial wetland loss and open-water conversion (Schepers et al. 2020). The highest median vegetated plain elevation was within the Norfolk subdomain, at the seaward end of the Bay. This is also the region with the highest tidal range, perhaps suggesting the influence of tidal range on vertical elevation trajectory (Kirwan and Guntenspergen 2010). There is a trend of vegetated plain elevation with distance from the seaward end of the Bay that suggests

a minimum near the middle of the Bay, with both the Blackwater-Fishing Bay and Patuxent subdomains having the lowest elevations on the east and west sides, respectively (Fig. 3A). Potential causes could be local vertical land motion (Sherpa et al. 2023), or antecedent geology and slope. Normalizing elevations by the tide range transforms the trend into a clear increasing elevation with distance from the mouth (Fig. 3B). The tide-normalized elevation is akin to the relative tidal elevation, or Z* (Holmquist and Windham-Myers 2022) and is often used as a proxy for delineating low marsh from high marsh regions. The Blackwater-Fishing Bay subdomain was excluded from this analysis as the VDatum tidal model had no data for over 50% of the marsh units.

The highest median UVVR (0.20) was observed across the Islands subdomain, consisting of several islands along the southeastern region of the estuary. These islands include Smith, Tangier, and Martin Islands. The enhanced

Table 1 Inventory, median values, and percentage of units above the 0.15 UVVR threshold for marsh units within each Chesapeake Bay subdomain (Ackerman et al. [2022]) (Fig. [1]). NAVD88, North American Vertical Datum of 1988; MTL, mean tide level from NOAA VDatum; UVVR, unvegetated-vegetated marsh ratio; GMSL, global mean sea level rise scenario. Total area includes vegetated and unvegetated areas

Subdomain	# of units	Total area (km²)	Marsh unit elevation (m NAVD88)	Vegetated plain elevation (m MTL)	Distance from Bay mouth (km)	Tide range (m)	UVVR	Lifespan GMSL 5 mm/y (y)	Lifespan GMSL 10 mm/y (y)	% units UVVR > 0.15
Southeast	3886	108	0.42	0.59	87	0.57	0.14	156	102	47%
East	4854	202	0.42	0.56	126	0.62	0.10	173	108	35%
Islands	1569	56	0.32	0.52	112	0.50	0.20	120	80	67%
Blackwater—Fishing Bay	7095	301	0.27	0.40	154	N/A	0.10	121	76	38%
Northeast 1	4010	48	0.45	0.56	195	0.42	0.06	206	122	23%
Northeast 2	1652	23	0.46	0.55	242	0.48	0.05	222	130	17%
Norfolk	1533	16	0.46	0.64	29	0.72	0.16	168	108	52%
James	3258	72	0.45	0.59	53	0.60	0.10	170	109	38%
York	4758	111	0.46	0.61	56	0.65	0.13	163	105	45%
Patuxent	1359	24	0.39	0.46	177	0.40	0.08	144	88	33%
Potomac	3586	46	0.41	0.52	143	0.44	0.11	148	95	42%
Rappahannock	3042	50	0.36	0.49	96	0.36	0.13	132	85	46%
Northwest	2256	42	0.57	0.63	254	0.34	0.05	232	137	23%

Fig. 3 **A** Subdomain-wide median vegetated plain elevation above mean tide level versus median marsh unit distance from mouth of Chesapeake Bay; and **B** subdomain-wide median tide-normalized vegetated plain elevation versus median marsh unit distance from mouth of Chesapeake Bay. Vertical and horizontal bounds are 25th and 75th percentiles of unit data within each subdomain. Blackwater-Fishing Bay subdomain (BW-FB) removed from tide-normalized comparison due to over 50% null values in the tide data set over that region

deterioration of these marshes may be related to a lack of connection with watershed sediment supply, as well as exposure to wind-waves and ensuing edge erosion. The Norfolk subdomain, near the mouth of the Bay, has a median UVVR of 0.16, exceeding the nominal 0.15 stability threshold established in prior studies (Ganju et al. 2022; Wasson et al. 2019). This area has been experiencing relatively high sea level rise and flooding (Ezer 2023) and therefore, there may also be a connection between inundation stress and wetland deterioration. Both the Islands and Norfolk subdomains also had the highest fraction of wetlands over the 0.15 threshold, with 67% and 52% respectively. All other subdomains had median UVVR below the 0.15 threshold, with lowest median values observed in the northern regions of the Bay (Northeast 1 and 2, Northwest subdomains). These regions also had less than 25% of units above the 0.15 threshold. The median UVVR for each subdomain shows a distinct increasing trend in the landward-to-seaward direction (Fig. 4). The correlation increases if the "Islands" subdomain is neglected (discussed below), and the 75th percentile value (upper bounds) also suggests a clear increase in the seaward direction.

Considering all marsh units together, elevation and UVVR were weakly negatively correlated ($r^2 = 0.07$), though bin-averaged data suggests a stronger trend ($r^2 = 0.92$) of decreased elevation with increasing UVVR (Fig. 5). On a subdomain-by-subdomain basis, some subdomains show distinct correlation between elevation and UVVR, whereas others do not (Fig. 6). The second-highest correlation ($r^2 = 0.87$) was found in the Islands subdomain, likely due to the presence of unvegetated, low elevation intertidal flats within marsh units. Virtually, no correlation was observed in the northwest of the Bay (Patuxent and Northwest subdomains).

The lifespan metric integrates elevation and UVVR and therefore shows no clear pattern relative to position in the Bay. Lifespans are lowest in the Islands and Blackwater-Fishing Bay subdomains, respectively due to UVVR and elevation. This suggests that the Islands subdomain is exhibiting a trajectory of horizontal deterioration despite significant elevation capital, while the Blackwater-Fishing Bay subdomain is exhibiting submergence with comparatively less horizontal deterioration (Ganju et al. 2023). Nonetheless, the lifespans are similar, which assists in prioritizing regional restoration based on this combined metric rather than one metric alone.

