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MANAGEMENT APPLICATIONS

Racial Composition and Homeownership Influence the Distribution of Coastal Armoring in South Carolina, USA

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Abstract
The desire to stabilize coastlines has led to widespread use of hard armoring infrastructure across the globe; however, ecologists and coastal managers have increasingly documented the deleterious effects of armoring on ecological communities. Although many studies have assessed economic and landscape correlates of armoring, few studies incorporate race as a predictor of armoring. Race may be an important force structuring the placement of armoring due to the long history of Black land loss in the US Southeast. Here, we assessed the distribution of armoring in the US state of South Carolina with respect to demographic and housing characteristics using a high spatial resolution data set and a combination of spatial statistics and generalized linear mixed models. We found clusters of high armoring counts in the more urbanized Beaufort and Charleston counties, with these clusters frequently occurring in large-scale, planned communities. We found a positive correlation between armoring count and the percentage of White residents, with the number of armoring structures predicted to increase from 1.61 to 7.77 between census block groups (CBGs) that are 0 to 100% White. Armoring count and the percentage of homeowners also showed a positive correlation with a similar magnitude of effect, with the number of armoring structures predicted to increase from 1.14 to 8.97 between CBGs that are 0 to 100% homeowners. These results highlight that racial composition and homeownership are strong predictors of armoring count on private, personal property, which provides critical context for how these structures are distributed and underscores that socioeconomic factors can control where their associated environmental impacts may be concentrated.

Keywords Shoreline armoring · Property owner · Coastline stabilization · Coastal development

Introduction

Over the past three decades, coastal researchers have increasingly recognized the ecological challenges presented by efforts to stabilize intrinsically dynamic coastlines. Infrastructure built parallel to the shore is often referred to as "armoring" and can take on a variety of forms that are primarily intended to limit erosion caused by tidal fluctuations and wave energy, as well as protect coastal land from tidal flooding and storm surge (Airoldi et al. 2005; Dugan et al. 2011; Smith et al. 2017). Hard, artificial objects such as seawalls, bulkheads, riprap, and other related infrastructure have been a default approach to armoring for decades, if not centuries (Charlier et al. 2005; Dugan et al. 2011; Rangel-Buitrago et al. 2018). Although built to protect and preserve the current shape of coasts, hard armoring frequently produces adverse effects on coastal environments. Hard armoring structures like seawalls have been tied to increased localized erosion along beachfronts (Miles et al. 2001; Defeo et al. 2009), and these structures sever connectivity between the beach and land ecotone (Hsu et al. 2007; Heerhartz et al. 2014). In the context of sea level rise (SLR), coastal ecosystems like salt marshes have the capacity to migrate landward depending on complex interactions of the magnitude of SLR, tidal amplitude, and sediment supply (Kirwan et al. 2010). Hard armoring, however, impedes this landward migration by presenting an impermeable barrier, producing the well-documented phenomenon of "coastal squeeze" (Chmura et al. 2003; Doody 2004; Pontee 2013).

Hard armoring not only affects the geomorphology of coastlines, but also affects biotic communities (Suedel

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et al. 2022). Studies across a variety of taxa have found that the physical complexity and composition of armoring influence community composition of benthic invertebrates and vegetation (Chapman 2003, p. 200; Seitz et al. 2006; Gittman et al. 2016; Gehman et al. 2018; Strain et al. 2020). Hard infrastructure can also alter species interactions such as competition and predation (Moreira et al. 2006; Bulleri and Chapman 2010), which can in turn facilitate the establishment of introduced species (Glasby et al. 2007; Tyrrell and Byers 2007; Airoldi et al. 2015). The relative impacts of armoring can vary depending on the type of armoring built. Some researchers have demonstrated that ecological engineering approaches, such as providing grooves, cuts, and fixtures, can ameliorate the impacts of hard armoring by providing structural complexity that mimics natural features (Coombes et al. 2015; Perkins et al. 2015; Bishop et al. 2022). The location of armoring also plays a role in the magnitude and direction of its ecological impacts. For example, the effects of armoring might be particularly pronounced in soft-sediment environments, where armoring provides hard surfaces that are naturally scarce but conducive to the settlement of sessile invertebrates or epiphytic algae (Bulleri 2005; Byers and Grabowski 2014). In these soft-sediment ecosystems, Dugan et al. (2018) proposed a broad typology of anticipated armoring effects based on the interaction of the energy of the environment and the purpose of the infrastructure. Under this model, the ecological impacts of armoring would be most pronounced in areas of high energy and with structures designed to completely halt the movement of water. They found that studies generally conformed to these predictions for the availability of natural habitat and community composition but noted a scarcity of research for other ecologically relevant variables such as productivity (Dugan et al. 2018).

