ENVIRONMENTAL RESEARCH
LETTERS

LETTER • **OPEN ACCESS**

Understanding tidal marsh trajectories: evaluation of multiple indicators of marsh persistence

To cite this article: Kerstin Wasson *et al* 2019 *Environ. Res. Lett.* **14** 124073

Recent citations

- Systematic assessments of tidal wetlands loss and degradation in Shanghai, China: from the perspectives of area, composition and quality
  Shiwei Lin *et al*
- Biogeomorphic patterns emerge with pond expansion in deteriorating marshes affected by relative sea level rise
  Man Qi *et al*
- Sediment Dynamics of a Divergent Bay–Marsh Complex
  Daniel J. Nowacki and Neil K. Ganju

IOP Publishing Environ. Res. Lett. **14** (2019) 124073 https://doi.org/10.1088/1748-9326/ab5a94

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
25 July 2019

REVISED
31 October 2019

ACCEPTED FOR PUBLICATION
22 November 2019

PUBLISHED
18 December 2019

LETTER

Understanding tidal marsh trajectories: evaluation of multiple indicators of marsh persistence

Kerstin Wasson[1,8], Neil K Ganju[2], Zafer Defne[2], Charlie Endris[1], Tracy Elsey-Quirk[3], Karen M Thorne[4], Chase M Freeman[4], Glenn Guntenspergen[5], Daniel J Nowacki[6] and Kenneth B Raposa[7]

[1] Elkhorn Slough National Estuarine Research Reserve, Royal Oaks, CA 95076, United States of America
[2] Woods Hole Coastal and Marine Science Center, U.S. Geological Survey, United States of America
[3] Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, United States of America
[4] Western Ecological Research Center, U.S. Geological Survey, United States of America
[5] Patuxent Wildlife Research Center, U.S. Geological Survey, United States of America
[6] Pacific Coastal and Marine Science Center, U.S. Geological Survey, United States of America
[7] Narragansett Bay National Estuarine Research Reserve, United States of America
[8] Author to whom any correspondence should be addressed.

E-mail: kerstin.wasson@gmail.com, nganju@usgs.gov, zdefne@usgs.gov, cendris@mlml.calstate.edu, tquirk@lsu.edu, kthorne@usgs.gov, cfreeman@usgs.gov, glenn_guntenspergen@usgs.gov, dnowacki@usgs.gov and kenneth.raposa@dem.ri.gov

Keywords: resilience, sea-level rise, tidal marsh, wetland, management

Supplementary material for this article is available online

Abstract

Robust assessments of ecosystem stability are critical for informing conservation and management decisions. Tidal marsh ecosystems provide vital services, yet are globally threatened by anthropogenic alterations to physical and biological processes. A variety of monitoring and modeling approaches have been undertaken to determine which tidal marshes are likely to persist into the future. Here, we conduct the most robust comparison of marsh metrics to date, building on two foundational studies that had previously and independently developed metrics for marsh condition. We characterized pairs of marshes with contrasting trajectories of marsh cover across six regions of the United States, using a combination of remote-sensing and field-based metrics. We also quantified decadal trends in marsh conversion to mudflat/open water at these twelve marshes. Our results suggest that metrics quantifying the distribution of vegetation across an elevational gradient represent the best indicators of marsh trajectories. The unvegetated to vegetated ratio and flood-ebb sediment differential also served as valuable indicators. No single metric universally predicted marsh trajectories, and therefore a more robust approach includes a suite of spatially-integrated, landscape-scale metrics that are mostly obtainable from remote sensing. Data from surface elevation tables and marker horizons revealed that degrading marshes can have higher rates of vertical accretion and elevation gain than more intact counterparts, likely due to longer inundation times potentially combined with internal recycling of material. A high rate of elevation gain relative to local sea-level rise has been considered critical to marsh persistence, but our results suggest that it also may serve as a signature of degradation in marshes that have already begun to deteriorate. This investigation, with rigorous comparison and integration of metrics initially developed independently, tested at a broad geographic scale, provides a model for collaborative science to develop management tools for improving conservation outcomes.

Introduction

Globally, scientists conduct assessments of ecosystem stability to inform policy and management (Sato and Lindenmayer 2018). Many different stability metrics have been developed, but most investigations only use one or a few, and multiple stability metrics have rarely been correlated to each other or integrated (Kéfi *et al* 2019). Yet in order to direct monitoring efforts and provide vital guidance to decision-makers, it is critical to evaluate multiple assessment alternatives, and potentially integrate them to determine ecosystem condition (Donohue *et al* 2016).

The resilience of tidal marshes in the face of external disturbances such as sea-level rise (SLR) and coastal development is a concern to coastal managers throughout the world. Tidal marshes provide a wide range of ecosystem services, including nutrient and carbon sequestration, habitat provision, and wave attenuation (Mitsch *et al* 2015, Barbier 2019). However, natural and anthropogenic processes modify the vertical and lateral dynamics of tidal marshes, through both physical and biogeochemical forcings. Physical forces, including wind-waves, tidal processes, and sediment supply play an important role in regulating the hydro-geomorphic response of the tidal marsh landscape (Fagherazzi *et al* 2012), while biogeochemical processes play a large role in biomass production, soil stability, and vertical accretion (Morris *et al* 2002, Cahoon *et al* 2019). Animals can also exert strong influences on marshes, through herbivory and burrowing (Stevenson *et al* 1985, Holdredge *et al* 2009). Human activities have altered many of these drivers of marsh integrity and persistence, such as eutrophication fueling rapid decomposition and resulting in degradation (Deegan *et al* 2012), decreases in sediment supply essential to vertical marsh growth (Weston 2014), and accelerating SLR rates (Kirwan and Megonigal 2013).

Management strategies to enhance tidal marsh persistence include restoration of riverine sediment supply, thin-layer sediment placement, drainage enhancement, shoreline protection, and invasive species management (Day *et al* 2007, Blum and Roberts 2009, Wigand *et al* 2017, Thorne *et al* 2018). Prioritizing restoration sites and identifying the most appropriate techniques requires reliable metrics to aid managers in directing resources to marshes that are vulnerable enough to require intervention, but not so threatened that investment in them will be wasted. Managers also need to identify marshes that have the greatest chance of persistence under future SLR conditions, so that they have high priority for conservation to protect and sustain their areal extent and the processes necessary for their persistence.

In the United States, federal organizations including the National Oceanic and Atmospheric Administration's National Estuarine Research Reserve System, the Department of the Interior's US Geological Survey, US Fish and Wildlife Service and National Park Service, as well as academic researchers have developed and monitored indicators of tidal marsh resilience and persistence. These range from point measurements (e.g. of sediment accretion or marsh elevation change at surface elevation tables) to estimates at the landscape scale (e.g. sediment flux or habitat change assessed from aerial photographs) to regional characterizations (e.g. of sea-level trends). The data from these monitoring efforts is used to parameterize mechanistic models of marsh dynamics (Craft *et al* 2008, Swanson *et al* 2014, Schile *et al* 2014, Byrd *et al* 2016). Some types of monitoring require relatively high investment, such as field measurements involving years of consistent repeat visits to detect trends. Others can be accomplished with less effort, such as analysis of aerial photographs. Ideally, coastal managers should invest in the monitoring that has the greatest predictive power for the least investment necessary. It is still an open question, however, as to which metrics will yield the greatest return on that investment (Wiberg *et al* 2019).

Recently, Raposa *et al* (2016) developed and tested three multi-metric indices based on a suite of ten tidal marsh metrics, specifically aimed at evaluating marsh persistence in the face of accelerations in the rate of SLR. All metrics were chosen based on previous research suggesting their importance to marsh response to SLR (marsh elevation, sediment concentration, etc). This assessment approach was applied to 16 NERR marshes and related resilience scores were used to recommend management strategies. Independently, Ganju *et al* (2013, 2015) linked sediment transport mechanisms with marsh trajectory, demonstrating with a pair of sites that intact marshes tend to import sediment, while degrading marshes export sediment. That analysis was extended to eight US sites (Ganju *et al* 2017), and a further link was quantified between the net sediment budget, the unvegetated to vegetated ratio (UVVR), and the flood-ebb sediment differential. The implication in Ganju *et al* (2017) was that marshes with high vegetative cover and low open-water area tend to trap and retain sediment, while marshes that are losing plant cover will further lose sediment and convert to open water.