Within each subdomain, the coherence between position and deterioration becomes more complex despite the coherence between elevation and UVVR. Three examples from different subdomains demonstrate different modes of deterioration (Fig. 7). The Southeast subdomain is dominated by fringing marsh which exhibits increasing elevation and decreasing UVVR (increasing horizontal integrity) moving upslope; this generally follows conceptual models of coastal

Fig. 4 Subdomain-wide median unvegetated-vegetated marsh ratio (UVVR) versus median marsh unit distance from mouth of Chesapeake Bay; colors indicate median sediment-based lifespan under global mean sea level rise (GMSL) of 5 mm/y. Vertical and horizontal bounds are 25th and 75th percentiles of unit data within each subdomain
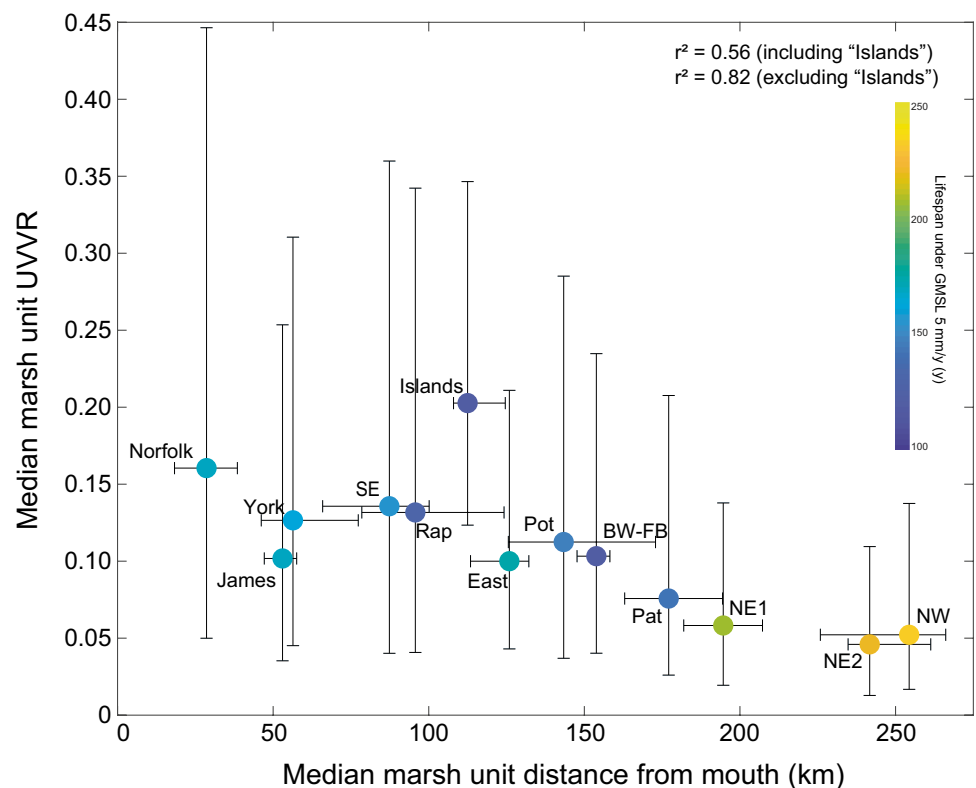
deterioration in response to sea-level rise (discussed below). Further north, a peninsula in the Blackwater-Fishing Bay subdomain shows interior deterioration in both elevation and horizontal integrity, a pattern seen throughout peninsulas in this area. The underlying cause may be distance from Bay or watershed sediment sources, or more complex interactions between tidal hydrology, frictional effects, sediment transport, and/or biogeochemical processes (Zapp and Mariotti 2023). Lastly, tidal river subdomains such as Rappahannock do not show clear patterns of elevation and UVVR. Marsh-unit geomorphology in these areas is likely controlled by location of the marsh relative to meanders, local sediment inputs, and antecedent slope/forest boundaries. Management of these areas might require finer-scale investigation to determine causes of wetland deterioration.

The general increase in deterioration and UVVR along a landward-to-seaward continuum aligns with the geomorphic concept of coastal transgression in response to sea-level rise (Fitzgerald et al. 2018). The physical forces associated with increased sea level at the seaward edge cause geomorphic instability and will tend to move landforms in the landward direction with sea-level rise. Open-water conversion of salt marshes and tidal wetlands will be one consequence of that transformation. The correlation between the UVVR and position is stronger if "Islands" marsh units are neglected, which is coherent with this concept, as the island marsh units are disconnected from both the watershed and lack a

landward-seaward geomorphic gradient. The spatial pattern of elevation (and therefore lifespan) somewhat confounds this interpretation, but the coherence between elevation and UVVR across most subdomains does support such a conceptual model. In addition, marsh units that conform to this conceptual model, as well as those units that do not, provide insight into management approaches using these data.

Management Applications

Geospatially comprehensive data provides a robust platform for landscape-scale decision-making and management. Once a common geospatial framework is established across a landscape, additional data sources of disparate spatiotemporal resolution can add information and contrast, identify a suite of potential management options, and enable even comparisons between landscape parcels. In this work, the marsh unit delineation along with quantification of vegetative cover and elevation metrics establishes an objective base data set which can be combined with in-situ observations of habitat quality, vertical elevation change, biomass, and carbon stocks for improved management. Marsh units are not necessarily the optimal aggregation scale for every management application, but they strike a balance by aggregating objective, pixel-based data into physically meaningful units that are bounded