Given these concerns over the cumulative impact of coastal armoring, numerous studies have mapped these structures in regions across the world. Research in Japan (Walker and Mossa 1986; Masucci and Reimer 2019), Taiwan (Hsu et al. 2007), Colombia (Rangel-Buitrago et al. 2018), Europe (Salman et al. 2004), and the USA (Gittman et al. 2015; Peterson et al. 2019), as well as global analyses (Bugnot et al. 2021; Floerl et al. 2021), have documented extensive coastal armoring. In the USA, most armoring along the Atlantic and Pacific coasts exists in areas not exposed to the open ocean, and armoring prevalence was higher in counties with higher GDPs and housing density (Gittman et al. 2015). In the US state of Georgia, the probability of armoring on an individual parcel increased with parcel slope, hydrological energy, erosion rates, and the presence of armoring on a neighboring parcel (Peterson et al. 2019). Additionally, county identity also influenced armoring presence, but not in ways that directly tracked population or urban/rural characteristics of those counties (Peterson et al. 2019). Other studies in the USA have examined the factors that drive homeowners to armor their shorelines. Prior research has examined how homeowner decision-making influences armoring presence through both modeling (Beasley and Dundas 2021; Gardner and Johnston 2021) and survey approaches (Scyphers et al. 2015; Stafford and Guthrie 2020; Gittman et al. 2021). Many of these studies concur that the presence of armoring in neighboring parcels is a strong, positive predictor of armoring (Scyphers et al. 2015; Stafford and Guthrie 2020; Beasley and Dundas 2021; Gittman et al. 2021). Other work has emphasized the importance of parcel-level landscape characteristics on armoring presence, suggesting that parcels at lower risk of water damage, such as those in areas with low wave energy or situated at higher elevations, are less likely to be armored (Gardner and Johnston 2021). These studies suggest that homeowners play a major role in coastal armoring, and therefore, rates of homeownership might be an important predictor of armoring at larger spatial scales. Throughout the paper, we refer to lots owned by homeowners as "private" or "private, personal" property and treat these as synonymous with a residential property occupied by the owner. Although private property can be understood more broadly, we specify when we are referring to other types of private property (e.g., rental properties, land owned by a homeowners association, businesses).

Notably, although many of the studies in the USA focus on what drives homeowners to armor their lots and incorporate economic variables, few have examined or theorized the relationship between race, homeownership, and coastal armoring. This omission may be partly due to the choice of spatial scale and methodology, as quantitative racial characteristics of households are typically not available and researchers using a survey instrument may be reluctant to ask detailed demographic questions out of fear of reducing survey response rates (Stafford and Guthrie 2020). Nonetheless, race may be an important but overlooked predictor of armoring on private property, particularly in the geographic context of the US Southeast. Research by Southern historians has documented the extensive loss of Black-owned land in the coastal Southeast from the mid-twentieth century to today (Fisher 1978; Kahrl 2012a). The mechanisms fueling this racially skewed land loss, including forced partition sales of property (Copeland 1984; Rivers 2006, p. 200; Dyer and Bailey 2008) and property tax hikes (Thomas 1978; Dean 2013; Kahrl 2016), have contributed to the transformation of the coastal Southeast from a mostly rural region of sparse development into the booming real estate and tourism market of today (Kahrl 2012b, 2014). If private, personal property is a core component of the armoring landscape, the racial dynamics of land ownership may readily influence the distribution of armoring (Scyphers et al. 2015; Peterson et al. 2019; Gardner and Johnston 2021).

This study builds off prior research that found race to be an important variable in the distribution of coastal infrastructure. In North Carolina, there was a negative correlation between the percentage armored coastline and the percentage of a census block group's (CBG) population that identified as non-White (Siders and Keenan 2020). Prior work on private docks found racial composition was a strong predictor of dock abundance in South Carolina (Beauvais et al. 2022). Although not armoring, that work demonstrates that another common type of infrastructure is correlated with racial composition at the scale of CBGs. Our study strives to improve our understanding of how the distribution of coastal armoring is influenced by racial composition and homeownership.

Because of the ecological impacts that can arise from coastal armoring, it is important to know what governs its distribution on the landscape. We address the distribution of armoring in South Carolina through three questions. First, does the count and density of shore-parallel armoring show spatial clustering in certain CBGs along the South Carolina coast? Second, to what extent is shore-parallel armoring co-located with other coastal infrastructure on private property? Questions 1 and 2 provide helpful system-level context to better interpret our third and most important question; how is the number of shore-parallel armoring structures distributed with respect to the demographic and housing characteristics of CBGs? For question one, we hypothesized that shore-parallel armoring would show spatial clustering in more populated, urban areas. For question two, we predicted that most coastal armoring would co-occur with other coastal infrastructure located on private property. For question three, we hypothesized that wealthier CBGs with a larger share of White residents and homeowners would possess a greater number of armoring structures. Together, these approaches support a detailed analysis of the socioeconomic distribution of shore-parallel armoring.

Methods

Study System and Area

We conducted our study in six counties along the South Carolina coast (Fig. 1). We chose South Carolina both because of the ready availability of pre-existing armoring data (Jackson 2017) and because the ecological, cultural, and political context of South Carolina is similar with that of other coastal Southeast states such as Georgia, North Carolina, and northern Florida. The coastlines of these counties consist primarily of intertidal estuaries that form the transition between the land and open ocean. The six counties in the study vary widely in their respective levels of development. Charleston County is the largest and most populous county, with the major urban center of Charleston located approximately halfway along the coast (Fig. 1). Beaufort and Horry counties also contain heavily developed portions such as Hilton Head Island and Myrtle Beach, respectively. Jasper, Colleton, and Georgetown counties are considerably more rural and contain only smaller towns.

