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The Relationship Between Shoreline Armoring and Adjacent Submerged Aquatic Vegetation in Chesapeake Bay and Nearby Atlantic Coastal Bays

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Abstract Shoreline armoring is an ancient and globally used engineering strategy to prevent shoreline erosion along marine, estuarine, and freshwater coastlines. Armoring alters the land water interface and has the potential to affect nearshore submerged aquatic vegetation (SAV) by changing nearshore hydrology, morphology, water clarity, and sediment composition. We quantified the relationships between the condition (bulkhead, riprap, or natural) of individual shoreline segments and three measures of directly adjacent SAV (the area of potential SAV habitat, the area occupied by SAV, and the proportion of potential habitat area that was occupied) in the Chesapeake Bay and nearby Atlantic coastal bays. Bulkhead had negative relationships with SAV in the polyhaline and mesohaline zones. Salinity and watershed land cover significantly modified the effect of shoreline armoring on nearshore SAV beds, and the effects of armoring were strongest in polyhaline subestuaries with forested watersheds. In high salinity systems, distance from shore modified the relationship between shoreline and SAV. The negative relationship between bulkhead and SAV was greater further off shore. By using individual shoreline segments as the study units, our analysis separated the effects of armoring and land cover, which were confounded in previous analyses that quantified average armoring and SAV abundance for much larger study units (subestuaries). Our findings suggest that redesigning or removing shoreline armoring structures may benefit nearshore SAV in some settings. Because armoring is ubiquitous, such information can inform efforts to reverse the global decline in SAV and the loss of the ecosystem services that SAV provides.

Keywords Shoreline hardening · Armoring · Riprap · Bulkhead · SAV · Land use · Land cover

Introduction

Submerged aquatic vegetation (SAV) is a keystone feature of estuarine and marine ecosystems worldwide. SAV beds provide structural habitat and cover for a wide variety of benthic invertebrates and fish (Heck and Thoman 1984; Heck and Duarte 2000). SAV also provides many other ecosystem functions. Healthy, dense SAV regulates physical conditions within a bed by providing oxygen to the water column (Hemminga and Duarte 2000; Lubbers et al. 1990; Findlay et al. 2006), by dampening wave energy, and by slowing down water movement (derHeide et al. 2007; Gruber et al. 2011). These physical changes promote deposition of fine particles, improvements to water clarity, and reductions in shoreline erosion (Hemminga and Duarte 2000; derHeide et al. 2007; Gruber et al. 2011). SAV also removes nutrients from the water column and reduces the potential for harmful algae blooms and anoxia (Wigand et al. 2001).

SAV is in global decline (Orth et al. 2006) for many reasons. Small disturbances like propeller damage and dredging have localized negative impacts on SAV (Orth et al. 2002). At larger spatial scales, land use practices (e.g., agriculture and urbanization) can reduce water quality through anthropogenic nutrient loading (Anderson et al. 2002; Gallegos and Bergstrom 2005), high levels of suspended sediments, and increases in colored dissolved organic matter (cDOM; Gallegos 2001; Hale et al. 2004; Gallegos et al. 2011). These changes drive decreases in SAV area and density

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(Stevenson et al. 1993; Brush and Hilgartner 2000; Li et al. 2007; Patrick et al. 2014).

Shoreline armoring is another potential driver of SAV loss (Gabriel and Bodensteiner 2012; Patrick et al. 2014). The installation of shoreline armoring or hardening to prevent erosion has a very long history in coastal human settlements (Rosen and Vine 1995). Modern armoring structures include wooden vertical walls (bulkhead), stone piles on the shoreline (riprap), vertical or concave cement walls (seawall), horizontal extensions from the shoreline (groinfields), and structures in the water parallel to shore to dampen wave energy (breakwaters) (Strayer and Findlay 2010). By changing the profile and incident angle of the shoreline, armoring structures change how wave energy is transferred into the littoral zone. Instead of dissipating onto a sloped shore or into a marsh, waves that encounter a steep hardened surface such as a bulkhead or riprap reflect to scour and damage the benthos, erode bottom sediments, and suspend fine particulates that reduce water clarity (Pope 1997; Wright 1995; Miles et al. 2001).

Given its potentially harmful effect on nearshore communities, shoreline armoring could be a worldwide environmental concern. Armoring can sometime replace much of the natural shoreline along highly developed coastlines. For example, San Diego Bay is 74 % armored, and in the Chesapeake Bay, eight subestuaries are more than 50 % armored and 23 more are between 30 and 50 % armored (Living Shoreline Summit Steering Committee 2006; Patrick et al. 2014). Armoring will probably increase in the coming century (Dugan et al. 2008) as coastal zone populations soar (Small and Nicholls 2003; EEA 2006; Curtis and Schneider 2011) and as sea level rises in response to global climate change (Dugan et al. 2008).

There is a small but growing body of literature on the effects of shorelines armoring on nearshore benthic communities (King et al. 2005; Rice 2006; Seitz et al. 2006; Balouskus and Targett 2012; Morley et al. 2012), but there are only a few direct studies of armoring effects on SAV (Gabriel and Bodensteiner 2012; Findlay et al. 2014; Patrick et al. 2014). Gabriel and Bodensteiner (2012) found changes in SAV community composition and reductions in total SAV coverage adjacent to armored lake shorelines. Patrick et al. (2014) also found negative correlations between shoreline hardening and SAV abundance when both were measured as averages for entire subestuaries; but they could not separate the effects of shoreline hardening from the effects of local watershed land cover. In contrast, Findlay et al. (2014) found inconsistent responses of SAV to shoreline hardening in the tidal fresh Hudson River. Additional study is needed to reconcile the conflicting published findings and to create a general understanding of the relationship between armoring and SAV abundance.