Fig. 5 Marsh unit elevation relative to mean tide level versus UVVR for all marsh units (Fig. 2), colored by lifespan under a global mean sea level rise (GMSL) scenario of 5 mm/y. Coefficient of determination (r.²) based on bin-averaged values (red points); bounds indicate 25th and 75th percentiles of elevation range within each UVVR bin (0.05 intervals)
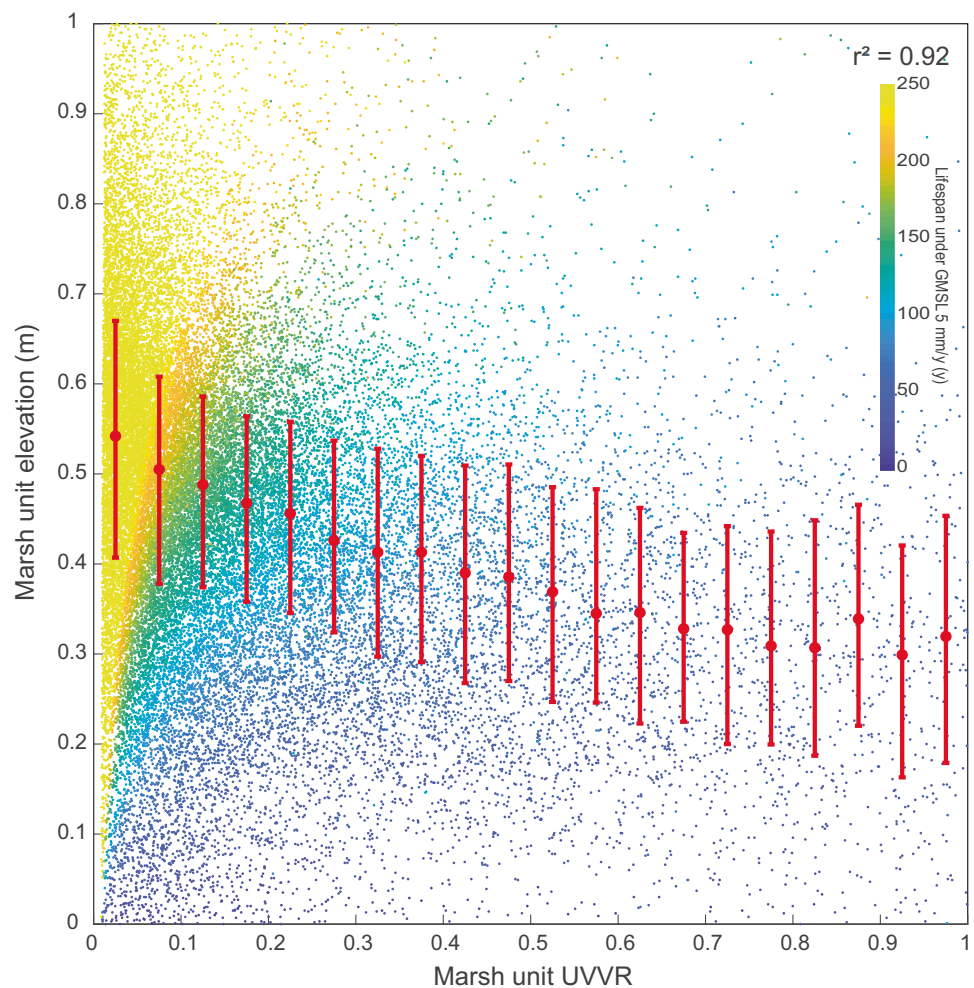

by geomorphic features. Furthermore, marsh units can be aggregated to larger scales as needed by managers, depending on the objective. The arbitrary aggregation performed across 13 subdomains in the Bay may be useful for Bay-wide prioritization, but agencies with specific interests may prefer to aggregate marsh units across state management areas, wildlife refuges, or national parks, to prioritize action. In the following sections, we demonstrate stand-alone uses of these data in management applications but also stress the importance of incorporating multiple data layers (e.g., land use, feasibility, monitoring locations) to refine management responses.

Decision Matrix

Elevation capital has traditionally served as the primary metric for determining wetland vulnerability to sea-level rise (Cahoon et al. 2019). The addition of the UVVR as a horizontal vulnerability metric offers an opportunity to base management decisions on three-dimensional considerations.

This study and prior efforts (Ganju et al. 2020, 2023) have quantified general trends between the UVVR and elevation, with higher marshes tending to have lower UVVR, and lower marshes exhibiting higher UVVR. While that general correlation is coherent with our understanding of marsh deterioration in response to sea-level rise, the outliers to that relationship can inform restoration practice. For example, we develop a simple 2×2 decision matrix based on thresholds of high and low elevation, and high and low UVVR. Depending on where a marsh unit falls within this matrix, different actions may be appropriate and can also be cast within the Resist-Accept-Direct framework (Schuurman et al. 2022).