We conducted all analyses at the census block group level, which is the smallest spatial scale at which the Census Bureau publishes data for years between decennial censuses. The six study counties were composed of 583 CBGs, which we reduced to 572 CBGs after removing five CBGs that were entirely military bases/housing and six CBGs that comprised the Port of Charleston and Charleston International Airport. This resulted in filtering out 97 structures totaling 14.18 km of armoring (electronic supplemental material, Table S1). Removing CBGs that were predominantly (or entirely) military and industrial helped us limit the study to areas where there could feasibly be an appreciable residential population that could own estuary adjacent property.

We further reduced the data to only CBGs with greater than 1 km of estuary or beach shoreline to remove areas that could not have coastal armoring. We chose a 1-km minimum shoreline requirement to reduce the likelihood of including CBGs with incorrectly assigned shoreline due to the relatively coarse, 30-m resolution land cover data we used to calculate shoreline length (Beauvais et al. 2022). This minimum shoreline requirement only excluded 25 structures totaling 2.9 km from the study (electronic supplemental material, Table S1). After applying all filters, our final full study area consisted of 246 CBGs.

Quantifying Shore-Parallel Armoring

We obtained data on armoring infrastructure (originally collected by Jackson 2017) from the Ocean and Coastal Resource Management division (OCRM) of the South Carolina Department of Health and Environmental Control. Armoring infrastructure was originally digitized from various aerial photography sources from 2003 to 2013 (Jackson 2017). Armoring data was represented as polylines, which we analyzed in ArcGIS Pro version 2.9 (ESRI 2021). Thirteen of these armoring structures crossed a single CBG boundary. In these cases, we split the structure into two new polylines and assigned them as belonging to their respective CBG. We chose to split these armoring structures instead of omitting them because it was a more accurate representation of how this armoring was shared among CBGs. In all 13 instances, the CBG with the smaller share of the armoring still contained at least 25% of the total length of the structure (electronic supplemental material, Table S2). We manually categorized armoring as being located along either the beach or estuary depending on whether the structure overlapped South Carolina's official beachfront jurisdictional lines (https://gis.dhec.sc.gov/shoreline/). We classified structures to compare the amount of armoring occurring between