Here, we jointly compare all metrics developed by Raposa *et al* (2016) and Ganju *et al* (2017) to evaluate which best predict tidal marsh persistence, which we define as the maintenance of vegetated marsh cover within the current marsh footprint. Twelve metrics (and three multi-metric indices incorporating them) were calculated for pairs of geographically similar marshes with varying trajectories of marsh persistence in six different US regions. Univariate and multivariate statistical approaches were employed to determine which metrics, separately or jointly, best correlated with marsh persistence, and whether this varied across regions. The twelve metrics were also related to actual decadal change in marsh vegetation at each site to determine which best predicted observed trajectories. This unprecedented analysis allows for robust recommendations to coastal decision-makers on the highest priority metrics, and provides guidance for prioritizing future monitoring strategies.

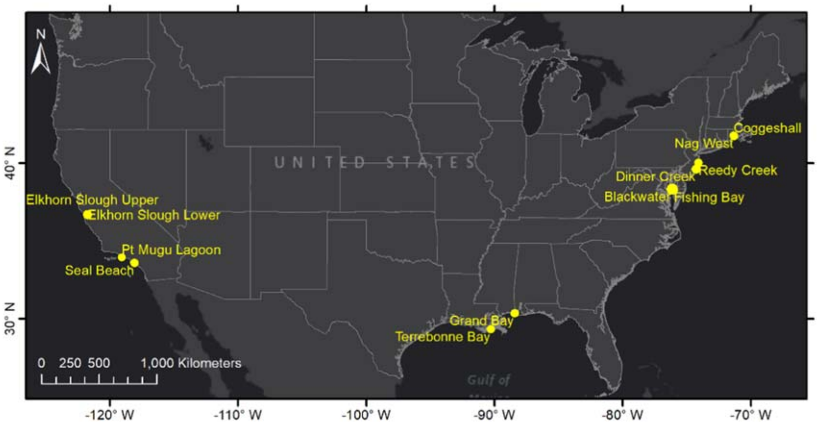


Figure 1. Location of study sites. Paired marshes in six regions were investigated; clockwise from the Northeast these are Narragansett Bay, Rhode Island (Coggeshall and Nag West), Barnegat Bay, New Jersey (Reedy and Dinner Point Creek), Chesapeake Bay, Maryland (Blackwater, Fishing Bay), Gulf coast (Grand Bay, Mississippi and Terrebonne Bay, Louisiana), southern California (Seal Beach, Pt. Mugu Lagoon), and central California (upper and lower Elkhorn Slough).

Methods

Study sites

To determine which metrics best identify tidal marsh persistence, we examined a pair of marshes with varying trajectories: one with a higher and one with a lower change in unvegetated to vegetated marsh ratio (UVVR) (see below) within each region. There were a total of six focal regions (figure 1). Five marshes had been previously examined by Raposa *et al* (2016) (both Narragansett Bay marshes, both Elkhorn Slough marshes; Grand Bay); six other marshes had been previously examined by Ganju *et al* (2017) (Reedy Creek, Dinner Point Creek, Blackwater, Fishing Bay, Point Mugu Lagoon, and Seal Beach). A description of each site is in the supplemental information (SI) is available online at stacks.iop.org/ERL/14/124073/mmedia.

MARS metrics

The ten MARS (MArsh Resilience to SLR) metrics were specifically chosen because they reflect conditions affected by SLR and therefore represent potential indicators of tidal marsh persistence (Raposa *et al* 2016). The three vegetation metrics are all derived from recent field assessments in a marsh. The five metrics for elevation change, accretion, sediments, and tidal range are all from longer-term monitoring over the most recent decade or coring, while the two SLR metrics are calculated from long-term NOAA tide station data. Each metric can individually reflect SLR impacts, but similar metrics are also averaged into one of five broader categories, which then are further integrated into the three multi-metric MARS indices, thus providing opportunities to examine marsh persistence in the face of SLR at three organizational levels (see tables 1 and S1).

Flood-ebb sediment differential

The difference in suspended-sediment concentration (SSC) on flood and ebb tides has been shown to indicate the directionality of tidal marsh channel sediment flux over time scales of months to years (Ganju *et al* 2017). It is intuitive that this sediment differential, defined as the mean SSC on flood tides minus the mean SSC on ebb tides as determined by velocity direction, is representative of whether a marsh channel imports or exports sediment: one expects that greater flood concentrations would result in sediment import. The sediment differential is preferable to mean SSC, a metric sometimes used to characterize marsh sediment availability, because it can indicate direction with negative values and because its absolute value scales with mean SSC, combining flux directionality and total sediment availability in a single metric (Nowacki and Ganju 2019). In this study we represent SSC with turbidity as a proxy, given the linearity between the two parameters, and relatively consistent slope in areas dominated by fine sediment (Ganju *et al* 2007). Details on calculations are in the SI.

UVVR

Ganju *et al* (2017) identified the UVVR as an indicator of tidal marsh trajectory due to its relationship with the marsh sediment budget. A stable tidal marsh, with intact marsh plains and little deterioration tends to a UVVR ~ 0.1. Values greater than this indicate a trajectory towards marsh plain deterioration, and increasing values correspond to increasing runaway marsh expansion (e.g. Mariotti 2016). Therefore, despite the UVVR being a snapshot in time, it indicates the open-water conversion process; e.g. a high UVVR translates to historical deterioration within a previously vegetated marsh plain. Conversely, a historically stable marsh will show a low present-day UVVR. For each marsh, UVVR was calculated using a reclassification of NAIP imagery into a normalized

Table 1. Summary of metrics and approaches used for each.

Category	Metric	Data needs
MARS metrics (Raposa *et al* 2016)		
Marsh elevation distributions	Percent of marsh below MHW	Frequency distribution of marsh elevations; estimate of mean high water
	Percent of marsh in lowest third of plant distribution	Frequency distribution of marsh elevations
	Skewness	Frequency distribution of marsh elevations
Marsh elevation change	Elevation change rate (mm yr^{-1})	Time series data from surface elevations tables (SETs)
Sediment/accretion	Short-term accretion rate (mm yr^{-1})	Time-series data from marker horizons
	Long-term accretion rate (mm yr^{-1})	Soil cores for radiometric dating
	Turbidity(NTU)	Mean turbidity from water quality sondes
Tidal range	Tidal range (m)	Mean daily tidal range from water quality sondes
Sea-level rise	Long-term rate of SLR (mm yr^{-1})	Long-term data from NWLON station
	Short-term inter-annual variability in water levels (mm)	Inter-annual variability data from NWLON station
Ganju *et al* (2017) metrics		
	Flood-ebb turbidity differential	Mean suspended sediment concentrations on flood and ebb tides
	UVVR	Relative area of vegetated marsh and unvegetated areas from aerial photographs
Observed change in vegetation		
	Decadal change in UVVR	UVVR (see above) assessed at 2 + points spanning ~10 years
	Percent of marsh plain with vegetation	Area of vegetated marsh divided by total marsh landscape area (vegetated+unvegetated) × 100
	Decadal change in percent vegetated	Change in above, assessed at 2 + points spanning ~10 year

difference vegetation index that allowed us to isolate and quantify healthy marsh vegetation from bare mud or water. Tidal marsh boundaries were clipped based on the wetland classification maps from the US Fish and Wildlife Service's National Wetlands Inventory (NWI). Specifically, it included the boundaries of estuarine intertidal subsystem from NWI's digitization of historic maps (as early as 1970s) to recently collected aerial imagery, thus in areas of recent loss, the boundaries included unvegetated areas that had been formerly vegetated (see SI for details).