Chesapeake Bay and the nearby Atlantic coastal bays provide an ideal study system to examine the impacts of shoreline armoring on SAV. Chesapeake Bay (11,600 km^2) is one of the largest estuaries in the world, and its long shoreline (18,800 km) encompasses many shoreline conditions. Like many estuaries worldwide, SAV coverage in the bay is below historical levels (Orth and Moore 1984; Orth et al. 2010a). Currently, the nearby Atlantic coastal bays have generally better water quality and higher current SAV prevalence than the Chesapeake Bay subestuaries (Patrick et al. 2014). The numerous tributaries of the Chesapeake Bay form over 100 smaller embayments (subestuaries) that have their own local watersheds. The subestuaries of the Chesapeake Bay and Atlantic coastal bays are convenient, replicated study units for comparing systems dominated by different land covers and salinity regimes (Li et al. 2007; Patrick et al. 2014). Monitoring programs have produced extensive data sets that report shoreline armoring (VIMS 2013a) and annual SAV coverage since 1984 (VIMS 2013b).

Previous analyses found significant negative relationships between the proportion of hardened shoreline and SAV abundance at the scale of subestuaries and their local watersheds (Patrick et al. 2014). The relationships between shoreline stressors and the SAV response differed among salinity zones, probably because the zones are dominated by different SAV species with different tolerances to changes in light, hydraulic regime, and benthic sediment composition (Patrick et al. 2014). However, earlier analyses were limited because it is difficult to disentangle the effects of shoreline hardening from the many other differences among subestuaries that might be related to SAV decline (Li et al. 2007). For example, among subestuaries, the prevalence of shoreline armoring is strongly positively correlated with the general intensity of human land use (agricultural and developed land cover) in the watershed (Patrick et al. 2014).

To better understand the relationships between shoreline hardening and SAV abundance, this paper analyzes the relationship a much finer spatial scale than our previous work (Patrick et al. 2014). We investigate the relationships between the condition (riprap, bulkhead, or natural) of individual shoreline segments and the immediately adjacent SAV beds. Analyzing individual segments of shoreline and adjacent SAV beds enables us to draw stronger linkages between shoreline condition and SAV abundance than we achieved through analyses of entire subestuaries (Li et al. 2007; Patrick et al. 2014).

This analysis also tested several a priori hypotheses. We predicted that there would be less potential SAV habitat and less SAV directly adjacent to armored shorelines than next to natural shorelines. We also expected the negative effects of armoring to differ among salinity zones (which contain different SAV communities) and among subestuaries with local watersheds dominated by different land covers (which can lead to differences in water quality and clarity). We predicted that the negative relationship between SAV and shoreline armoring would be stronger in the polyhaline zone than in the lower salinity zones because the dominant polyhaline species (*Zostera marina*) is more sensitive to reductions in sediment quality and light than lower salinity species (Batiuk et al. 2000; Kemp et al. 2004). Finally, we predicted the negative relationships between armoring and SAV would be weaker in human-impacted subestuaries than in subestuaries with forested watersheds, because the strong negative effects on SAV of watershed drivers of poor water quality would overwhelm the signal of local shoreline effects on SAV.

Methods

Study Site

We studied the Chesapeake Bay and the Atlantic coastal bays of Maryland, Virginia, and Delaware in the mid-Atlantic USA (Fig. 1). We developed or acquired digital spatial data sets describing shoreline condition, salinity zones, bathymetry, the boundaries of subestuaries and their local watersheds, the land cover in each local watershed, observed SAV, and potential SAV habitat. Salinity zones of Chesapeake Bay were categorized as oligohaline (OH, 0.5–5 ppt), mesohaline (MH, 5–18 ppt), or polyhaline (PH, >18 ppt) based on the Chesapeake Bay Program segmentation scheme (Chesapeake Bay Program 2004) (Fig. 1). The Coastal Bay systems were all polyhaline. Bathymetry data for Chesapeake Bay were developed by NOAA and provided on a 30×30 m grid through the bay (NOAA 2006). Bathymetry data for the Atlantic coastal bays came from the NOAA National Geophysical Data Center's US Coastal Relief Model of the Southeast Atlantic, which provides depths on an 82×82 m grid (NOAA (National Oceanic and Atmospheric Administration) 2011).

We started with 116 previously delineated subestuaries in the Chesapeake Bay and Atlantic coastal bays (Li et al. 2007; Patrick et al. 2014). Subestuaries were defined as embayments that had distinct local watersheds with at least one perennial tributary stream, and their local watersheds were delineated using topographic analysis of digital elevation maps (Li et al. 2007; Patrick et al. 2014). Coastal plain and low elevation watersheds were manually corrected and checked against stream maps (Allord 1992; Baker et al. 2006) and against digital maps of hydrologic unit boundaries (USGS (US Geological Survey) 2006).

Shoreline Condition

Shoreline condition was described in published digital shoreline situation maps (VIMS 2013a). Those maps were created from data collected by a field team who surveyed the shoreline by boat while recording shoreline structures and their locations as determined by a global positioning system. Different areas were mapped in different years between 1998 and 2009. Rectified digital orthophoto quadrangles were used to align recorded features with identifiable structures in the images (VIMS 2013a). The data set provides the lengths and condition of 51,512 shoreline segments that are unaltered (natural) or are covered by linear constructed features (shoreline hardening). There are nine categories of constructed features, but we focused on three shoreline types: riprap, bulkhead, and unaltered (natural) shorelines, which together compose most of the mapped shoreline (see "Results"). Other categories were too sparsely distributed to include in our statistical analyses of shoreline effects. Shoreline data are not available for some parts of the Chesapeake Bay, including the lower Eastern Shore, the upper Potomac, and parts of the James and York Rivers (VIMS 2013a); so, those areas were not included in our analyses. We summarized shoreline condition for the three major shoreline types (riprap, bulkhead, and natural shoreline) as well as the other minor types (debris, groinfield, jetty, marina, seawall, shipyard, unconventional,