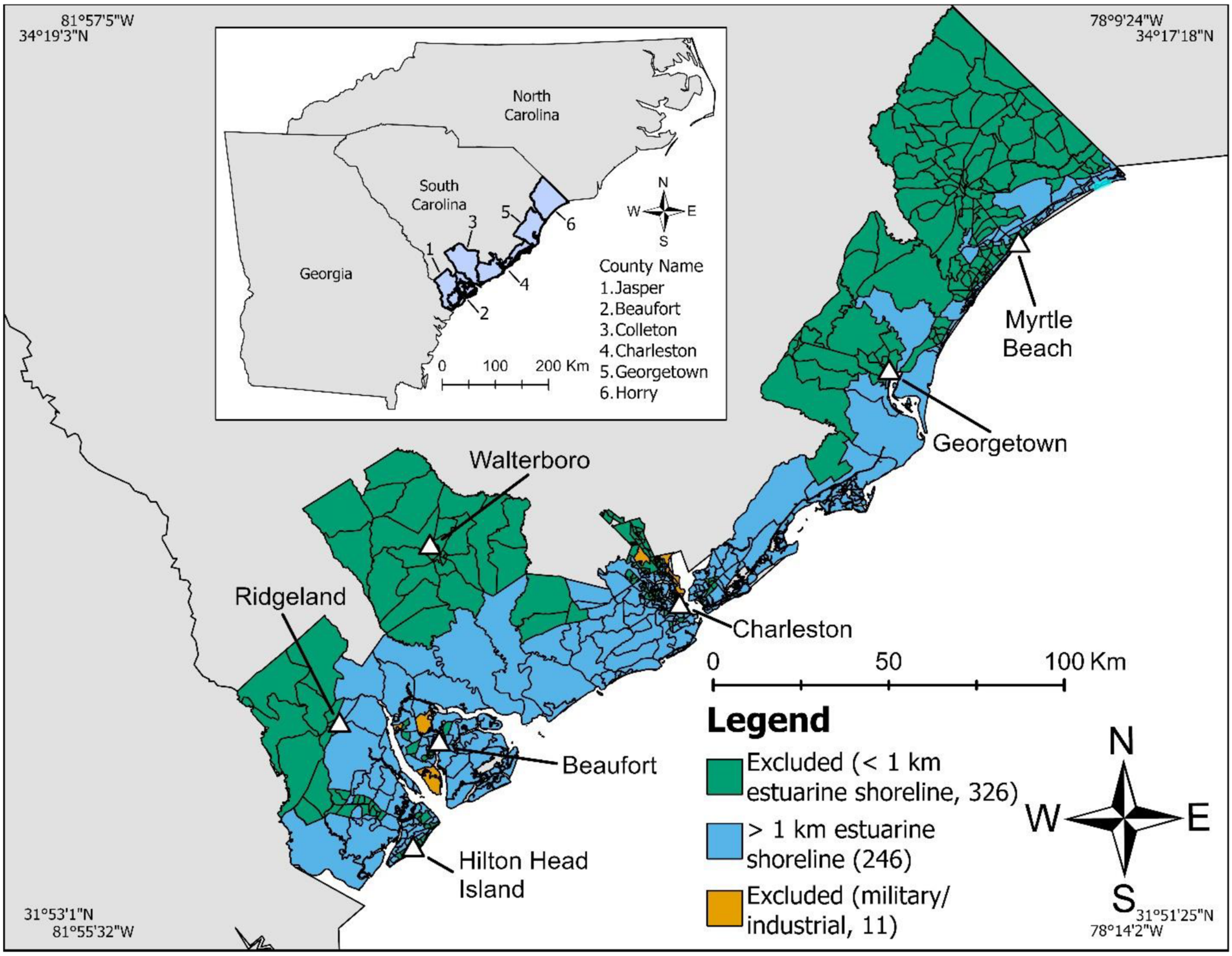

Fig. 1 The main map shows census block groups (CBGs) in the six coastal counties of South Carolina. Orange CBGs are entirely military or industrial areas that we excluded from all analyses. Green CBGs contain less than 1 km of estuarine shoreline and are excluded from the study. Blue CBGs contain more than 1 km of estuarine shoreline and are included in the study. Numbers in parentheses in the legend represent the number of CBGs in each category. The inset map (top left) shows South Carolina, the six counties for which armoring data was available, and neighboring states. Major cities in the study counties are marked by white triangles and associated text. Main map scale 1:1,250,000 and county inset map scale 1:8,250,000

these two different energy environments (Dugan et al. 2018). Additionally, South Carolina banned the construction of new seawalls along the beach in 1988 (S.C. Code Ann. § 48-39-290(B)(2)(a-e)), so we anticipated that these environments might have distinct levels of armoring as a result.

We extracted CBG information to each polyline and summarized the total number and length of each type of armoring in R version 4.2.1 (R Core Team 2022). The initial data set distinguished between multiple types of shore-parallel armoring (e.g., riprap, bulkhead, seawall). Because we were interested in the totality of shore-parallel armoring and not in distinguishing between individual classes, we grouped all shore-parallel structures into a single category for analysis. Likewise, the small number of structures located along the beach prevented us from running separate analyses for the beach and estuary structures, so we analyzed all structures together and only report on these categories separately in descriptive statistics.

To visualize the distribution of armoring at finer spatial scales, we used the "Point Density" tool in ArcGIS Pro to map the density of armoring across the 246 CBG study area. The "Point Density" tool works by first dividing the entire study region into a grid of cells with a user specified area (0.01 km^2, or 100 m × 100 m). The tool then searches a user defined circular area around the center of each cell, counts the number of armoring structures found within the search area (based on the midpoint of the armoring polyline), and divides this total count by the area of the search circle. We chose a 1 km search radius (π km^2 search circle) to allow for easily interpretable density values.

Table 1 Count and cumulative lengths of all shore-parallel armoring in each of the six coastal counties (which excludes 11 census block groups (CBGs) that made up military bases and the Port of Charleston). Co-located refers to armoring that was determined to be within 50 m of a private dock. Determined from data originally collected by Jackson 2017

County	Armoring count	Armoring length (km)	Total shoreline (km)	Percent armored shoreline	Number of docks	Co-located armoring count	Percent co-located	Co-located armoring length (km)	Percent length co-located
Beaufort	732	65.82	1513.69	4.35	2803	350	47.81	25.18	38.26
Charleston	683	60.88	1817.32	3.35	4953	452	66.18	31.23	51.30
Colleton	36	1.23	369.52	0.33	305	31	86.11	0.84	68.29
Georgetown	63	6.22	293.09	2.12	1217	11	17.46	1.03	16.56
Horry	63	18.37	216.50	8.48	636	9	14.29	0.73	3.97
Jasper	34	6.78	258.35	2.62	178	12	35.29	0.57	8.41
Total	1611	159.30	4468.47	3.56	10,092	865	53.69	59.58	37.40

Question 1—How is Armoring Clustered?

To quantify spatial clustering of armoring, we used the "Hot Spot Analysis" tool in ArcGIS Pro on both raw armoring counts and the density of armoring (armoring count/total shoreline length). The "Hot Spot" tool calculates a Getis-Ord Gi* value (Ord and Getis 1995) for every CBG, allowing us to analyze clustering at the same spatial scale as our other analyses (i.e., at the CBG level). We chose to test both armoring counts and density because they provide distinct ways of assessing armoring intensity. A hot spot analysis of the raw counts very simply highlights a cluster of neighboring CBGs with higher (hot spots) or lower (cold spots) armoring counts than would be expected if armoring was randomly distributed across our study area. An analysis of armoring density shows where there is a neighborhood of CBGs with unexpectedly high/low armoring counts relative to the amount of shoreline.

We used the "Incremental Spatial Autocorrelation" tool to find an appropriate distance band for the analysis, which returned peaks at the 6 km and 16 km range. We chose the 6 km band because 16 km was much too large to meaningfully reflect spatial relationships in urban areas where CBGs were often less than 3 km^2. Due to the irregular shapes and disparate sizes of CBGs, this 6 km distance band resulted in some of the larger CBGs having no neighbors. To correct this, we modeled spatial relationships between CBGs using a spatial weights matrix with a fixed distance band of 6 km, while also forcing all CBGs to have a minimum of two neighbors.

Question 2—To what Extent is Armoring Co-located with Infrastructure on Private Property?