Observed vegetation change

For this study, we also evaluated the actual observed trends in vegetation occurring at each site, assessing marsh persistence trajectories by quantifying decadal change in two ways. First, we calculated change in UVVR (equation (1)). We calculated this from two or more data points over an approximate 10 year span. We found that rates of change were similar when conducted by simply subtracting values approximately a decade apart versus conducting a linear regression with multiple points spanning a decade, though the latter is likely to be more accurate (see SI).

Second, we also calculated the change in percent of the marsh area that was vegetated (vegetated/(unvegetated + vegetated)) over the same period, using the subtraction method (equation (2)). We present the raw value for percent vegetated as well as the change value in the results, since the contrasts among sites in percent vegetated are stark.

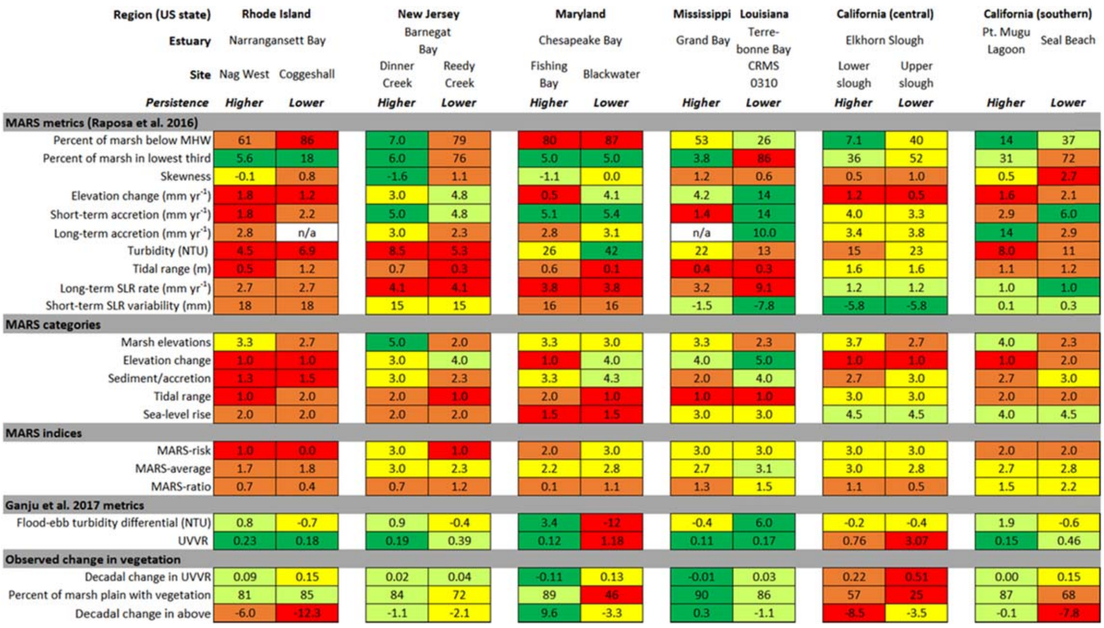
$$\begin{aligned}&[((\text{unvegetated area}_{(\text{initial year})}/\text{vegetated area}_{(\text{initial year})}\\&\quad-(\text{unvegetated area}_{(\text{final year})}/\text{vegetated area}_{(\text{final year})}))\\&\quad/\text{number of years between initial and final}]\times 10\end{aligned} \tag{1}$$

$$\begin{aligned}&[(((\text{vegetated area}_{(\text{initial year})}/\text{total area}_{(\text{initial year})})\times 100)\\&-((\text{vegetated area}_{(\text{final year})}/\text{total area}_{(\text{final year})})\times 100))\\&/\text{number of years between initial and final}]\times 10\end{aligned} \tag{2}$$

Analyses

To examine differences related to marsh trajectories, we calculated the percent difference among marsh pairs within a region for each metric or index. We subtracted the value for the site with a trajectory of higher marsh loss from the value for the site with higher marsh persistence. This difference was divided by the largest absolute value for any of the 12 sites, then multiplied by 100 to convert this to a percent difference. To assess which metrics/indices performed well, with a large difference in the expected direction (lower marsh persistence members of the pair scoring lower), we averaged the values across all six regions, and counted the number of regions with negative value of <-10.

In order to determine whether the 12 marshes group by higher versus lower persistence trajectories based on the metrics we assessed, and which metrics best correlate with this grouping, we conducted a suite of related non-metric multi-dimensional scaling analyses using Primer v. 7.0 (Clarke *et al* 2014). We



Region (US state)	Rhode Island		New Jersey		Maryland		Mississippi	Louisiana	California (central)		California (southern)	
Estuary	Narragansett Bay		Barnegat Bay		Chesapeake Bay		Grand Bay	Terrebonne Bay	Elkhorn Slough		Pt. Mugu Lagoon	Seal Beach
Site	Nag West	Coggeshall	Dinner Creek	Reedy Creek	Fishing Bay	Blackwater		CRMS 0310	Lower slough	Upper slough		
Persistence	*Higher*	*Lower*	*Higher*	*Lower*	*Higher*	*Lower*	*Higher*	*Lower*	*Higher*	*Lower*	*Higher*	*Lower*
MARS metrics (Raposa et al. 2016)												
Percent of marsh below MHW	61	86	7.0	79	80	87	53	26	7.1	40	14	37
Percent of marsh in lowest third	5.6	18	6.0	76	5.0	5.0	3.8	86	36	52	31	72
Skewness	-0.1	0.8	-1.6	1.1	-1.1	0.0	1.2	0.6	0.5	1.0	0.5	2.7
Elevation change (mm yr^{-1})	1.8	1.2	3.0	4.8	0.5	4.1	4.2	14	1.2	0.5	1.6	2.1
Short-term accretion (mm yr^{-1})	1.8	2.2	5.0	4.8	5.1	5.4	1.4	14	4.0	3.3	2.9	6.0
Long-term accretion (mm yr^{-1})	2.8	n/a	3.0	2.3	2.8	3.1	n/a	10.0	3.4	3.8	14	2.9
Turbidity (NTU)	4.5	6.9	8.5	5.3	26	42	22	13	15	23	8.0	11
Tidal range (m)	0.5	1.2	0.7	0.3	0.6	0.1	0.4	0.3	1.6	1.6	1.1	1.2
Long-term SLR rate (mm yr^{-1})	2.7	2.7	4.1	4.1	3.8	3.8	3.2	9.1	1.2	1.2	1.0	1.0
Short-term SLR variability (mm)	18	18	15	15	16	16	-1.5	-7.8	-5.8	-5.8	0.1	0.3
MARS categories												
Marsh elevations	3.3	2.7	5.0	2.0	3.3	3.0	3.3	2.3	3.7	2.7	4.0	2.3
Elevation change	1.0	1.0	3.0	4.0	1.0	4.0	4.0	5.0	1.0	1.0	1.0	2.0
Sediment/accretion	1.3	1.5	3.0	2.3	3.3	4.3	2.0	4.0	2.7	3.0	2.7	3.0
Tidal range	1.0	2.0	2.0	1.0	2.0	1.0	1.0	1.0	3.0	3.0	2.0	2.0
Sea-level rise	2.0	2.0	2.0	2.0	1.5	1.5	3.0	3.0	4.5	4.5	4.0	4.5
MARS indices												
MARS-risk	1.0	0.0	3.0	1.0	2.0	3.0	3.0	3.0	3.0	3.0	2.0	2.0
MARS-average	1.7	1.8	3.0	2.3	2.2	2.8	2.7	3.1	3.0	2.8	2.7	2.8
MARS-ratio	0.7	0.4	0.7	1.2	0.1	1.1	1.3	1.5	1.1	0.5	1.5	2.2
Ganju et al. 2017 metrics												
Flood-ebb turbidity differential (NTU)	0.8	-0.7	0.9	-0.4	3.4	-12	-0.4	6.0	-0.2	-0.4	1.9	-0.6
UVVR	0.23	0.18	0.19	0.39	0.12	1.18	0.11	0.17	0.76	3.07	0.15	0.46
Observed change in vegetation												
Decadal change in UVVR	0.09	0.15	0.02	0.04	-0.11	0.13	-0.01	0.03	0.22	0.51	0.00	0.15
Percent of marsh plain with vegetation	81	85	84	72	89	46	90	86	57	25	87	68
Decadal change in above	-6.0	-12.3	-1.1	-2.1	9.6	-3.3	0.3	-1.1	-8.5	-3.5	-0.1	-7.8