For this example, we select a 0.4 m vegetated plain elevation threshold (relative to NAVD88), and the established 0.15 UVVR threshold to delineate a 2×2 matrix (Fig. 8). This elevation is close to the median elevation of marsh units across the domain (Table 1). Marsh units with high elevation and a UVVR < 0.15 (vertically and horizontally least vulnerable; Ganju et al. 2022) are essentially not a high priority for restoration given no deterioration. However, these
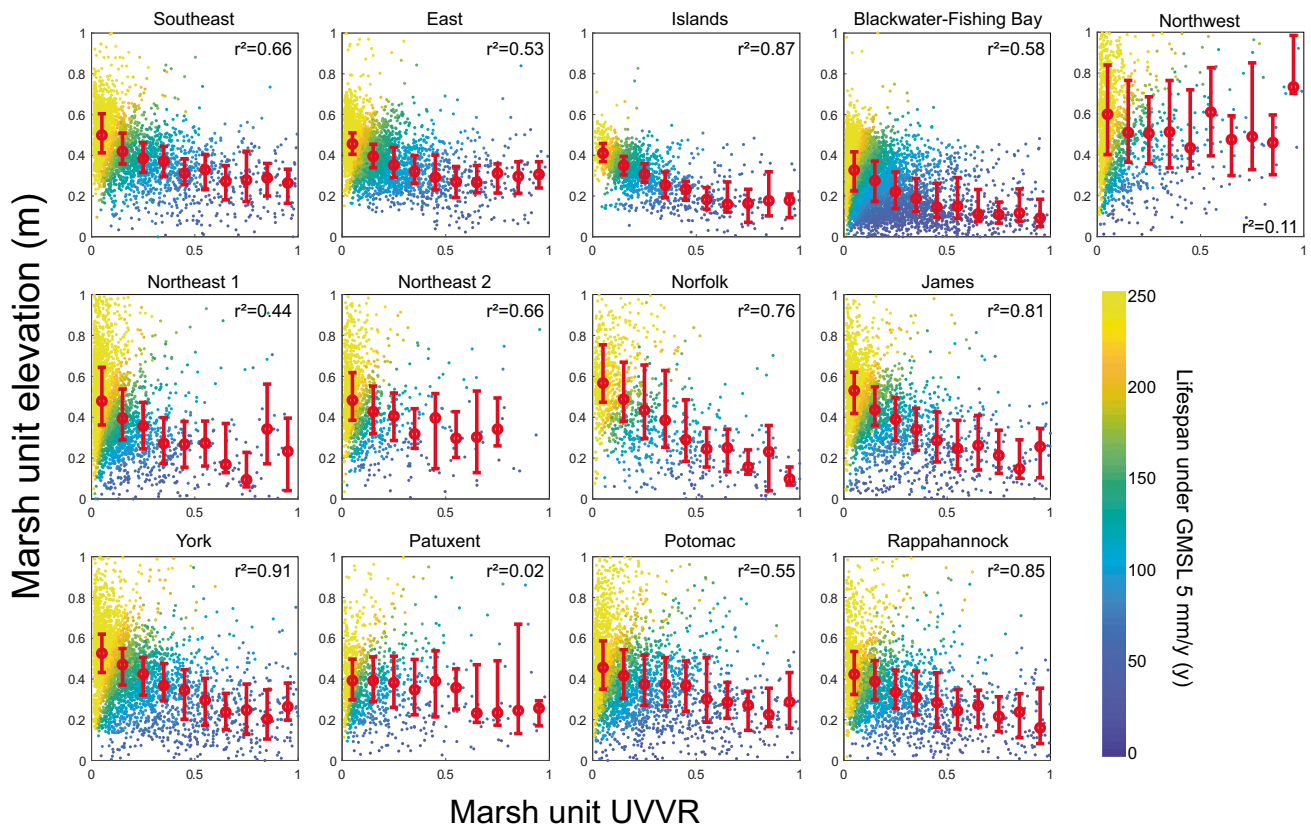
Fig. 6 Marsh unit elevation relative to NAVD88 versus UVVR for each of thirteen subdomains (Fig. 1), colored by lifespan under a global mean sea level rise (GMSL) scenario of 5 mm/y. Coefficient of determination (r.²) for each subdomain based on bin-averaged values (red points); bounds indicate 25th and 75th percentiles of elevation range within each UVVR bin (0.10 intervals)

units would be candidates for protection and conservation if not already protected. Furthermore, if these units are adjacent to potential migration corridors, the upland area could also be targeted for conservation as the marsh is intact and will have a higher capacity to remain intact as sea-level and storms aim to push the marsh-upland boundary landward. This example can be cast as a "Direct" action, where the conservation of intact boundary units aims to facilitate transformation of the upland land class to salt marsh in the future.

In the lower right quadrant of the decision matrix, we identify low elevation, high UVVR marsh units: vertically vulnerable and already exhibiting signs of horizontal deterioration. There are several potential actions that may be appropriate for such parcels, but if resources are limited then the first step would be evaluation of the co-benefits of the marsh parcel. For example, is the parcel valuable habitat for listed species, or adjacent to vulnerable infrastructure? In the case of limited resources and/or limited co-benefits of restoring the parcel (i.e., not serving as critical habitat or coastal protection), the "do-nothing" approach may be warranted, which falls under the "Accept" category. However, if the parcel is serving an important function as habitat or infrastructure protection, for example,

then sediment augmentation and/or re-vegetation may be suitable. This would constitute a "Resist" action: the benefits of restoring the parcel outweigh the costs despite potentially short lifespan in response to restoration.

In the lower left quadrant, we identify low elevation units that are still horizontally intact (low UVVR). While these units may be susceptible to submergence, they have not yet exhibited loss of vegetated plain, and therefore, improvement options may be somewhat limited. These units would be ideal candidates for increased monitoring, so that any signs of submergence or horizontal deterioration (e.g., open-water expansion or ponding) can be detected before rapid changes in ecosystem services. Along with monitoring, investigation of potential causes would be warranted and could include impaired hydrology, locally high subsidence, or sediment deficits.