We examined the locations of armoring and private docks (the most common type of coastal infrastructure in the Southeast) to determine whether coastal infrastructure often co-occurred and augmented the development footprint in an area. We collected 2011 private dock data using 1-m resolution imagery from the USDA's National Agriculture Imagery Program (Beauvais et al. 2024). We digitized docks by placing a point at the base and end of each dock at 1:2500 scale. Because public infrastructure like fishing piers or docks associated with public boat landings are sometimes visually indistinguishable from privately owned docks, we cross-referenced all digitized structures with county and state websites to ensure that we did not include any public infrastructure. The removal of military and industrial CBGs also eliminates structures that we are certain do not belong to homeowners.

To analyze the co-occurrence of docks and armoring, we converted armoring polylines to a single point placed at the midpoint of an armoring structure. We then used the "Generate Near Table" tool in ArcGIS Pro to identify whether the base of a dock was located within a 50 m radius of the center of each armoring structure. Although the 50 m radius is arbitrary, we argue it is a large enough search area to identify association with docks on the same private parcel while minimizing spurious associations with docks on adjacent lots (e.g., an adjacent public lot). This analysis provides an estimate of the number of armoring structures located on a privately owned lot; however, there are two counteracting assumptions to be mindful of. First, our analysis underestimates the number of armoring structures located on private, personal lots, as some homeowners might have armoring but not a dock. Second, some of these docks are located on other types of private property (e.g., small businesses, residential rental properties, land owned by homeowners associations). We argue that the enormous number of docks along the coast (10,092, Table 1) means that most of these structures are occurring on privately owned, single-family home lots.

Question 3—What Demographic and Housing Characteristics Correlate with Armoring?

We used a generalized linear mixed model framework to test whether the number of armoring structures was correlated with CBG demographic and housing characteristics. Because we were analyzing aggregated armoring data at the

CBG scale, we chose to use armoring count instead of length as the dependent variable in the model. While both counts and lengths (Siders and Keenan 2020) are valid ways to measure the amount of armoring in an area, counts provided more detailed information that directly related to our interest in the importance of homeowners in the armoring landscape. For example, an analysis of total length would be unable to disentangle whether the amount of armoring in a CBG was driven by a few very large structures or many smaller structures (suggestive of armoring on individual private lots).

We collected all demographic and housing predictor variables from the 2013 American Community Survey (ACS) 5-year average using the R package "tidycensus" version 1.2.3 (Walker and Herman 2022). The ACS is an annual survey of 3.5 million households that the Census Bureau conducts in years between decennial censuses. Even though most of the armoring data came between 2006 and 2011, we chose the 2013 ACS 5-year average due to limited API availability of pre-2013 ACS data at the time of analysis. We selected six demographic and housing variables to include as fixed effects. We included median household income (MHI) and the percentage of the CBG population that identified as White as fixed effects for the economic and racial composition, respectively. We chose these variables based on our prior work in the system (Beauvais et al. 2022) and because they are standard variables used in other studies evaluating the socioeconomic distribution of ecological features (Kim et al. 2019; Riley and Gardiner 2020). We also included total population and the mean age of the CBG population (Kim et al. 2019) as fixed effects to account for discrepancies in CBG population size and control for the potential influence of coastal South Carolina's sizeable population of retirement communities (Faulkenberry et al. 2000). We selected the percentage of the CBG population that owned their home as the variable representing homeownership. Lastly, we also included the percentage of housing units built after 1989 as a fixed effect to account for the potential influence that newer housing stock might have on armoring. The year 1989 was chosen both because it roughly split our data in half (median percentage of homes built after 1989 was 41.5%) and to provide symmetry with the 1989 beachfront armoring ban mentioned above (S.C. Code Ann. § 48-39-290(B)(2)(a-e)).

In addition to the six demographic and housing variables, we also incorporated the total length of saltwater and beach shoreline as a fixed effect, drawing on prior work (Beauvais et al. 2022) that measured shore length using 30-m resolution land cover data from NOAA's Digital Coast (https://coast.noaa.gov/digitalcoast/data/). Preliminary analysis showed a strong concentration of shore-parallel armoring in Beaufort and Charleston counties, suggesting that county identity might play a significant role in armoring. We included county as a fixed effect in the analyses. To account for the spatial nestedness of census data, we include census tract (a sub-county geographic unit used by the Census Bureau that is composed of multiple CBGs) and CBG as random intercepts.

For armoring counts, we fit a negative binomial mixed effects model using the "glmmTMB" package version 1.1.4 (Brooks et al. 2017) for all 246 CBGs. We included all fixed and random effects described above for the count model. We also centered and scaled all fixed effects in the model by their standard deviations to allow for comparison of fixed effects. Because the county fixed effect was a categorical variable with six levels, we were unable to scale this term. We found no evidence of multicollinearity among the independent variables for the count model after assessing the Pearson correlation values (electronic supplemental material, Figure S1). The Pearson correlation coefficient for the percentage White and percentage homeowner term was modest ($r = 0.37$). Furthermore, we assessed the variance inflation factor (VIF) for all model fixed effects and saw no additional evidence of collinearity (all VIF $\leq$ 2.20). We conducted further diagnostic tests using the "DHARMa" package version 0.4.6 (Hartig 2022). Model residuals conformed to assumptions of homoscedasticity; however, the armoring count model showed evidence of modest underdispersion. Additionally, given the inherent spatial nature of census data, we examined residuals from the count model for spatial autocorrelation using Moran's I test assuming inverse-distance spatial weights. We found no evidence of residual spatial autocorrelation in the count model ($z = 1.45$, $p = 0.15$).