Figure 2. Summary of metrics and indices. MARS metrics, categories, and indices developed by Raposa *et al* (2016) are shown in the top three sections; two additional metrics developed by Ganju *et al* (2017) are shown in the fourth section. The assessment of actual marsh persistence trajectories is shown last, with the change in UVVR and change in percent of marsh with vegetation. The percent of marsh with vegetation is also shown to help describe these sites. Green indicates greatest marsh resilience, red lowest marsh resilience. Scoring is summarized in supplemental table 1.

included all the metrics in this analysis, but omitted MARS categories and indices, because they are not independent of the metrics. The assessment of observed decadal marsh trajectories was not included in the multivariate analyses, because it was intended to describe, not predict marsh persistence. Data were normalized to enable comparison between metrics with different scales. We created a Euclidean similarity matrix and visualized differences among higher versus lower marsh persistence sites using a two-dimensional ordination plot and carried out an analysis of similarity (ANOSIM) to test for differences by persistence and by region. We used similarity percentages (SIMPER) to further examine groupings and the metrics that best distinguished them. This unconstrained ordination analysis was followed by a discriminant analysis using canonical analysis of principal coordinates (CAP) because paired sites were determined within regions *a priori* (Anderson and Robinson 2003, Anderson and Willis 2003). Thus, the CAP procedure maximizes paired site differences rather than maximizing the total variation among all sites. CAP was then used to test for significant differences among regions and among higher marsh persistence versus lower sites.

We also carried out univariate analyses (regressions) to examine the relationship between actual observed marsh cover trajectories (decadal change in UVVR and percent vegetated) and all individual metrics and indices. We further conducted regressions of these variables to examine the relationship between vegetation distribution across an elevation gradient and accretion and elevation change/SLR. We graphically present only the significant relationships and report Pearson's correlation coefficient for all. These analyses were conducted in R version 3.5.2 (R Core Team 2018).

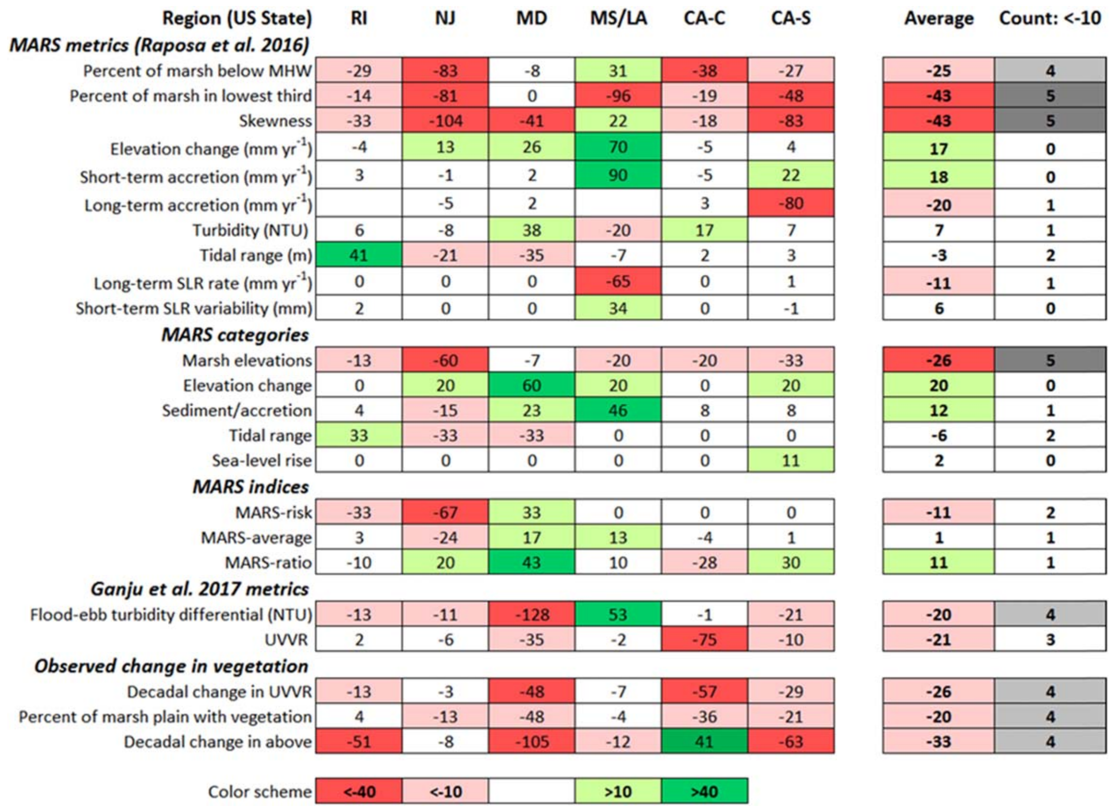
Results

Overall comparisons of scores and persistence

The overall patterns of marsh metric scores were complex, and differences between paired sites classified as more versus less persistent were not immediately obvious (figure 2). The simplest expectation would be that more persistent marshes in each of the six pairs have high scores (green) and less persistent marshes have low scores (red). Instead, differences between the higher versus lower persistence member of each pair were mixed, and not always occurring in the expected direction.

The scoring of the six pairs of sites according to the various metrics revealed strong contrasts among regions and metrics (figure 2). Sites did not typically score uniformly (low across all metrics or high across all metrics), but rather showed a mix of scores. Overall, the Rhode Island sites had the greatest number of low scores, though the UVVR scores were relatively high. An opposite pattern was seen in central California, where the lowest UVVR scores were found, but other scores were moderate.

The assessment of change in the UVVR that quantified the actual observed change in vegetated marsh loss over the past decade showed high variation among regions. It is clear that what counts as high marsh persistence in one region may represent low persistence in



Region (US State)	RI	NJ	MD	MS/LA	CA-C	CA-S	Average	Count: <-10
MARS metrics (Raposa et al. 2016)								
Percent of marsh below MHW	-29	-83	-8	31	-38	-27	-25	4
Percent of marsh in lowest third	-14	-81	0	-96	-19	-48	-43	5
Skewness	-33	-104	-41	22	-18	-83	-43	5
Elevation change (mm yr^{-1})	-4	13	26	70	-5	4	17	0
Short-term accretion (mm yr^{-1})	3	-1	2	90	-5	22	18	0
Long-term accretion (mm yr^{-1})		-5	2		3	-80	-20	1
Turbidity (NTU)	6	-8	38	-20	17	7	7	1
Tidal range (m)	41	-21	-35	-7	2	3	-3	2
Long-term SLR rate (mm yr^{-1})	0	0	0	-65	0	1	-11	1
Short-term SLR variability (mm)	2	0	0	34	0	-1	6	0
MARS categories								
Marsh elevations	-13	-60	-7	-20	-20	-33	-26	5
Elevation change	0	20	60	20	0	20	20	0
Sediment/accretion	4	-15	23	46	8	8	12	1
Tidal range	33	-33	-33	0	0	0	-6	2
Sea-level rise	0	0	0	0	0	11	2	0
MARS indices								
MARS-risk	-33	-67	33	0	0	0	-11	2
MARS-average	3	-24	17	13	-4	1	1	1
MARS-ratio	-10	20	43	10	-28	30	11	1
Ganju et al. 2017 metrics								
Flood-ebb turbidity differential (NTU)	-13	-11	-128	53	-1	-21	-20	4
UVVR	2	-6	-35	-2	-75	-10	-21	3
Observed change in vegetation								
Decadal change in UVVR	-13	-3	-48	-7	-57	-29	-26	4
Percent of marsh plain with vegetation	4	-13	-48	-4	-36	-21	-20	4
Decadal change in above	-51	-8	-105	-12	41	-63	-33	4
Color scheme	<-40	<-10		>10	>40			

Figure 3. Differences among more versus less persistent marshes. The difference in value for the metrics and indices shown in figure 2 was calculated for each pair of sites (subtracting the less persistent from the more persistent site). This difference was divided by the largest absolute value for any of the 12 sites, then multiplied by 100 to convert this to a percent difference. The first six data columns show the percent differences for each state. Negative numbers (shown in shades of red for values less than −10) represent cases where the less persistent marsh scored lower on a metric, as would be expected; positive numbers represented the reverse (shown in shades of green for values larger than 10). The next column shows the average difference among pairs. The final column is a count of the number of regions (out of 6 possible) in which the difference was −10 or more negative; this is one way of assessing whether this is a useful indicator of marsh persistence. Counts of 4 are shown in light gray, 5 in dark gray.

another; for instance, the low persistence site in New Jersey scored higher than many high persistence sites elsewhere, and the high persistence site in central California scored lower than any low persistence site elsewhere (figure 2).