Lastly, we identify marshes in the upper right quadrant: high UVVR and high elevation, indicating horizontal deterioration but significant elevation capital of the vegetated marsh plain. These units may be candidates for techniques that either increase sediment mass and/or increase vegetated cover. The existing elevation capital provides some indication of resilience of the remaining vegetated plain,
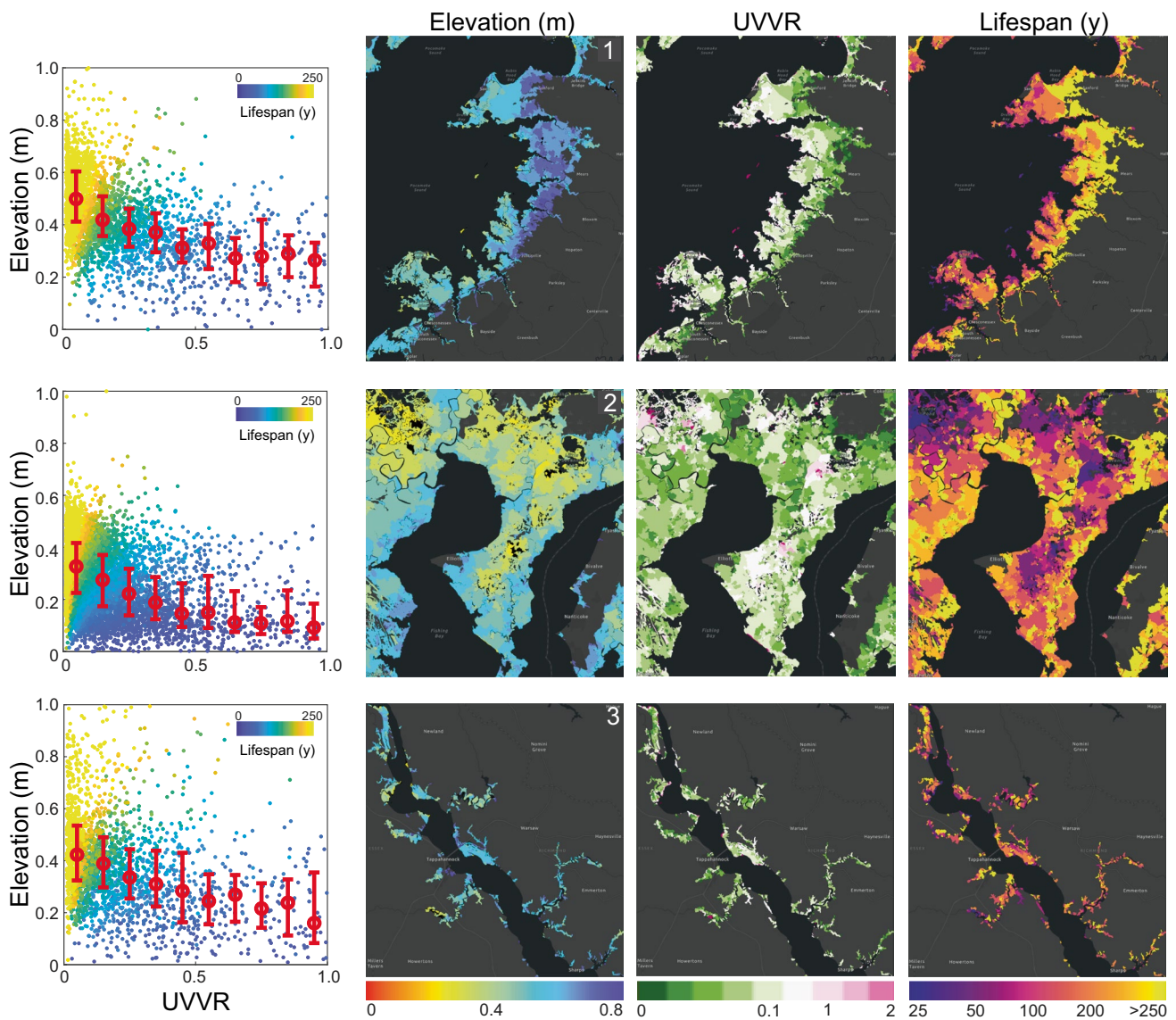
Fig. 7 Mean marsh unit elevation versus UVVR for three subdomains, with insets of elevation, UVVR, and lifespan under 5 mm/y GMSL from Southeast (top row), Blackwater-Fishing Bay (middle row), and Rappahannock (bottom row) subdomains. Locations correspond to insets in Fig. 2

and perhaps requires less resources given the higher elevation starting point. Thin-layer placement, passive sediment augmentation, and related techniques would increase the "balance" in the parcel's sediment account. Depending on the elevation of the unvegetated areas, poorly drained areas could potentially revegetate via runnels (Besterman et al. 2022), while bare well-drained areas could be revegetated through manual planting. In some locations within Chesapeake Bay, these units appear on marsh-forest boundaries, and restoration of these units may facilitate marsh migration.

The benefit of this approach arises from the ability to rapidly map decisions on the landscape (Fig. 9; https://geonarrative.usgs.gov/uscoastalwetlandsynthesis/) in tandem with other geospatial or geo-referenced data. For example, units that fall in the upper left quadrant (high elevation, low UVVR) can immediately be mapped in comparison with conservation layers, and any units that are not currently protected can be prioritized. Units in the lower left quadrant (low elevation, low UVVR) can be compared against existing on-the-ground measurements of elevation change, aboveground biomass, and/or species distribution so that if observational protocols are not in place, a monitoring program can be instituted to detect impending submergence or open-water conversion. Units in the bottom right quadrant can be compared with ecosystem services (habitat, carbon stock) and infrastructure layers so that units with higher service or coastal protection value can be prioritized for improvement