We calculated p-values for fixed effects using likelihood ratio tests. For the categorical county fixed effects, we conducted a post hoc Tukey HSD with a Bonferroni correction using the "emmeans" package version 1.8.1-1 (Lenth 2022). For the continuous fixed predictors, we plotted marginal effects for model terms using the "ggeffects" package version 1.1.3 (Lüdecke 2018).

Results

General Distribution of Armoring and Study Area

Overall, 1611 shore-parallel armoring structures covered 159.30 km in our study area (Jackson 2017; Table 1). Only 34 pieces of shore-parallel armoring totaling 10.66 km occurred along South Carolina's officially defined beachfront, with the remaining armoring occurring in estuarine areas. Armoring was unevenly distributed across the coast (Fig. 2). Large patches of high armoring densities occurred in primarily residential and resort areas of Charleston and Beaufort counties (Fig. 2). In Charleston County, these areas included James Island and the Isle of Palms/Wild Dunes

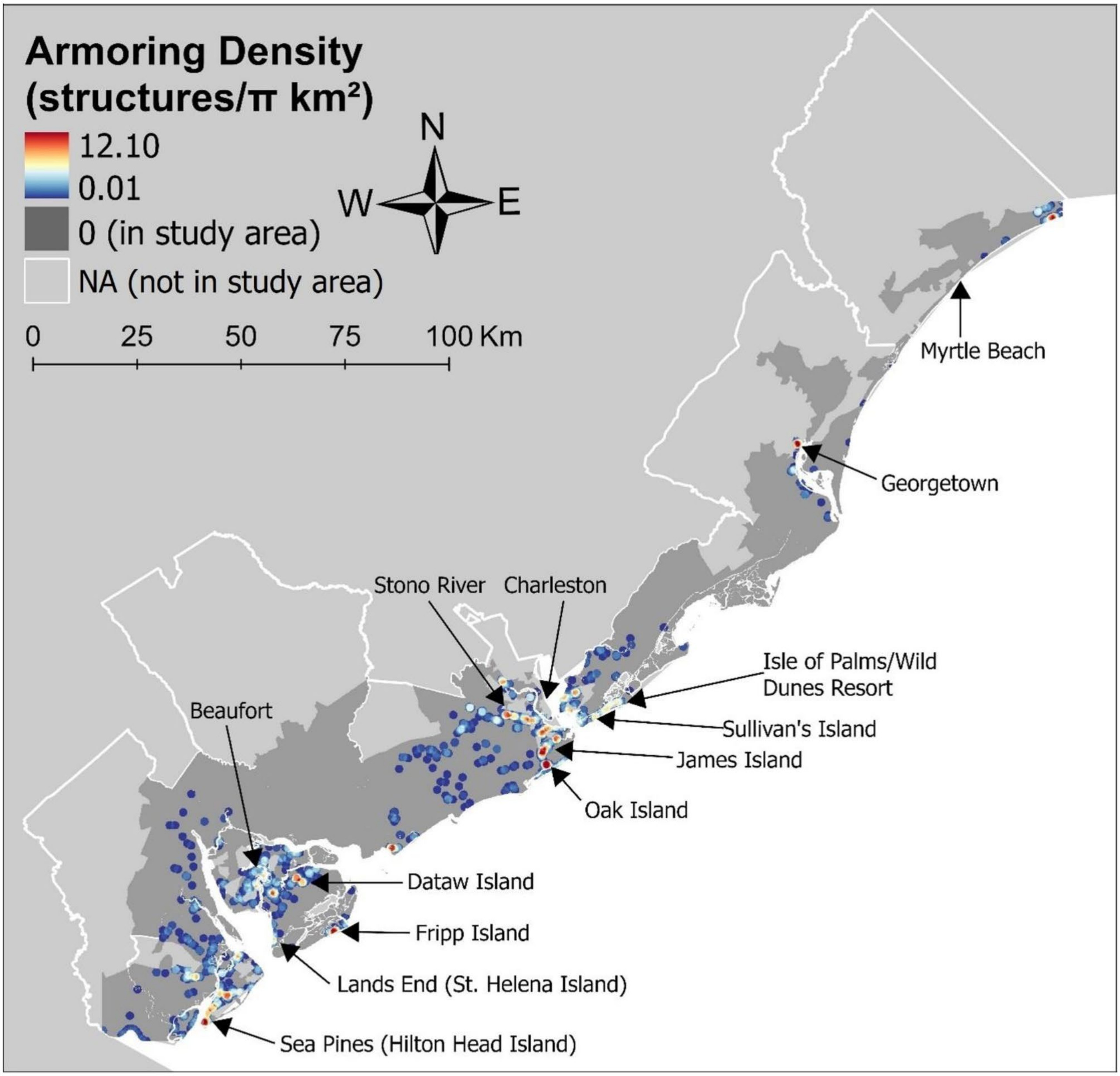

Fig. 2 Point density map of all shore-parallel armoring. White lines represent boundaries for the six coastal counties, light gray represents areas outside the study ("NA"), dark gray represents areas in the 246 CBG study area without any armoring in the search area (i.e., had a density value of 0), and the color ramp reports densities as the number of structures per π km^2 (circular search area with a radius of 1 km) for each 0.01 km^2 grid cell. Map scale 1:1,250,000

Resort. In Beaufort County, high armoring densities were in the Sea Pines Resort on Hilton Head Island, Fripp Island, and Dataw Island. Smaller, isolated patches of high armoring also occurred along the northeastern most section of the Intercoastal Waterway in Horry County and in downtown Georgetown (Fig. 2). The percentage of armored shoreline was low in each county. Horry was the most hardened county with shore-parallel armoring covering 8.48% of the coastline, while Colleton County was the least armored at 0.33% (Table 1). These county-level findings agree with county-level armoring estimates by Gittman et al. (2016), who used the National Oceanographic and Atmospheric Administration's Environmental Sensitivity Index to measure the percentage of armored shoreline.