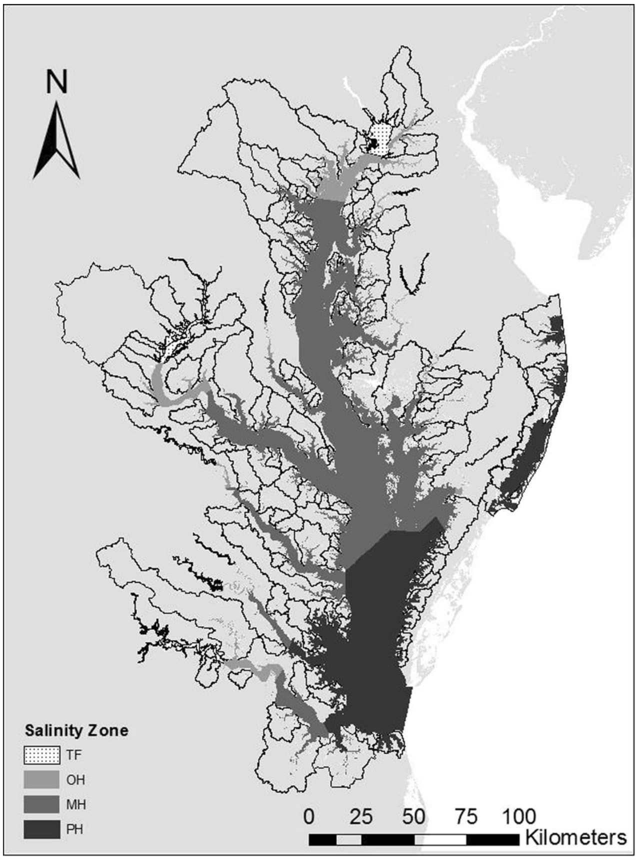

Fig. 1 The Chesapeake Bay and Atlantic coastal bay study subestuaries. Subestuaries are enclosed by their local watersheds (*black outlines*). Coastal waters are shaded by four salinity categories: *TF* tidal fresh, *OH* oligohaline, *MH* mesohaline, and *PH* polyhaline

wharf, and miscellaneous) for the entire study area and for each salinity zone.

Land Cover

For the local watershed of each subestuary (Fig. 1), we summarized total watershed area and the percentages of cropland, herbaceous wetland, total forested land, and total developed land from the circa 2000 National Land Cover Data Set, which was derived from Landsat 7 imagery (30 m resolution; Homer et al. 2004). We classified each subestuary system into one of the three land cover categories based on the dominant land cover of its local watershed: (1) forested (≥60 % forest and forested wetland), (2) human impacted (≥50 % developed land or ≥40 % cropland), or (3) mixed land cover (watersheds which did not fit into categories 1 and 2) (King et al. 2005); Li et al. 2007; Patrick et al. 2014) (Table 2). We considered the effects of watershed land cover on SAV only for shoreline segments occurring within subestuaries; not for shoreline segments along the main stem of the Chesapeake or along the main shorelines of larger tributaries, such as the Potomac River subestuary. There was no way to assign a relevant local watershed for such segments.

Shoreline Characteristics of Subestuaries

We intersected the shoreline layer with the subestuary boundaries (Patrick et al. 2014) to quantify the prevalence of shoreline types within each subestuary. There were 17, 74, and 22 subestuaries with shoreline data in the oligo-, meso-, and polyhaline zones, respectively. We summarized the shoreline characteristics of the subestuaries in each salinity zone and each dominant land cover category.

Submerged Aquatic Vegetation

SAV spatial extent was calculated from published maps of SAV beds digitized from annual aerial photography for the years 1984–1987 and 1988–2009 (Moore et al. 2000; VIMS 2013b). Digital map layers from all years were overlain to create a layer of maximal extent of SAV observed, which was used to estimate the area occupied by SAV adjacent to each shoreline segment. SAV data from 1984 to 2009 were included to represent the average response of SAV to shoreline stressors. We considered the average response because we did not have information on when armoring structures were installed. We also estimated the potential SAV habitat area. We began with areas ≤2 m deep in the digital bathymetry layers—the area that the Chesapeake Bay Program considers to be potential habitat for SAV based on its tier III restoration goal (Batiuk et al. 2000). We removed areas designated as SAV no-grow zones because of high exposure to waves or consistent SAV absence dating back to the 1930s (USEPA 2003), and then we added areas where SAV had been observed in historical surveys and in the more recent aerial surveys (Moore et al. 2000; VIMS 2013b). The proportion of occupied SAV habitat for an area adjacent to a shoreline segment was calculated by dividing the maximal extent of occupied SAV area by the area of potential habitat. SAV area, potential habitat area, and the proportion of occupied potential habitat were summarized for the entire study area and for the three salinity zones.

Comparison Among Shoreline Types

We used analysis of variance (ANOVA) to test for differences in the prevalence of SAV and SAV habitat among the three shoreline types (riprap, bulkhead, and natural). To select a sample of segments for this analysis, we focused on segments of a length that was representative across the region and also comparable among shoreline types. To develop objective length criteria for including segments in the analysis, we analyzed the distributions of shoreline lengths in each shoreline category (riprap, bulkhead, and natural) throughout the Bay. We selected 75–125 m shoreline segments for our analysis because this length range is representative of the two innerquartiles of all three shoreline categories. This process retained 11,514 (about half) of the original segments of the three main shoreline types. A random subsample of these (as explained below) was then selected for each analysis using stratified random sampling.

To quantify SAV coverage near the selected shoreline segments, we created a 250 m-wide buffer around each segment. We intersected those buffers with the map of potential SAV habitat and the map of observed SAV. SAV area and potential habitat area for each segment were normalized by dividing by shoreline segment length to give measures of potential habitat and observed maximal SAV coverage per length of shoreline. We also calculated the proportion of occupied habitat by dividing observed SAV area by potential habitat area. Segments were categorized by salinity zone, and segments located within a subestuary were also assigned the dominant land cover in the local watershed of the subestuary. Overlapping buffered segments were excluded from analyses.