The assessment of percent difference in metric scores between higher versus lower marsh persistence sites also revealed differences among metrics (figure 3). Here, we expected the difference to be negative, indicating that the lower persistence site scored lower on metrics than the paired site in the same region, indicated by red shading. This was indeed the case for many metrics. However, for various interrelated scores (accretion, marsh elevation change rate, turbidity), values were higher at the lower marsh persistence sites, indicating that sediment concentration or accretion was greater there. A tally of regions where the scores were more than 10% lower at the lower marsh persistence site identified that three MARS metrics (all related to vegetation distribution), the associated MARS vegetation category average, and the flood-ebb sediment differential all functioned as reliable indicators.

Multivariate analyses

The non-metric multi-dimensional scaling yielded a robust ordination of sites, with visually apparent separation among marshes with higher versus lower persistence, and significant separation in ANOSIM (figure 4). Region was a highly significant factor and CAP ordination illustrated whether regional differences overshadowed paired site differences in persistence metrics (figure S9). For many sites (e.g. southern California, Rhode Island, Mississippi/Louisiana) there was little separation between higher and lower persistence marshes, owing to regional similarities in metrics such as tidal range and SLR rates, and to greater regional differences in the metrics (figure S10). For example, CA-C and CA-S had a higher mean tidal range (1.6 m and 1.1–1.2 m, respectively) than all but one (RI-lower) of the other marshes. Relatively high rates of relative SLR and short-term accretion seemed to influence the clustering of MS/LA marshes and higher persistence marshes in NJ and MD. Overall, accounting for the regional grouping of paired marshes, marshes with trajectories of lower persistence were significantly different than those with higher persistence

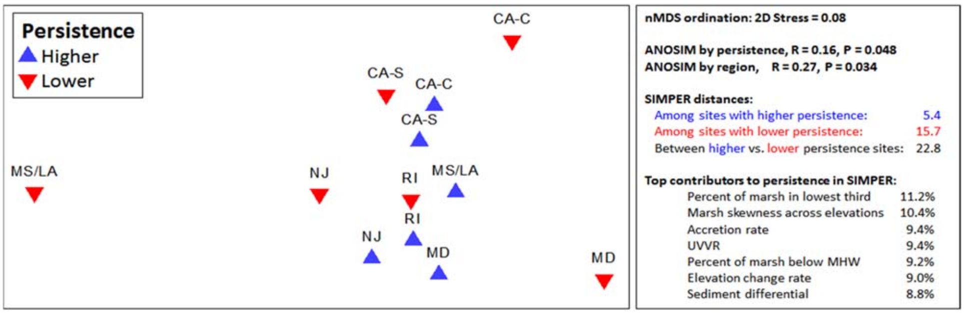


Figure 4. Non-metric multi-dimensional scaling analyses.

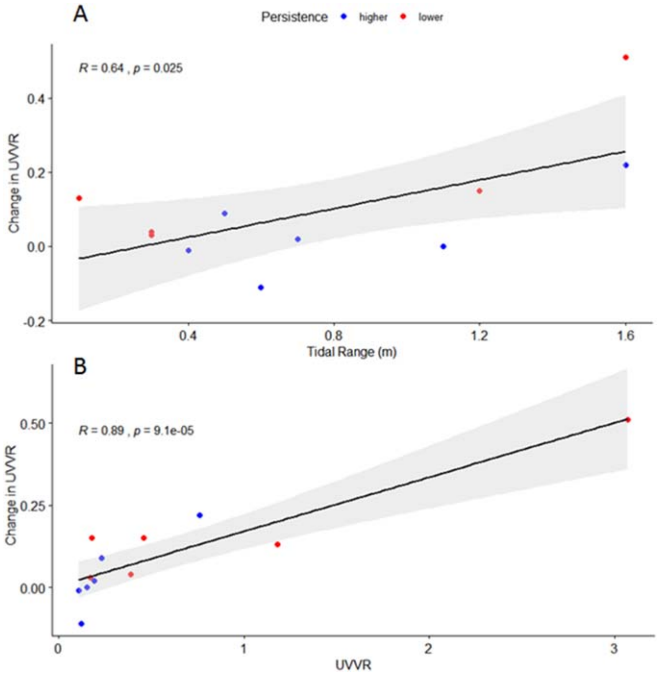


Figure 5. Relationships between decadal change in UVVR and selected metrics. Change in UVVR was positively correlated with (A) Tidal range and (B) UVVR. Higher persistence sites are shown as blue points; lower persistence sites as red points. The Pearson correlation coefficient is shown.

($p = 0.033$; figure S9). For sites such as MD, NJ, and CA-C, marshes with lower persistence were clearly different than those with higher persistence.

A SIMPER analysis revealed that average squared distance among sites within the higher persistence grouping is much less than within the lower persistence grouping. The SIMPER analysis identified seven metrics that jointly explained 67% of the difference in higher versus lower persistence, with each contributing 9%–11% (figure 4). These are very similar to metrics identified as important by comparing differences among pairs (figure 3, final columns).

Univariate analyses

Examination of the relationship between actual observed marsh trajectories (change in UVVR and percent of vegetated marsh over the past decade) and every individual metric, category and index revealed very few significant correlations (table S2). The MARS metric Tidal Range (and related MARS category Tidal Range) and the UVVR metric showed significant positive relationships (figure 5). Examination of the color-coding by persistence in this figure makes clear, as noted earlier (figure 2) that scoring of higher versus lower persistence was relevant within a region, but does not hold across regions (otherwise all the red points in these figures would have been in the far right of the graphs). None of the metrics had a significant relationship with change in percent of vegetated marsh.

We also conducted univariate analyses to more closely examine metrics that had showed unexpected relationships: accretion, elevation change, and the MARS ratio (elevation change/SLR) that were higher in lower persistence marshes, on average (figure 3). We correlated these metrics to two vegetation metrics, percent of marsh in the lower third of tolerance, and also the simple percent of the marsh area that is