Fig. 8 Restoration decision matrix based on elevation and UVVR thresholds. Ensuing map (Fig. 9) uses a 0.4 m vegetated plain elevation threshold, and the established 0.15 UVVR threshold. Decisions within the matrix represent potential options; managers with specific mandates and considerations must establish options that conform to their goals, objectives, and constraints
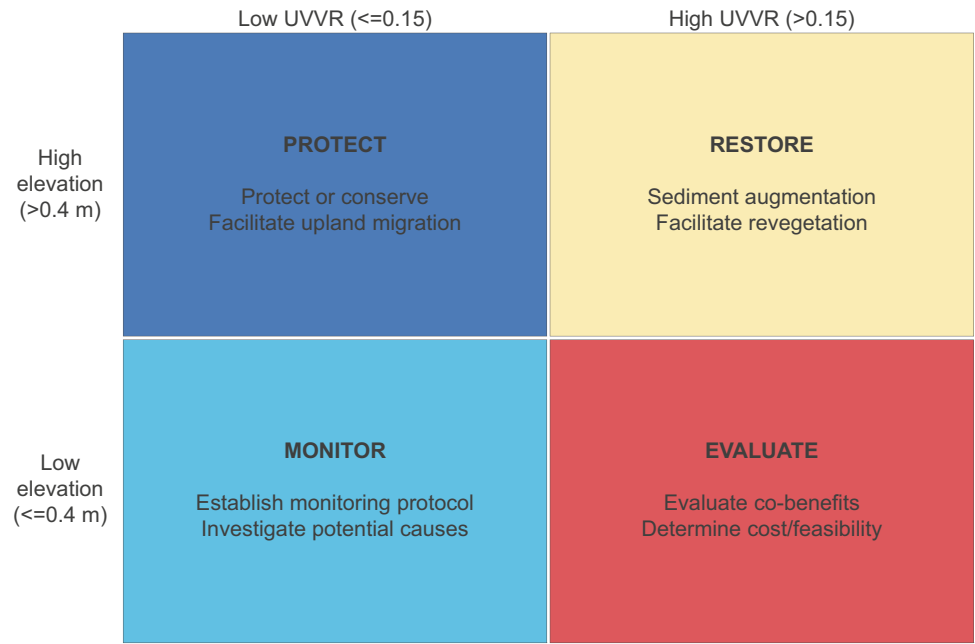
(these units can also be compared with known dredging locations to minimize distance for beneficial sediment re-use). Units in the upper right quadrant can be overlain with upland migration corridors to prioritize units for improvement in order to facilitate migration. For all cases, the elevation and UVVR thresholds can be modulated as needed to split the decisions into bins of any desired acreage (e.g., if an agency targets a certain acreage of marsh for improvement or acquisition).

Fig. 9 Decision matrix using a 0.4 m vegetated plain elevation and 0.15 UVVR threshold mapped on two different areas of the Blackwater-Fishing Bay subdomain. Upper example represents a low elevation, horizontally degraded unit within a larger open-water area; if substantial co-benefits are identified upon evaluation, restoration may be an option. Lower example represents a high elevation, horizontally degraded unit adjacent to the marsh-forest boundary. Restoration may be a suitable option given the potential for landward migration of intact salt marsh. Right panels refer to starred polygon on left panels
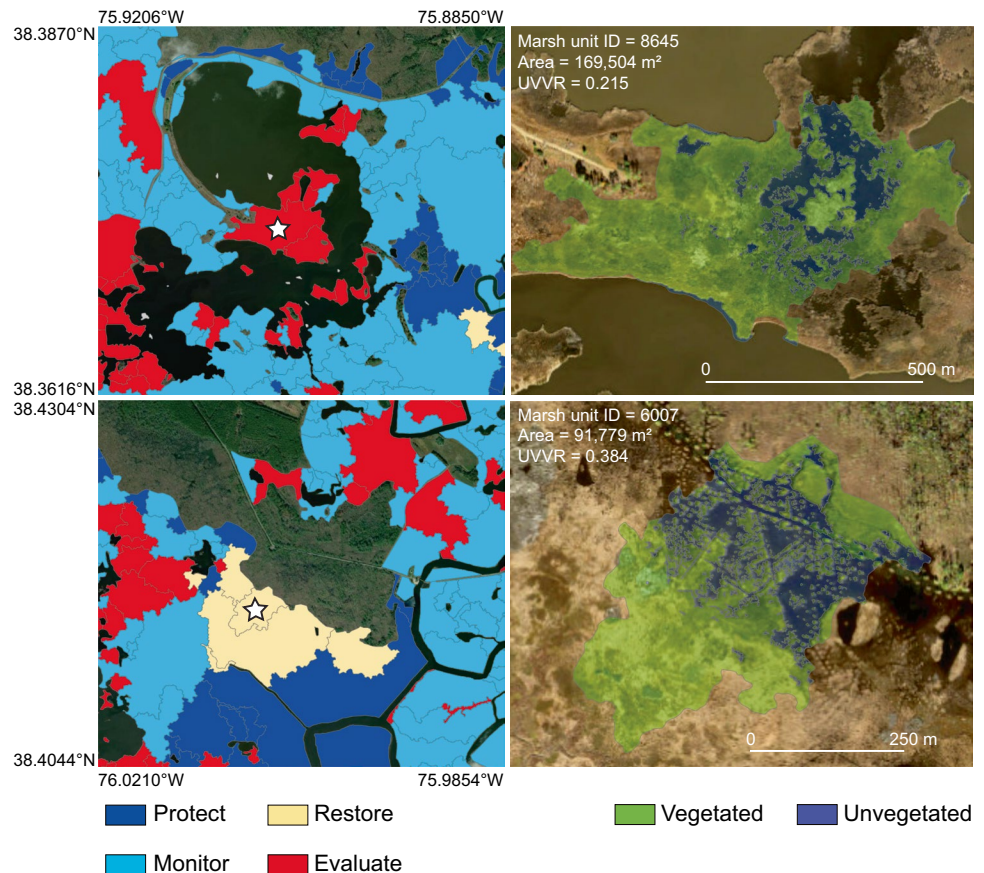
Lifespan Calculation in Response to Restoration Actions

Once a marsh unit has been identified as a candidate for restoration, an objective method to estimate the relative benefits of restoration is critical. The lifespan metric potentially serves as a straightforward quantity that can account for restoration-induced changes in elevation and vegetation. The lifespan metric concept aims to combine elevation, horizontal deterioration, and sea-level rise into a single timescale. It is not a quantitative prediction of when a marsh parcel will cease to exist: as long as there is some vegetated plain above mean sea level, the lifespan will have a positive value. Nienhuis and van de Wal (2021) present a similar sediment balance model for predicting deltaic response to sea-level rise, which compares sediment supply with relative sea-level rise and yields the time rate of change of delta area. In contrast, our lifespan calculation holds present marsh area constant and predicts the "expenditure" of that marsh substrate sediment mass by sediment deficits induced by sea-level rise and open-water conversion. Based on Eqs. 1–5, we can explicitly include any restoration action that aims to increase sediment mass, elevation, or vegetative cover, and implement variable sea-level rise rates. We will discuss each modification sequentially and describe two case studies from Chesapeake Bay that we identify with the 2×2 decision matrix.