Effects of Shoreline Type and Salinity Zone

The main effects of shoreline type (shoreline, bulkhead, or natural) and salinity zone (oligohaline, mesohaline, or polyhaline) and their interaction were examined using two-way ANOVA. This analysis considered shoreline segments throughout the study area, including segments that were not located within the defined subestuaries. However, we excluded the tidal fresh zone because of gaps in the shoreline condition data and the small number of shoreline segments that occurred within the selected size range. To achieve a balanced test, we randomly selected the same number (250) of shoreline segments for each of the nine possible combinations of shoreline and salinity.

Interactions Among Shoreline Type, Salinity Zone, and Watershed Land Cover

We used three-way ANOVA to examine the interacting effects of shoreline alteration, salinity, and the dominant land cover of the local watershed on the proportion of occupied habitat. We selected all the riprap, bulkhead, and natural shoreline segments (2730) that met the length criteria (see above) *and were within a defined subestuary* so that a dominant land cover could be assigned. We used a fully crossed, unbalanced ANOVA with three dominant land cover categories (human impacted, mixed, and forested watersheds), three shoreline types (bulkhead, riprap, and natural), and three salinity zones (oligohaline, mesohaline, and polyhaline).

Interaction of Shoreline Type and Distance from the Shore in the Polyhaline Zone

For the polyhaline zone, we tested whether the effects of shoreline type on SAV differed with distance from the shoreline. We divided the 0–250 m response zone (above) into two bands (0–100 m and 100–250 m from shore) and quantified the proportion of habitat occupied by SAV in each band (as described above). To achieve a balanced design, we randomly selected 280 polyhaline shoreline segments for each of the three shoreline types. We standardized the SAV data by calculating z scores for occupied SAV habitat in each distance band, and then we used MANOVA to relate the two standardized proportions of occupied habitat (0–100 m and 0–250 m) to shoreline type. Standardization was necessary to make the data comparable between bands because the bands differed in area, depth, and slope. We also performed a paired t test comparing the proportion of occupied habitat within 0–100 m to the proportion occupied within 100–250 m for each shoreline type to provide additional information to interpret the MANOVA.

All spatial analyses were implemented with the ArcGIS geographic information system (ESRI 2011). All statistical analyses were performed in the statistical program R (R Development Core Team 2012), except for the MANOVA, which was performed using SAS (SAS software version 9.1.3 2004). For significant ANOVA models, we performed Tukey's HSD post hoc tests to identify which levels of main effects were significantly different from one another.

Results

Shoreline Characteristics and SAV Coverage

Across the entire study area, 17 % of the surveyed shoreline was hardened. Among subestuaries, the shoreline ranged from mostly hardened to mostly unhardened (Table 1). Bulkhead and riprap were the two largest categories of hardened shoreline, occupying 6 and 7 % (respectively) of the shoreline in both the subestuaries and the main channel. Subestuaries had averages of 8 % riprap and 9 % bulkhead along their shorelines (Table 2); however, some subestuaries had as much as 42 % riprap and 52 % bulkhead. Individual shoreline segments also varied greatly in size. The longest sections of armored shoreline (riprap or bulkhead) were more than a kilometer long, but the average shoreline length for both types of armoring was ~110 m.

SAV coverage was also spatially variable; some areas have consistently large SAV beds while other sections of shoreline are always devoid of aquatic plants. Across the entire study area, SAV occupied 28 % of the potential habitat within 250 m of shore, but the percent occupation was higher than that average in the tidal fresh and oligohaline zones and lower than the average in the mesohaline zone (Table 3).

Comparison Among Shoreline Types

Effects of Shoreline Type and Salinity Zone

For all three response variables, the two-way ANOVA of shoreline type and salinity zone had a significant interaction between shoreline condition and salinity. Shoreline condition and salinity individually affected SAV area and occupied potential habitat (Table 4). SAV area and occupied potential habitat were significantly higher in the oligohaline than in the mesohaline and polyhaline zones (OH vs MH: Tukey's HSD $p<0.0001$, Tukey's HSD OH vs PH: $p<0.0001$; Fig. 2, Table 5). There was significantly less SAV area adjacent to bulkhead than adjacent to riprap shoreline (Tukey's HSD $p<0.001$). Both natural (Tukey's HSD $p=0.008$) and riprap (Tukey's HSD $p<0.001$) shorelines had a higher proportion of adjacent occupied habitat than bulkhead shorelines.

The effect of shoreline type on response variables differed among salinity zones (Table 3). In the polyhaline zone, natural shoreline had a significantly more SAV area than bulkhead and riprap. Occupied potential habitat near natural shoreline was significantly higher than near bulkhead, but not significantly different from riprap shoreline (Table 5, Fig. 3). In mesohaline subestuaries, both riprap and natural shoreline had significantly higher proportions of occupied habitat and SAV area than bulkhead shorelines, but riprap and natural did not differ from one another (Table 5, Fig. 3). There was no difference in potential habitat among shoreline types in the

Table 1 Total lengths (km) of different types of natural and constructed shoreline in each salinity zone and in the entire study area. Shoreline data from VIMS (2013a)

Variable	Salinity zone				Entire study area
	Tidal fresh	Oligohaline	Mesohaline	Polyhaline	
Bulkhead	24.0	126.5	718.	203	1071
Riprap	36.4	92.03	1060	113	1301
Natural	1349	2215	8084	2722	14,370
Breakwater	0.30	3.59	25.8	6.16	35.9
Debris	2.27	4.78	10.9	2.74	20.7
Dilapidated bulkhead	1.96	5.57	23.5	4.52	35.6
Groinfield	2.40	16.8	183.	10.8	213
Jetty	1.03	0.94	12.5	2.17	16.6
Marina	9.19	24.8	125	17.6	176
Miscellaneous	0.83	16.2	79.4	10.1	107
Seawall	0.00	0.00	3.45	3.29	6.74
Shipyard	0.00	0.00	10.3	0.00	10.3
Unconventional	5.20	2.60	20.6	3.58	32.0
Wharf	0.98	1.37	28.6	30.6	61.6
Total shoreline length	1434	2510	10,390	3129	17,460

polyhaline zone and mesohaline zones. In the oligohaline zone, the patterns were very different. Natural shoreline had less potential habitat and SAV area than bulkhead or riprap, but there was no shoreline effect on the proportion of occupied habitat (Table 5, Fig. 3).