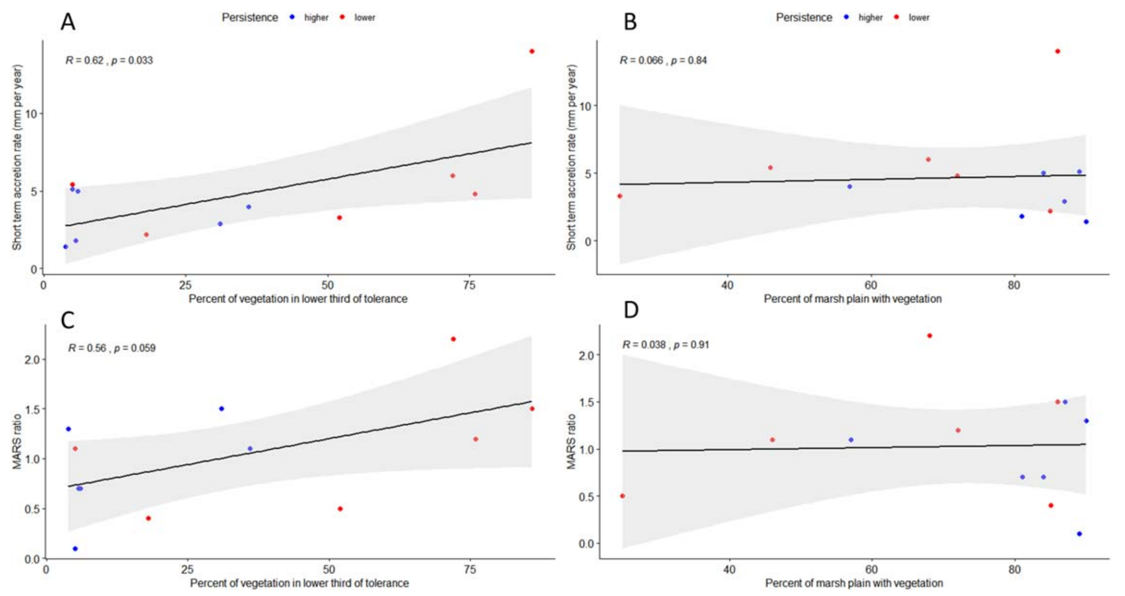


Figure 6. Relationships between selected metrics. Short-term accretion rate is plotted against percent of vegetation in the lower third of tolerance (A) and percent of marsh plain that is vegetated (B). MARS ratio is plotted against percent of vegetation in the lower third of tolerance (C) and percent of the marsh plain that is vegetated (D). Higher persistence sites are shown as blue points; lower persistence sites as red points. The Pearson correlation coefficient is shown.

vegetated. Short-term accretion rate showed a significant positive relationship with the former (figure 6(A)) but no relationship with the latter (figure 6(B)). A similar but slightly weaker pattern emerged for the MARS ratio (figures 6(C) versus (D)) and elevation change (not shown).

Discussion

Universal indicators of tidal marsh trajectories

Are there universal indicators that are closely associated with persistence versus degradation of tidal marshes across diverse geographies and marsh dynamics? Our results suggest that there are: the distribution of vegetation across the elevational landscape of the marsh is a reliable indicator of the marsh's trajectory. The three metrics related to this (percent of marsh below MHW, percent of marsh in lower third of vegetation tolerance, and skewness of the distribution of vegetation across elevations) had the highest average difference among marshes with higher versus lower persistence across the six regions (figure 3), and were the highest contributors in the expected direction in the multivariate analysis (figure 4). The average of all three of these metrics (the marsh elevation category) was the only indicator that scored in the expected direction across all pairs of marshes (worse in the less persistent marshes; figure 3). Thus, the distribution of vegetation across the elevational landscape appears to be the most robust indicator of marsh persistence. Marshes with the majority of the vegetation distributed low in the tolerance range degraded, while those with vegetation high within the marsh landscape were more stable. This supports earlier studies highlighting the importance of the elevational distribution of vegetation in marsh dynamics (McKee and Patrick 1988, Morris 2006, Schile *et al* 2011, Kirwan and Megonigal 2013, Janousek *et al* 2016, Cole Ekberg *et al* 2017). Robust numeric models of marsh response to SLR depend on identification of critical indicators of marsh persistence (Wiberg *et al* 2019), thus our results suggest that the elevational distribution of vegetation across the marsh landscape should be given particular attention in numeric models.

The sediment differential and UVVR also emerged as relatively strong indicators of marsh trajectories across regions, with moderately high average differences among marshes with higher versus lower persistence (figure 3) and high contributions to dissimilarity among these groups overall (figure 4). Our results thus build on the earlier results (Ganju *et al* 2013, 2015, 2017) highlighting the importance of these indicators. The five indicators that were most reliable are all spatially-integrated metrics that assess marshes at a landscape scale, rather than point-measurements. Each of these single metrics outperformed the composite multi-metric MARS indices (Raposa *et al* 2016).

Variability across marshes

While we identified indicators of marsh trajectory that responded consistently across regions, we also detected substantial geographic variability. Narragansett Bay marshes scored consistently low on MARS metrics, but relatively high on UVVR, while Elkhorn Slough marshes showed the reverse pattern (figure 2). For the six regions, five different metrics had the largest relative difference among pairs (skewness in two regions, tidal range, percent of vegetation in top third, sediment differential, and UVVR each in one region only). The rate of SLR also varied dramatically across regions, with highest rates experienced by Gulf coast and mid-Atlantic marshes (figures 2, S10). This suggests that evaluation of multiple metrics better characterizes marsh trajectories at a broad, comparative scale than any single metric, and that assessments at regional scales may be more effective at identifying marsh persistence trajectories than those at larger national or global scales.

As such, we found that some metrics are effective as relative, but not absolute indicators of marsh trajectories. In particular, UVVR was excellent at differentiating the marshes with higher versus lower persistence within a region, but not across regions—Elkhorn Slough's high persistence site scored worse on the UVVR metric than all except one of the low persistence sites elsewhere (figure 2). This likely points to inherent differences in a baseline, critical UVVR that may be dependent on tide range, vegetation type, and other regionally varying factors.

Ideally, the observed change in vegetation over the past decade would serve as a method of ground-truthing the predictive value of different metrics. However, we found that regional differences such as those described above made this challenging. For instance, our results suggest that sites with higher tidal ranges degrade faster (counter to the general understanding that microtidal systems are at greatest risk), but this result (figure 5(A)) was strongly influenced by Elkhorn Slough marshes, that have high tidal ranges and little recent SLR, yet are rapidly degrading. Geographical variability thus made this sort of simple regression analysis less valuable than our other approaches to assessing marsh trajectories. Future work is needed to explore the degree to which tide range, biome, regional sediment supply, and extreme events account for differences between regions. Ultimately, from a land management perspective, comparing marsh parcels within the same geographic region is the most practical approach given the scale and jurisdictional aspects of coastal land management (i.e. refuge or state-by-state basis).

Causes versus consequences of marsh dieback

For managers, the most useful indicators of marsh persistence have predictive power, allowing for timely intervention to prevent dieback of marshes in their current footprint, or consideration of alternative strategies such as facilitating marsh migration to higher ground. The most robust predictions likely come from factors directly related to the drivers of marsh dieback. Some of the metrics included in our analyses have this potential. In particular, the MARS metrics related to marsh elevation change and sediment supply were originally included (Raposa *et al* 2016) because of their role in potentially driving marsh resilience to SLR (Morris *et al* 2002, Fagherazzi *et al* 2012).

In our study of paired marshes of higher versus lower persistence trajectories, however, these metrics related to marsh elevation change and sediment concentration showed the opposite relationship with persistence as provided in conceptual models of vertical stability (e.g. Cahoon *et al* 2019). In 4 out of 6 of the regions studied, marsh elevation change and indicators of sediment concentration (turbidity and short-term accretion rate) were greater in the less persistent marsh, and the average value was greater in the lower persistence marsh across all sites (figure 3). The MARS-ratio (ratio of marsh elevation change to local SLR) was also higher in low persistence marshes (figure 3). Elevation change and accretion rate also emerged as significant in the multivariate analysis—in the reverse direction as anticipated.