Most counties had sizable variation in demographic characteristics across the 246 CBG study area (Fig. 3). The smaller populations in Colleton and Jasper counties meant a small number of CBGs to begin with, which were further reduced to only three and five CBGs after filters were applied, respectively. Charleston was the most populous

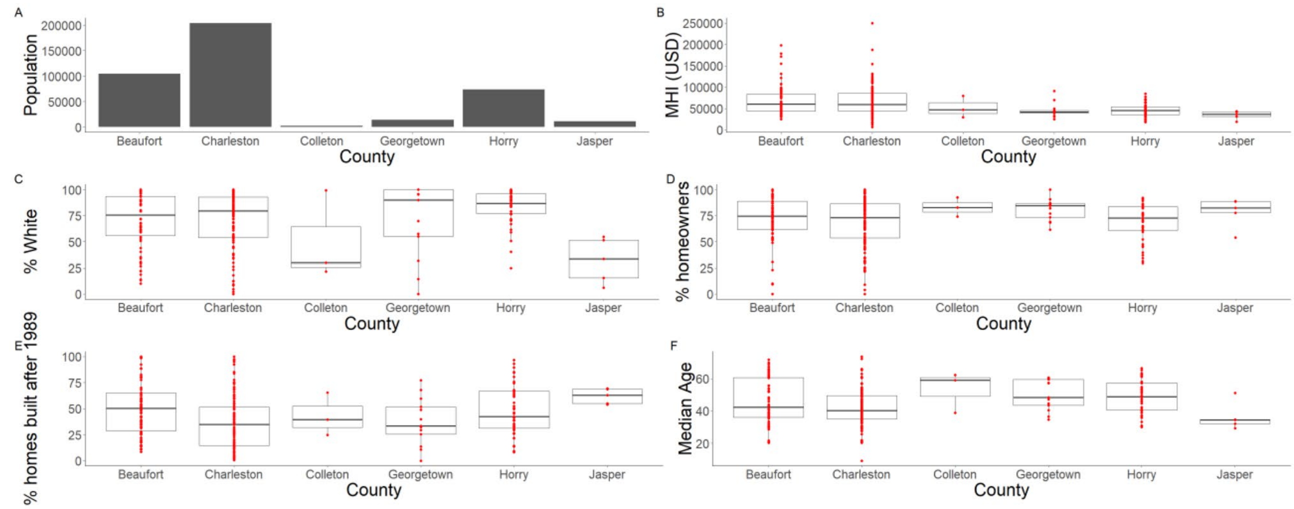

Fig. 3 Summary statistic figures for the six demographic and housing variables used in the GLMM of armoring count. **A** County population, **B** median household income (MHI), **C** the percentage of population that identifies as White, **D** the percentage of population that own their residence, **E** the percentage of homes that were built after 1989, and **F** the median age of residents. For boxplots, the black midline of the boxplot represents the median, box edges represent the 25th and 75th percentile (interquartile range, IQR), error bars (also known as the upper and lower fence) represent 1.5 * IQR, and individual red points represent the raw data

of the counties with 204,045 residents while Colleton was the least populous with only 2264 residents (Fig. 3A). Racial composition showed wide variation within counties (Fig. 3C), and the median CBG percentage White was highest in Georgetown County (90.10%) and lowest in Colleton County (29.73%). Note again that the small number of CBGs in Colleton County resulted in a very imbalanced distribution of racial composition. The median percentage homeownership was over 70% in all six counties, although Beaufort, Charleston, and Horry counties did show a wide distribution of homeownership rates (Fig. 3D).

Question 1—How is Armoring Clustered?

The results of the hot spot analysis differed depending on whether we analyzed armoring count (Fig. 4A) or density (Fig. 4B). For counts, we identified 28 hot spots, all of which were in the more urbanized Beaufort and Charleston counties (Fig. 4A). In Beaufort County, hot spots occurred in CBGs encompassing downtown Beaufort, the southern portion of the Sea Pines resort on Hilton Head Island, Dataw Island, southern St. Helena Island, and Fripp Island. In Charleston County, we identified hot spots around the James Island and Folly Island region. We also identified 30 cold spots, which were concentrated around the northern Ashely River in Charleston and North Charleston, as well as along the Intracoastal Waterway in Myrtle Beach and North Myrtle Beach.