Interactions Among Shoreline Type, Salinity Zone, and Watershed Land Cover

All the independent variables (salinity, watershed land cover, and shoreline condition) in the three-way ANOVA were significantly related to proportion of occupied habitat (Table 6, Fig. 3). We observed more nearshore occupied habitat in the oligohaline zone than in the more saline parts of the bay (Tukey's HSD $p<0.001$). The effects of shoreline are hard to generalize because there was a significant three-way interaction among shoreline type, watershed land cover, and salinity (Table 6). In the polyhaline zone, there was more SAV adjacent to natural than bulk headed shorelines in forested and mixed land cover watersheds (Tukey's HSD $p<0.001$), and the SAV in all shoreline categories increased as human activity in the watershed decreased (Tukey's HSD $p<0.001$, Fig. 3). Furthermore, the absolute size of the difference between bulkhead and natural shoreline increased proportionally with increases in total SAV coverage. This pattern agreed with our expectations, but was not repeated in the other salinity zones. In the mesohaline, there was more SAV overall in the mixed land cover subestuaries (Fig. 3). In the oligohaline, forested watersheds tended to have more SAV overall (matching our a priori predictions), but bulkhead had as high or higher

Table 2 Percentages of three shoreline types (average percentage and standard deviation) for subestuaries grouped into nine categories defined by salinity zone and local watershed dominant land cover.

Salinity zone	Dominant land cover	Number of subestuaries	Percentage of shoreline		
			Riprap	Bulkhead	Natural
Oligohaline	Forest	5	2±1.9	7±10.7	89±7.0
	Human	9	5±3.1	12±4.3	80±19
	Mixed	4	4±2.8	10±14	84±11
Mesohaline	Forest	22	9±4.7	10±11	79±12
	Human	13	15±9.5	17±13	64±17
	Mixed	39	12±8.3	9±7.9	77±14
Polyhaline	Forest	4	4±2.0	2±0.91	94±2.8
	Human	3	9±9.4	2±22	65±36
	Mixed	15	3±3.9	7±9.4	89±12

"Human" land cover refers to watersheds with either >40 % agricultural land or >50 % developed land. "Forested" refers to watersheds with >60 % forest. Watersheds that do not fit into either those categories are "Mixed" (Li et al. 2007)

Table 3 SAV response variables in each salinity zone and in the entire study area

Variable	Salinity zone				Entire study area
	Tidal fresh	Oligohaline	Mesohaline	Polyhaline	
Maximum SAV area	68.1	94.4	271	127	561
Potential habitat area	189.	266	1120	453	2027
Proportion occupied habitat	0.36	0.35	0.24	0.28	0.28

Areas (km^2) were summarized for the zone 0–250 m from the shoreline. SAV data from VIMS (2013b)

proportion of occupied habitat adjacent to it than did natural and riprapped shorelines (Fig. 3).

Interaction of Shoreline Type and Distance from the Shore in the Polyhaline Zone

There was no effect of distance from shore on the proportion of occupied habitat in the MANOVA model applied in the polyhaline zone ($df=1835$; $F<0.001$; $p=0.99$). However, there was a significant effect of shoreline type ($df=2835$; $F=14.3$; $p<0.001$) and a significant interaction between shoreline type and distance from shore on the proportion of occupied SAV habitat (Fig. 4; $df=2835$; $F=3.93$; $p<0.02$). The proportion of occupied habitat 100–250 m offshore was significantly lower than 0–100 m offshore for bulkhead shoreline (Fig. 4; $T=3.08$, $df=277$, $p=0.002$). There was no difference in coverage between nearshore and offshore bands adjacent to natural shorelines (Fig. 4; $T=-1.18$, $df=279$, $p=0.24$). There was also no difference between SAV coverage in bands near the shore and offshore from riprap ($T=-0.86$, $df=279$, $p=0.39$).

Discussion

Our analysis of the relationship between shoreline armoring and SAV coverage in adjacent waters is the first to place SAV response to adjacent shoreline hardening within the context of larger-scale factors such as salinity zone and dominant watershed land cover. Only a few studies have considered SAV responses to armoring at any scale (Gabriel and Bodensteiner 2012; Findlay et al. 2014; Patrick et al. 2014), so there is little published work to compare with our results. Gabriel and Bodensteiner (2012) found that natural shorelines in Wisconsin lakes had more SAV than riprapped shores. Patrick et al. (2014) found negative relationships between shoreline hardening and SAV. However, they quantified both hardening and SAV using average values for entire subestuaries, and there are confounding correlations among shoreline hardening, land cover, and other factors at that scale. Finally, Findlay et al. showed variable effects of hardening on SAV in the Hudson River (Findlay et al. 2014). Our present analyses add to this small, but growing body of research by showing that SAV abundance can be negatively related with

Table 4 ANOVA tables for the effects of shoreline type and salinity zone on SAV response variables