A tidal marsh that has already lost much vegetation may have more sediment mobilized through tidal and wave processes, and loss of elevation may result in increased accretion due to longer submergence times (Morris *et al* 2002, Reed 2002, Wiberg *et al* 2019). Thus, for some marshes that have already lost significant areas of vegetation, sediment accretion and subsequent elevation gain can be symptoms of instability (Ganju *et al* 2015), not drivers of stability. This is why we found that many marshes with vegetation distributed lower in the tolerance range had higher accretion and higher ratios of elevation gain to local SLR (figures 6(A), (C)). This is apparently driven by the low elevation of the remaining marsh, since the percent of the area that was vegetated did not show these relationships (figures 6(B), (D)). Marshes distributed low in the elevation range are not likely to recover despite high accretion rates: once they have lost significant elevation, simply tracking SLR is not enough to convert a mudflat back into a marsh—the elevation gain would have to dramatically exceed SLR. Greater elevation gain in degrading marshes was not a universal pattern however: at Narragansett Bay and Elkhorn Slough, the marshes with lower persistence had lower elevation gain rates, and lower ratios of elevation gain to SLR rate than the marshes with higher persistence. We thus conclude that these classic indicators of tidal marsh persistence based on networks of point measurements (i.e. SETs) should be reconsidered, because they do not always perform as consistent indicators. For marshes that are still largely intact, with high elevation and vegetated cover, elevation gain equal to or surpassing local SLR is likely essential (e.g. Cahoon *et al* 2019). Conversely, elevation loss poses a challenge to tracking SLR, whether resulting from microbial decomposition fueled by nutrient-loading (Deegan *et al* 2012) or less inorganic sediment supply and accretion due to changes to river morphology (Day *et al* 2007). However, once elevation and vegetation has been lost, these metrics lose their value as predictors of marsh persistence, and instead can signal marsh degradation. The marshes in our study with trajectories of lower persistence appear likely to disappear in the near future, counter to the common perspective of marshes being able to maintain equilibrium through enhanced accretion following elevation loss (FitzGerald and Hughes 2019).

Some of our other metrics, such as the sediment differential and UVVR, may perform well as indicators due their association with consequences (rather than causes) of marsh degradation. The flood-ebb differential implicitly accounts for the source and direction of sediment transport, whereas mean values of SSC do not. Therefore, degrading wetlands will typically have high mean SSC but negative differentials, while an expanding wetland will have a positive differential, indicating sediment import. We also suggest that values of UVVR up to 0.5–1.0 may have predictive value for marsh persistence, but beyond this the marsh has degraded so far that sensitivity as an indicator has been lost. Once a system has crossed a UVVR of ~1.0, the increasing role of estuarine processes (i.e. wind-wave resuspension, larger scale circulation patterns) may confound application of marsh metrics to predominantly shallow-water systems.

Additional metrics may shed light on causes of marsh dieback. For instance, marsh degradation in both of the California regions included in this study appears likely to be driven by deeper subsidence than what is measured by surface elevation tables, perhaps resulting from groundwater overdraft or seismic events. Longer time series of vegetative cover may also have greater predictive power; thus extending the UVVR change analysis to begin with the earliest aerials dating back almost a century might prove to be a powerful tool.

Selecting marsh monitoring approaches

Our results suggest that geospatially derived metrics can be an effective approach for assessment of marsh stability at the landscape scale. While we calculated the vegetation distributions from field transects of vegetation cover and elevation, this can also be done with aerial image analysis and digital elevation models, though some field ground-truthing is essential (Buffington *et al* 2016, Ekberg *et al* 2017). The UVVR is also assessed from aerial imagery. Therefore, four of the five most effective indicators in this study can mostly be obtained from remote sensing.

Decadal change in UVVR intuitively provides a valuable perspective on vegetation cover trends at the marshes. Accurate calculation of the rate of change requires consistent analysis of aerial images over time, ideally from 3 + years to calculate a robust trend. However, we found that for these 12 marshes, current UVVR was very highly correlated ($R^2 = 0.93$) with decadal rate of change of UVVR (figure 5). Thus simply assessing the current UVVR is sufficient and provides a suitable metric with a single temporal snapshot. Given the evidence for ‘runaway’ open-water expansion (e.g. Mariotti 2016), as the UVVR increases it is expected that processes leading to expansion begin to dominate and increase in magnitude

Point measurements at a network of SETs have been promoted as a salt marsh monitoring approach (e.g. Webb *et al* 2013, Osland *et al* 2017). For instance, Lovelock *et al* (2015) analyzed recent trends in mangrove surface elevation changes at 27 sites across the Indo-Pacific region using data from a network of SETs and found that adequate sediment availability can enable mangrove forests to maintain rates of soil-surface elevation gain that match or exceed that of SLR. However, obtaining reliable rates of change from SETs requires multiple site visits over many years, and, given spatial variability, multiple stations per marsh. The SET methodology can also provide critical information on mechanisms underlying marsh dynamics, and thus merits continued inclusion in an extensive portfolio of marsh monitoring.

Conclusions

Understanding tidal marsh trajectories—of persistence versus degradation—is critical for coastal management, especially in the face of accelerating SLR. Marshes likely to persist in place can serve as the centerpiece of conservation initiatives that protect them from damaging land uses or other stressors; marshes with moderate persistence should be prioritized for restoration action; while those with the lowest likelihood of persisting may not represent wise investment opportunities. Our study has identified that indicators related to the distribution of vegetation across the landscape of marsh elevations most strongly predict marsh trajectories, while sediment differential and the UVVR are also associated with marsh persistence but to a lesser degree. Our results indicate that overall, the most robust monitoring approach involves spatially comprehensive characterization of marsh ecosystems.

We found that persistent marshes across the United States resemble each other more than do degrading marshes (figure 4), bringing to mind the opening lines of Tolstoy’s Anna Karenina (‘Happy families are all alike; every unhappy family is unhappy in its own way.’) This suggests that marshes must have attributes in common to be persistent in the face of sea level rise, while marsh degradation can occur through many different pathways.

Nonetheless, our investigation also revealed signatures of marsh degradation. While an ample sediment supply and substantial elevation gain can clearly enhance marsh persistence in the long-term, the majority of degrading marshes in our study had higher accretion and elevation gain rates on a decadal scale than did their paired higher persistence counterparts. This finding reinforces the notion that caution must be applied to the spatial interpretation and extrapolation of data from SETs, underscoring the need for a holistic marsh assessment (Ganju 2019). Marsh accretion data must be interpreted in the context of spatial location, elevation and vegetation. For a vegetated marsh high in the tidal frame, elevation gain will help with persistence in the face of future SLR. But the findings of our study expand and support earlier work (Ganju *et al* 2015) indicating that for a marsh that has lost significant elevation and vegetation, increased accretion can signal degradation.

This synthesis represented a cross-disciplinary effort, and involved a critical examination of metrics independently developed by different teams, a highly unusual endeavor (Kéfi *et al* 2019). By working across disciplines, we were able to detect weaknesses in earlier approaches. For instance, we found that the multimetric MARS indices were less effective at predicting marsh trajectories than were single metrics. We also determined that the UVVR metric loses sensitivity as an indicator of marsh persistence beyond a certain threshold of marsh degradation, and is generally less closely associated with marsh trajectories than is the elevational distribution of vegetation. But together we have also succeeded in identifying an improved approach to monitoring and understanding marsh persistence, which consists of combined application of a subset of the metrics. Because no single metric was reliable at a broad geographic scale, we recommend that assessments focus at regional scales and include vegetation distribution across an elevation gradient, sediment differential, and UVVR. Our investigation identifying the most robust ensemble of metrics to predict persistence serves as a template for other studies developing and testing monitoring approaches that can inform conservation and management.

Acknowledgments

This study was supported by funding from NOAA's Office for Coastal Management and the USGS Coastal and Marine Hazards/Resources, Land Change Science and Ecosystems programs. GRG thanks L Schepers for the use of his field data at Blackwater and Fishing Bay in the calculation of certain marsh metrics. Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the US Government. We are grateful to J A Carr and two anonymous reviewers for providing thoughtful suggestions that improved the clarity of the paper.