Techniques such as sediment placement on unvegetated marsh plain, within pannes, or within ditches represent an incremental addition of sediment mass into the M_{sed} variable in Eq. 3. Sediment placement is prescribed by specifying an addition area, thickness, and dry bulk density as placed, with the additional mass M_{add} specified as:

$$M_{add} = A_{add} \times d_{add} \times \rho_{add} \tag{6}$$

where A_{add} is the addition area in m², d_{add} is the addition thickness in meters above mean sea level, and r_{add} is the addition dry bulk density in kg m⁻³. The new lifespan in years, L_{new}, is now calculated as:

$$L_{new} = -(M_{sed} + M_{add})/(Q_b \times A) \tag{7}$$

In the case of revegetation after sediment addition, the mass added due to revegetation is calculated in the same manner as Eq. 6, except the dry bulk density of the existing substrate from Eq. 3 is used. This assumes that biogeochemical processes will ultimately modify the substrate density to match the existing marsh substrate density. The revegetated and initial sediment addition areas must also be separated to avoid double-counting of the sediment mass. Separate input of thickness and density allows the user to neglect compaction processes that may occur after placement but do not affect mass. Conceptually, the mass should only be considered an addition if placed above mean sea level, with the implication that

supplying sediment to subtidal areas below mean sea level will not directly benefit the vegetated marsh plain; however, this constraint can be neglected if external sediment is placed within the marsh complex (as opposed to peripheral intertidal flats). Techniques such as subtidal placement could be represented if external mineral supply was expected to increase due to the action, and that can be considered using the mineral sediment supply modification described below.

Increasing vegetative cover has a two-fold effect: it decreases the UVVR and therefore decreases sediment export via open-water conversion as estimated by Eq. 1, and it also adds the sediment mass above MSL that is below the vegetated area (i.e., marsh substrate) in Eq. 3 as mentioned above. The latter increase applies in situations where replanting or natural revegetation is expected after a sediment addition to a specific elevation relative to MSL, or if unvegetated areas already above MSL are revegetated. If revegetation of a near-MSL bare area (e.g., a low elevation, runneled panne) is expected, the only increase in lifespan would arise from the decrease in UVVR. An updated UVVR, $UVVR_{new}$, is computed from the new vegetated area, A_{v_new}, as:

$$A_{v\_new} = A_{v\_old} + A_{reveg} \tag{8}$$

$$A_{uv\_new} = A - A_{v\_new} \tag{9}$$

$$UVVR_{new} = A_{uv\_new}/A_{v\_new} \tag{10}$$

where A_{v_old} is the original vegetated area, A_{reveg} is the additional vegetated area, A_{uv_new} is the updated unvegetated area, and A is the total marsh unit area.

If local measurements or estimates are available, changes in organic accretion and/or external mineral sediment input due to hydrologic modifications can be implemented by modifying the sediment budget term (Eq. 1). Organic accretion can be applied to the vegetated plain area as an annual sediment input, while external supply is added as an annual mass flux rate to the entire unit, as:

$$Q_{b\_new} = Q_b + (Q_{org} \times A_{veg}) + Q_{ext} \tag{11}$$

where Q_{b_new} is the updated sediment budget, Q_b is the original sediment budget, Q_{org} is the organic accretion rate in kg m⁻² y⁻¹, A_{veg} is the vegetated plain area, and Q_{ext} is external mineral sediment supply in kg y⁻¹. Both modifications serve as a "deposit" in the sediment account and will extend the lifespan of the unit. In the case of specifying external supply based on in-situ measurements, the predicted sediment budget from Eq. 1 could be eliminated, unless the external supply is a modification to the system's current state (e.g., removal of a sediment-retaining structure). An interactive lifespan calculator that

implements these geospatial data and restoration actions can be accessed via the USGS Coastal Wetland Synthesis Geonarrative (https://geonarrative.usgs.gov/uscoastalwetlandsynthesis/). Users can implement the above restoration scenarios as well as variable sea-level rise rates. Lifespan estimates due to sea-level rise only (i.e., ignoring the sediment flux — UVVR relationship in Eq. 1, and setting $Q_b = 0$ in Eq. 2) can be calculated as an additional option.

Based on the 2×2 matrix, we identify two marsh unit examples in Chesapeake Bay that fall into potential restoration scenarios and apply the same restoration activities to both (Fig. 9). First, a low elevation, high UVVR marsh unit (unit ID 8645, 75.9036 W, 38.3732 N) in Savannah Lake between the Nanticoke River and Fishing Bay falls into the "evaluate co-benefits/determine cost" category. The total marsh unit area is 169,504 m², the vegetated plain elevation is 0.29 m above mean tide level, and the UVVR is 0.215 (Table 2). With regard to co-benefits, the unit is within a larger open water area and not adjacent to infrastructure that it might protect. However, comparison with ecological community layers may reveal it as important habitat and therefore deemed suitable for intervention. The present-day lifespan estimate is 66 years under 5 mm y^{-1} of GMSL (7.6 mm y^{-1} locally, with a 2 mm y^{-1} historical background rate). A sediment placement project that covers 25,000 m² of unvegetated area to 0.29 m (same elevation as the marsh, assuming an initial elevation of 0 m) at a bulk density of 500 kg m^{-3} will yield a new lifespan estimate of 82 years. If we further assume that half (12,500 m²) of that area will then revegetate at that

elevation, we reduce the UVVR to 0.115, and estimate a lifespan increase to 100 years.