Factor or interaction	Degrees of freedom	Sum of squares	Mean squared error	*F*	*p*
Potential habitat					
Shoreline type	2	8.90	4.44	11.6	<0.001
Salinity	2	0.10	0.05	0.14	0.9
Shoreline type × salinity	4	8.70	2.18	5.71	<0.001
Residuals	2241	855	0.38		
Maximum SAV area					
Shoreline type	2	5.30	2.66	9.61	<0.001
Salinity	2	41.3	20.7	74.8	<0.001
Shoreline type × salinity	4	18.7	4.66	16.9	<0.001
Residuals	2241	619	0.28		
Proportion occupied habitat					
Shoreline type	2	2.68	1.34	13.4	<0.001
Salinity	2	29.6	14.9	149	<0.001
Shoreline type × salinity	4	4.42	1.11	11.1	<0.001
Residuals	2241	224	0.10		

Table 5 Comparisons of SAV response variable means between shoreline types within each salinity zone

Salinity zone	Comparison	Mean difference	*p*
Proportion of occupied habitat			
Oligohaline	Riprap-natural	0.06	0.57
	Natural-bulkhead	−0.05	0.74
	Riprap-bulkhead	0.01	0.99
Mesohaline	Riprap-bulkhead	0.13	<0.001
	Natural-bulkhead	0.10	0.01
	Riprap-natural	0.03	0.97
Polyhaline	Natural-bulkhead	0.09	0.03
	Riprap-bulkhead	0.06	0.43
	Riprap-natural	−0.03	0.97
Maximum SAV area			
Oligohaline	Riprap-natural	0.18	0.002
	Natural-bulkhead	−0.15	0.04
	Riprap-bulkhead	0.04	0.99
Mesohaline	Riprap-bulkhead	0.18	0.005
	Natural-bulkhead	0.15	0.04
	Riprap-natural	0.03	0.99
Polyhaline	Natural-bulkhead	0.14	0.05
	Riprap-bulkhead	0.01	0.43
	Riprap-natural	−0.04	0.99
Potential habitat area			
Oligohaline	Riprap-natural	0.33	<0.001
	Natural-bulkhead	−0.30	<0.001
	Riprap-bulkhead	0.03	0.99
Mesohaline	Riprap-natural	0.11	0.61
	Natural-bulkhead	−0.09	0.80
	Riprap-bulkhead	0.01	0.99
Polyhaline	Riprap-natural	0.07	0.94
	Natural-bulkhead	−0.04	0.99
	Riprap-bulkhead	0.03	0.99

Tukey's HSD test was applied to the results of the two-way ANOVA tests relating SAV response variables to shoreline type and salinity (Table 4). Comparisons are ranked within each salinity zone in order of the statistical significance of the difference between the means

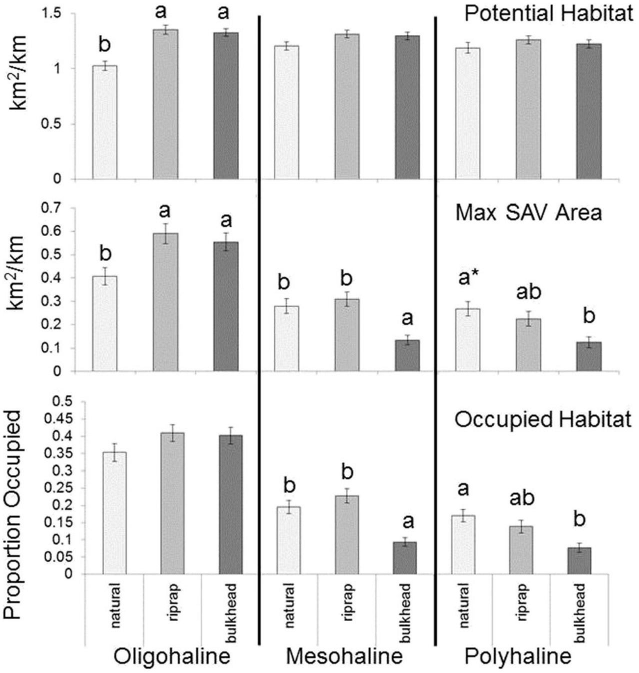

Fig. 2 Relationships of SAV response variables to shoreline condition and salinity. Each of the nine panels shows the response of an SAV measure to riprap, bulkhead, and natural shoreline. A *column of panels* presents one salinity zone (oligohaline, mesohaline, or polyhaline), and *row of panels* is one response variable: potential habitat area (km^2 per km of shoreline), SAV area (km^2 per km of shoreline), and the proportion of occupied habitat. *Error bars* are simple standard errors, and *bars* with the same letter in a panel are not significantly different (p>0.05); however, the difference in SAV area between natural and riprap shoreline in the polyhaline (marked with a*) is nearly significant (p=0.052, Tukey's HSD)

shoreline armoring, but the type of armoring and the surrounding environment strongly affect the relationship between armoring and SAV (Figs. 2 and 3). Armoring was negatively associated with SAV (as predicted) in the polyhaline zone, but there were different associations between SAV and armoring type in the oligohaline and mesohaline zones. Those differences indicate that armoring effects depend on the context and suggest that the species composition of the SAV community (which is controlled by salinity) is important. This study also enhances our prior work (Patrick et al. 2014) by more clearly separating the effects of shoreline alteration from the effects of land cover.