ORCID iDs

Kerstin Wasson https://orcid.org/0000-0002-1858-4505
Neil K Ganju https://orcid.org/0000-0002-1096-0465
Zafer Defne https://orcid.org/0000-0003-4544-4310
Tracy Elsey-Quirk https://orcid.org/0000-0002-2068-592X
Karen M Thorne https://orcid.org/0000-0002-1381-0657
Chase M Freeman https://orcid.org/0000-0003-4211-6709
Glenn Guntenspergen https://orcid.org/0000-0002-8593-0244
Daniel J Nowacki https://orcid.org/0000-0002-7015-3710
Kenneth B Raposa https://orcid.org/0000-0002-9998-3881

References

Anderson M J and Robinson J 2003 Generalized discriminant analysis based on distances *Aust. N. Z. J. Stat.* **45** 301–18

Anderson M J and Willis T J 2003 Canonical analysis of principal coordinates: a useful method of constrained ordination for ecology *Ecology* **84** 511–25

Barbier E B 2019 The value of coastal wetland ecosystem services *Coastal Wetlands* (Amsterdam: Elsevier) pp 947–64

Blum M and Roberts H 2009 Drowning of the Mississippi delta due to insufficient sediment supply and global sea-level rise *Nat. Geosci.* **2** 488–91

Buffington K J, Dugger B D, Thorne K M and Takekawa J Y 2016 Statistical correction of lidar-derived digital elevation models with multispectral airborne imagery in tidal marshes *Remote Sens. Environ.* **186** 616–25

Byrd K B, Windham-Myers L, Leeuw T, Downing B, Morris J T and Ferner M C 2016 Forecasting tidal marsh elevation and habitat change through fusion of Earth observations and a process model *Ecosphere* **7** e01582

Cahoon D R, Lynch J C, Roman C T, Schmit J P and Skidds D E 2019 Evaluating the relationship among wetland vertical development, elevation capital, sea-level rise, and tidal marsh sustainability *Estuaries Coasts* **42** 1–15

Clarke K R, Gorley R N, Somerfield P J and Warwick R M 2014 *Change in Marine Communities: An Approach to Statistical Analysis and Interpretation* (Plymouth: Primer-E)

Cole Ekberg M L, Raposa K B, Ferguson W S, Ruddock K and Watson E B 2017 Development and application of a method to identify salt marsh vulnerability to sea level rise *Estuaries Coasts* **40** 694–710

Craft C, Clough J, Ehman J, Joye S, Park R, Pennings S, Guo H and Machmuller M 2008 Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystems services *Front. Ecol. Environ.* **7** 73–8

Day J W *et al* 2007 Restoration of the Mississippi Delta: lessons learned from Hurricanes Katrina and Rita *Science* **315** 1679–84

Deegan L A, Johnson D S, Warren R S, Peterson B J, Fleeger J W, Fagherazzi S and Wollheim W M 2012 Coastal eutrophication as a driver of salt marsh loss *Nature* **490** 388

Donohue I *et al* 2016 Navigating the complexity of ecological stability *Ecol. Lett.* **19** 1172–85

Fagherazzi S *et al* 2012 Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors *Rev. Geophys.* **50**

FitzGerald D M and Hughes Z 2019 Marsh processes and their response to climate change and sea-level rise *Annu. Rev. Earth Planet. Sci.* **47** 481–517

Ganju N K 2019 Marshes are the new beaches: Integrating sediment transport into restoration planning *Estuaries Coasts* **42** 917–26

Ganju N K, Defne Z, Kirwan M L, Fagherazzi S, D'Alpaos A and Carniello L 2017 Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes *Nat. Commun.* **8** 14156

Ganju N K, Kirwan M L, Dickhudt P J, Guntenspergen G R, Cahoon D R and Kroeger K D 2015 Sediment transport-based metrics of wetland stability *Geophys. Res. Lett.* **42** 7992–8000

Ganju N K, Nidzieko N J and Kirwan M L 2013 Inferring tidal wetland stability from channel sediment fluxes: Observations and a conceptual model *J. Geophys. Res.: Earth Surf.* **118** 2045–58

Ganju N K, Schoellhamer D H, Murrell M C, Gartner J W and Wright S A 2007 Constancy of the relation between floc size and density in San Francisco Bay *Estuarine and Coastal Fine Sediments Dynamics* (Amsterdam: Elsevier Science BV) pp 75–91

Holdredge C, Bertness M D and Altieri A H 2009 Role of crab herbivory in die-off of New England salt marshes *Conserv. Biol.* **23** 672–9

Janousek C N *et al* 2016 Potential effects of sea-level rise on plant productivity: species-specific responses in northeast Pacific tidal marshes *Mar. Ecol. Prog. Ser.* V **548** 111–25

Kéfi S, Domínguez-García V, Donohue I, Fontaine C, Thébault E and Dakos V 2019 Advancing our understanding of ecological stability *Ecol. Lett.* **22** 1349–56

Kirwan M L and Megonigal J P 2013 Tidal wetland stability in the face of human impacts and sea-level rise *Nature* **504** 53

Lovelock C E *et al* 2015 Sea level rise and the fate of mangroves *Nature* **526** 559–63

Mariotti G 2016 Revisiting salt marsh resilience to sea level rise: Are ponds responsible for permanent land loss? *J. Geophys. Res.: Earth Surf.* **121** 1391–407

McKee K and Patrick W H 1988 The relationship of smooth cordgrass (*Spartina alterniflora*) to tidal datums: a review *Estuaries* **11** 143–51

Mitsch W J, Bernal B and Hernandez M E 2015 *Int. J. Biodivers. Sci. Ecosyst. Serv. Manage.* **11** 1–4

Morris J T 2006 Competition among marsh macrophytes by means of geomorphological displacement in the intertidal zone *Estuarine Coastal Shelf Sci.* **69** 395–402

Morris J T, Sundareshwar P V, Nietch C T, Kjerfve B and Cahoon D R 2002 Responses of coastal wetlands to rising sea level *Ecology* **83** 2869–77

Nowacki D J and Ganju N K 2019 Simple metrics predict salt-marsh sediment fluxes *Geophys. Res. Lett.* **46** 12250–7

Osland M J *et al* 2017 Assessing coastal wetland vulnerability to sea-level rise along the northern Gulf of Mexico coast: gaps and opportunities for developing a coordinated regional sampling network *PLoS One* **12** e0183431

Raposa K B *et al* 2016 Assessing tidal marsh resilience to sea-level rise at broad geographic scales with multi-metric indices *Biol. Conservation* **204** 263–75

R Core Team 2018 R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria (https://R-project.org/)

Reed D J 2002 Sea-level rise and coastal marsh sustainability: geological and ecological factors in the Mississippi delta plain *Geomorphology* **48** 233–43

Sato C F and Lindenmayer D B 2018 Meeting the global ecosystem collapse challenge *Conservation Lett.* **11** e12348

Schile L M, Callaway J C, Parker V T and Vasey M C 2011 Salinity and inundation influence productivity of the halophytic plant *Sarcocornia pacifica Wetlands* **31** 1165–74

Schile L M, Callaway J C, Morris J T, Stralberg D, Parker V T and Kelly M 2014 Modeling tidal marsh distribution with sea-level rise: evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency *PLoS One* **9** e88760

Stevenson J C, Kearney M S and Pendleton E C 1985 Sedimentation and erosion in a Chesapeake Bay brackish marsh system *Mar. Geol.* **67** 213–35

Swanson K M, Drexler J Z, Schoellhamer D H, Thorne K M, Casazza M L, Overton C T, Callaway J C and Takekawa J Y 2014 Wetland accretion rate model of ecosystem resilience (WARMER) and its application to habitat sustainability for endangered species in the San Francisco Estuary *Estuaries Coasts* **37** 476–92

Thorne K *et al* 2018 US Pacific coastal wetland resilience and vulnerability to sea-level rise *Sci. Adv.* **4** eaao3270

Webb E L, Friess D A, Krauss K W, Cahoon D R, Guntenspergen G R and Phelps J 2013 A global standard for monitoring coastal wetland vulnerability to accelerated sea-level rise *Nat. Clim. Change* **3** 458

Weston N B 2014 Declining sediments and rising seas: an unfortunate convergence for tidal wetlands *Estuaries Coasts* **37** 1–23

Wiberg P L, Fagherazzi S and Kirwan M L 2019 Improving predictions of salt marsh evolution through better integration of data and models *Annu. Rev. Mar. Sci.* **12**

Wigand C, Ardito T, Chaffee C, Ferguson W, Paton S, Raposa K, Vandemoer C and Watson E 2017 A climate change adaptation strategy for management of coastal marsh systems *Estuaries Coasts* **40** 682–93