Secondly, we consider a high elevation, high UVVR marsh unit (unit ID 6007, 76.0074 W, 38.4150 N) on the marsh-forest boundary between the Transquaking River and Blackwater National Wildlife Refuge that falls within the "sediment augmentation/facilitate revegetation" category. The total marsh unit area is 91,779 m², the vegetated plain elevation is 0.50 m above mean sea level, and the UVVR is 0.384 (Table 3). This unit already benefits from high elevation capital and a far landward position that suggests upland migration may be possible if the marsh is intact. The present-day lifespan estimate is 87 years under 5 mm y^{-1} of GMSL (7.6 mm y^{-1} locally, with a 2 mm y^{-1} historical background rate). A sediment placement project that covers 25,000 m² of unvegetated area to 0.50 m (same elevation as the marsh, assuming an initial elevation of 0 m) at a bulk density of 500 kg m^{-3} will yield a new lifespan estimate of 130 years. If we further assume that half (12,500 m²) of that area will then revegetate at that elevation, we reduce the UVVR to 0.16, and estimate a lifespan increase to 161 years. Note in both of these examples that the sediment addition and revegetation actions must be input separately over the project areas if revegetation of the initial sediment addition area is expected: for example, the sediment addition-only action is specified over 25,000 m², while the addition assuming revegetation is specified as two separate actions over 12,500 m² each: one as a sediment addition without revegetation, and a second as a sediment addition with revegetation.

Table 2 Lifespan calculator inputs and outputs for marsh unit 8645 (Fig. 9). Post-restoration scenarios include (1) sediment addition over a pre-defined area that assumes the unvegetated area was at mean sea level and sediment was added to the elevation of the existing vegetated marsh plain and (2) addition with assumed revegetation of 50% of the addition area to the same elevation as the existing vegetated marsh plain

Input	Pre-restoration	Sediment addition	Addition and 50% revegetation
Total area (m²)	169,504	169,504	169,504
UVVR	0.215	0.215	0.115
Unvegetated area (m²)	29,937	29,937	17,437
Elevation of vegetated plain (m)	0.286	0.286	0.286
Bulk density of future deposits (kg/m³)	159	159	159
Bulk density of existing substrate (kg/m³)	373	373	373
Historical SLR (m/y)	0.00201	0.00201	0.00201
Future SLR (m/y)	0.0076	0.0076	0.0076
Bulk density of sediment addition (kg/m³)	-	500	500
Sediment addition area (m²)	-	25,000	12,500
Revegetation area (m²)	-	0	12,500
Outputs			
Total sediment (kg)	14,888,718	18,463,718	18,009,693
Sediment budget under future SLR (kg/y)	−224,305	−224,305	−180,144
Lifespan under future SLR (y)	66	82	100
Sediment addition mass (kg)	-	3,575,000	1,787,500
Revegetated area additional sediment mass (kg)	-	-	1,333,475

Table 3 Lifespan calculator inputs and outputs for marsh unit 6007 (Fig. 9). Post-restoration scenarios include (1) sediment addition over a pre-defined area that assumes the unvegetated area was at mean sea level and sediment was added to the elevation of the existing vegetated marsh plain and (2) addition with assumed revegetation of 50% of the addition area to the same elevation as the existing vegetated marsh plain

Input	Pre-restoration	Sediment addition	Addition and 50% revegetation
Total area (m^2)	91,779	91,779	91,779
UVVR	0.384	0.384	0.164
Unvegetated area (m^2)	25,465	25,465	12,965
Elevation of vegetated plain (m)	0.503	0.503	0.503
Bulk density of future deposits (kg/m^3)	159	159	159
Bulk density of existing substrate (kg/m^3)	373	373	373
Historical SLR (m/y)	0.00201	0.00201	0.00201
Future SLR (m/y)	0.0076	0.0076	0.0076
Bulk density of sediment addition (kg/m^3)	-	500	500
Sediment addition area (m^2)	-	25,000	12,500
Revegetation area (m^2)	-	0	12,500
Outputs			
Total sediment (kg)	12,441,824	18,729,324	17,930,811
Sediment budget under future SLR (kg/y)	− 143,685	− 143,685	− 111,317
Lifespan under future SLR (y)	87	130	161
Sediment addition mass (kg)	-	6,287,500	3,143,750
Revegetated area additional sediment mass (kg)	-	-	2,345,237

These examples serve to illustrate the integration of geospatial metrics into a simple decision-making framework. The underlying data are used to identify potential actions, and a straightforward mass balance calculation quantifies the impact of those actions with a timescale metric. With these tools, managers can both set expectations for lifecycles of projects, as well as track the performance of both the project and the decision-making framework. This framework can also be used to compare potential interventions at a single site versus multiple sites in terms of costs and potential increases in lifespan.

Conclusions

Anthropogenic and external physical forces are transforming salt marsh ecosystems, forcing coastal land managers to make rapid decisions regarding restoration investments. Field-based observations have improved our understanding of coupled biogeomorphic processes in response to climate change and sea-level rise, and geospatial analyses serve to extend that understanding across landscapes for effective management. Chesapeake Bay contains more salt marsh acreage than any other estuary in the USA, and several agencies are tasked with selecting marsh restoration projects and associated techniques. The geospatial analyses here quantify the spatial variability in horizontal and vertical vulnerability at both the marsh unit scale (~ 1 ha) and over larger Bay regions. The marshes within the "Islands"

subdomain were the most vulnerable likely due to their exposure to coastal forces and disconnection from the watershed; the landward-most subdomains of the Bay were the least vulnerable, with high elevation and intact vegetated plains. We demonstrate a simple yet novel decision matrix that uses elevation and UVVR thresholds to classify marsh units and then associated potential management decisions with those units. For example, high elevation, horizontally intact (low UVVR) marshes are candidates for protection/acquisition, while low elevation, horizontally degraded (high UVVR) marshes may be evaluated for restoration based on feasibility and potential co-benefits. Lastly, we expanded the sediment-based lifespan concept to account for restoration actions, which provides managers with quantification of potential gains from restoration investments. Though these management applications are relatively simple, they are based on spatially complete, integrative data metrics that represent a potential step towards optimizing investments in salt marsh restoration. Importantly, the metrics, applications, and their results can be tested and updated as projects are implemented across the landscape.

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