The differences among salinity zones in the effects of shoreline alteration on SAV (Figs. 2 and 3) may be due to differences in the dominant SAV species (Moore et al. 2000) and their habitat requirements (Kemp et al. 2004). In the oligohaline zone, Eurasian water milfoil (*Myriophyllum spicatum*) and hydrilla (*Hydrilla verticillata*) are both canopy-forming species, and wild celery (*Vallisneria americana*) requires 2–9 % of incident light to reach its leaves (Steward 1991; Kimber et al. 1995). All three of these dominant oligohaline species are substrate indifferent, growingly equally well in sand or silt bottoms. The dominant mesohaline species (redhead grass *Potamogeton perfoliatus* and sago pondweed *Stuckenia pectinata*) require 2–14 % incident light reaching the leaves and are also substrate indifferent (Bourn 1932; Goldsborough and Kemp 1988). In contrast, the dominant polyhaline species (widgeon grass *Ruppia maritima* and eelgrass *Zostera marina*) need more light (as much as 37 % of incident light) and require sandy substrate (Backman and Barilotti 1976; Congdon and McComb 1979; Short et al. 1995; Mills and Fonseca 2003). Eelgrass is also heat stressed in Chesapeake Bay and often dies backs during warm summer months (Moore and Jarvis 2008; Orth et al. 2010a).

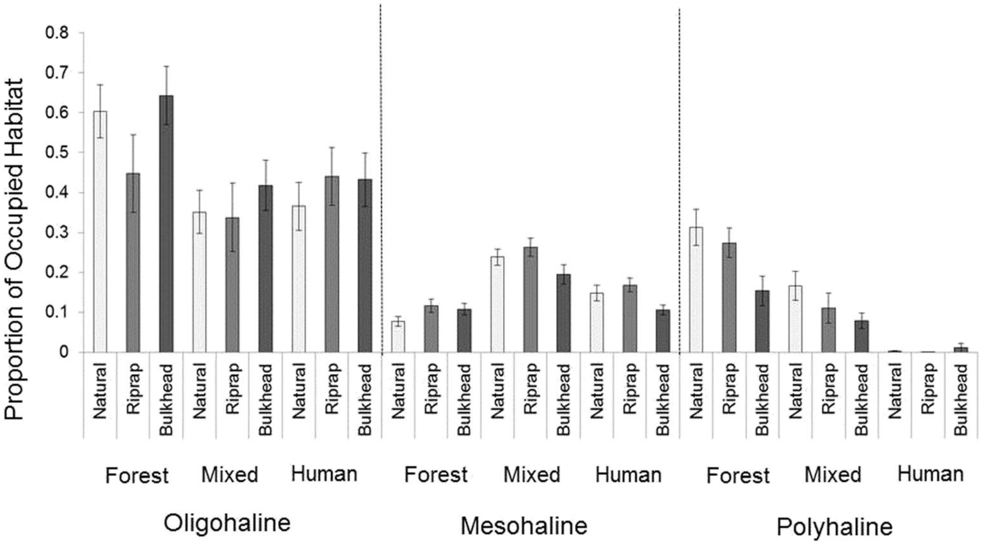

Fig. 3 Relationships of SAV response variables to shoreline condition, salinity, and watershed dominant land cover. Land cover categories are defined in the heading of Table 1. *Error bars* are simple standard errors

Because the polyhaline SAV species require sandy substrate and high light availability, and may sometimes be heat stressed, the negative impacts of shoreline armoring on SAV should be most evident in the polyhaline zone (as we observed). While shoreline alteration probably does not affect temperature, heat stress lowers the resilience of SAV to reductions in light and substrate quality, two factors that hardening can affect. In the polyhaline salinity zone, there is a clear hierarchy of stressors affecting SAV coverage, going from the subestuary-wide effects of watershed land cover down to the local effects of shoreline alteration. The larger-scale stressor constrains the effect of the smaller-scale stressor. As we predicted, the effects of different shoreline types on the proportion of occupied SAV habitat were most evident in polyhaline subestuaries with forested watersheds (Fig. 3, right), where the potential for SAV is greatest because the negative impacts of agriculture and land development on SAV are minimal (Li et al. 2007; Patrick et al. 2014). Concordantly, shoreline type had little effect on adjacent SAV coverage in polyhaline subestuaries with watersheds dominated by agriculture and development (Fig. 3, right), probably because water quality in those subestuaries was too low for SAV regardless of shoreline type. Our results suggest that in other estuaries, shoreline armoring is most likely to negatively affect SAV species that have lower tolerances for light limitation and substrate alteration. In estuaries with similar species to those found in the Chesapeake Bay, we would predict that the negative effects of shoreline hardening on SAV coverage would be less severe in low salinity areas. The variable responses of wild celery to shoreline hardening in the tidal fresh Hudson River estuary (Findlay et al. 2014) are also consistent with this idea.

In the mesohaline and polyhaline zones (which are together 77 % of the mapped shoreline in our study area, Table 1), bulkhead had stronger negative relationships with SAV coverage than did riprap (Figs. 2 and 3), probably because bulkhead is a larger change from the natural shoreline profile than riprap. A bulkhead is a solid vertical wall, and water depth adjacent to that wall is often a meter or more. These characteristics increase the potential for wave reflection and shallow water habitat reduction (Miles et al. 2001). Reflected waves can directly damage and bury SAV beds by scouring them and covering them with sediment (Marba et al. 1994; Paling et al. 2003; Mills and Fonseca 2003; Dan et al. 1998). Our finding

Table 6 ANOVA table of the effects of shoreline armoring (riprap, bulkhead, natural), watershed dominant land cover (forested, mixed, human), salinity (oligohaline, mesohaline, polyhaline), and their interactions on the proportion of occupied habitat

Factor or interaction	Degrees of freedom	Sum of squares	Mean squared error	*F*	*p*
Shoreline	2	0.02	0.008	7.38	<0.001
Land cover	2	0.08	0.039	38.1	<0.001
Salinity	2	0.34	0.170	167.12	<0.001
Shoreline × land cover	4	0.01	0.001	0.85	0.49
Land cover × salinity	4	0.17	0.042	42.05	<0.001
Shoreline × salinity	4	0.01	0.002	2.33	0.054
Shoreline × land cover × salinity	8	0.02	0.003	2.45	0.012
Residuals	2703	2.73	0.001		

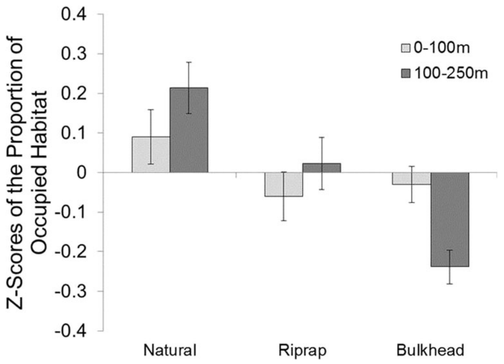

Fig. 4 Relationships between shoreline condition and the proportion of occupied habitat nearshore (0–100 m, *light gray*) and offshore (100–250 m, *dark gray*). *Bars* depict *z* scores to correct for differences in the potential habitat and depth gradient of the two distance zones (see "Methods"). The difference between nearshore and offshore is statistically significant for bulkhead but not for the other shoreline types. *Error bars* are standard errors

that bulkhead in the polyhaline had a stronger effect on SAV in the offshore band of potential habitat suggests wave reflection was severe enough to increase turbidity and reduce the quality of deeper water potential habitat. In contrast, riprap is more variable in construction than bulkhead. Some riprap is built of very large flat rocks with few interstitial spaces, and this construction has a high potential to reflect waves, similar to bulkhead. Other riprap structures are composed of smaller irregular stones (~30–40 cm diameter) with large interstitial spaces that dissipate waves. Some riprap structures are built upon former SAV habitat, but other configurations are completely exposed at low tide and do not occupy potential SAV habitat.

Counterintuitively, bulkhead and riprap seemed to be positively associated with SAV area in the oligohaline zone (Fig. 2). This unexpected result may reflect the unique growth habits of two of the dominant oligohaline species (Eurasian water milfoil and *Hydrilla*; Posey et al. 1993; Moore et al. 2000). These two invasive species are substrate-indifferent canopy formers that are less limited by reduced water quality than other SAV species. The positive effect of bulkhead on oligohaline SAV may reflect these two species exploiting the disturbed habitat adjacent to bulkhead. Other studies report that the disturbance of shoreline armoring promotes invasive aquatic macrophytes (Gabriel and Bodensteiner 2012), and *Hydrilla* does flourish in disturbed areas of the Chesapeake Bay oligohaline zone (Robert Orth, personal communication). Additional research is needed on the exploitation of habitat next to shoreline armoring by invasive macrophytes.

Directions for Future Research

Our analyses help produce a framework for the relationships between general shoreline types and SAV coverage, but more detailed information on armoring construction would enhance future analyses of SAV and other estuarine responses. There are important variations in armoring design that were not reported in the shoreline data that we used (VIMS 2013a). Riprap ranges from small (~1 m tall) piles of large cobbles to massive (>3 m high) structures of neatly fitted multi-ton boulders. Some of the shorelines mapped as riprap were actually "living shorelines" that consist of a riprap sill slightly offshore with a marsh planted between the sill and the shoreline (Currin et al. 2007). Understanding the effects of living shorelines is important because they are now widely recommended for new shoreline stabilization and for restoring shorelines with existing bulkhead and riprap (Living Shoreline Summit Steering Committee 2006; Bulleri and Chapman 2010; Currin et al. 2010). Better data on variation in riprap design would enable analysis of the role of construction features on the relationship between riprap and adjacent SAV. It is also important to know whether armoring begins above mean low tide line or below it, where armoring covers potential SAV habitat. Better knowledge of responses to different armoring types would be particularly valuable to managers who design and regulate new construction or the renovation of existing structures.

Our study did not implement a controlled experimental manipulation of shoreline type, so we have not proven a causal connection between shoreline armoring and SAV coverage. However, it would be very difficult to implement a manipulative experiment at the scale of our study (entire Chesapeake Bay plus some mid-Atlantic coastal bays), and the scale of the analysis gives us high confidence in the associations documented here. We analyzed the responses of SAV to individual shoreline segments because we previously found that subestuary-scale measures of shoreline armoring were correlated with other variables at that broader scale (Patrick et al. 2014). The shoreline data set that we used was not a sample of shoreline segments, but instead a nearly wall-to-wall mapping of tens of thousands of segments representing most of the total shoreline in the study area (VIMS 2013a). Within that exhaustive map, we selected hundreds or thousands of shoreline segments for each statistical analysis. Those many segments were sampled across the ranges of many possible covariates, including subestuary size, fetch, fetch angle, and many others. We also analyzed ANOVA models that incorporated broader scale factors (salinity and local watershed land cover) to test a priori expectations that these factors affect the local impact of shoreline type on SAV abundance (Patrick et al. 2014). The huge sample size, the use of ANOVA, and the focus on testing a priori expectations together make a powerful approach to revealing the direct effects and the interactions among factors operating at different scales. Other authors have noted the need for such approaches to understanding multiple stressor effects on SAV (Blake et al. 2014).

An important next step will be future studies that follow changes in estuarine responses through time as different types of armoring structures are installed or removed. Better data on the times when different structures were installed would allow this to be performed spatially on historic data such as those we used for analyses here. As new shoreline stabilization projects are permitted, a suite of other variables (including water clarity, substrate type, measuring nearshore wave energy, and the SAV species present) could be directly measured in the field to help discern the mechanisms by which armoring affects sea grasses and other macrophytes.

Conclusions

SAV is in worldwide decline (Orth et al. 2006). We show that shoreline armoring, an erosion control strategy widely used throughout in the world, can have negative relationships with adjacent SAV coverage and so could be a contributing factor in that decline. The relationship between armoring and SAV coverage varies among SAV species assemblages and environmental conditions. The demand for more coastal armoring will grow with population increase and sea levels rise due to global climate change (Dugan et al. 2008). We need a more mechanistic understanding of how different types of shoreline armoring affect nearshore environments so that we can develop management strategies that minimize negative impacts.

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