The hot spot analysis of armoring density returned substantially fewer cold spots (6) and more hot spots (54). Although the number of identified hot and cold CBGs was markedly different for armoring density, the same broad geographic patterns held in that hot spot CBGs were again concentrated in Beaufort and Charleston County (Fig. 4B). Beaufort County gained additional hot spots on Hilton Head Island but lost hot spots in the larger CBGs that made up the Dataw, Fripp, and southern St. Helena islands. Likewise, Charleston picked up new hot spots in the suburban areas of Mt. Pleasant and Sullivan's Island but lost a hot spot in a large CBG on James Island and the hot spots in Folly Island. A new cluster of hot spots was picked up in CBGs that made up downtown Georgetown. The only cold spots that were preserved were along the Intracoastal Waterway in Myrtle Beach. There were no instances in which the analyses for armoring counts and density returned contradictory results (e.g., no hot spot in one analysis was a cold spot in another or vice versa). A full reporting of the differences between the two variables is available in the electronic supplemental material (Figure S2).

Question 2—To What Extent is Armoring Co-located with Infrastructure on Private Property?

We found that 898 of the 1611 (55.74%) armoring structures in the data set occurred within 50 m of a private dock (Table 1). In terms of length, these co-occurring armoring structures account for 71.25 km of the 159.30 km (44.73%) of armoring along the South Carolina coast. The number of armoring structures co-located with private docks varied depending on the county. Beaufort, Charleston, Colleton, and Horry counties all had more than 47% of their armoring located within 50 m of a dock, while Georgetown and

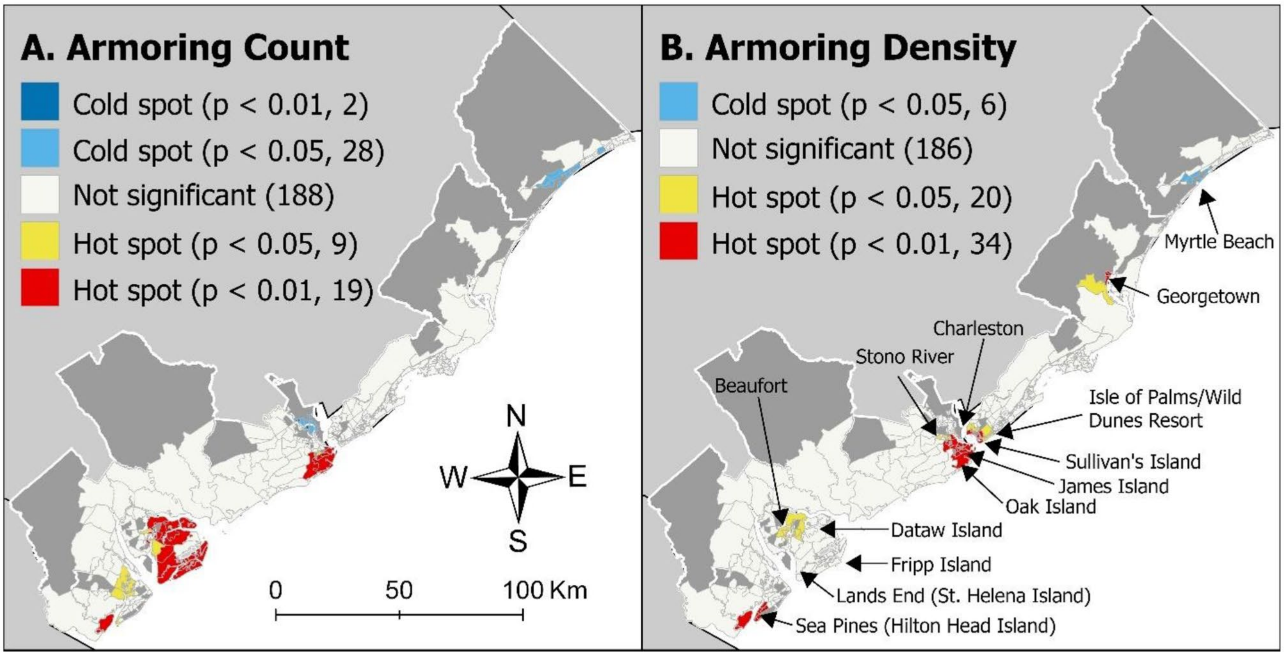

Fig. 4 Hot spot analysis (conducted at the CBG level) for raw armoring counts (**A**) and armoring density (counts/km of shoreline, **B**). White lines and dark gray fill represent county boundaries, and the color ramp represents *p*-values of cold spots and hot spots as calculated from the Getis-Ord Gi* statistic. Numbers in parentheses in the legend represent the number of CBGs in that *p*-value range. Map scale: 1:1,850,000

Jasper counties had relatively low co-occurrences of docks and armoring (<36%, Table 1).

Question 3—What Demographic and Housing Characteristics Correlate with Armoring?

The negative binomial model showed a positive correlation between armoring count and the percentage of the CBG population that identified as White (Table 2, standardized $\beta = 0.42$, χ^2 (1) = 7.55, $p = 0.0060$). The model also found a positive correlation between armoring count and percentage homeowner ($\beta = 0.42$, χ^2 (1) = 7.22, $p = 0.0072$). The similar standardized coefficients suggest that the racial composition and percentage homeowners in a CBG have a similar magnitude of effect on armoring count. An examination of the marginal effect plots for these variables helps contextualize the magnitude of their effects (Fig. 4). The number of armoring structures in a CBG was predicted to increase

Table 2 Summary of output for fixed and random effects for the negative binomial GLMM of armoring count

Fixed effects				
Variable	Standardized coefficient (β)	SE	χ^2 value	*p*-value
Intercept	2.34	0.22	—	—
Income (thousands $)	−0.21	0.17	1.39	0.24
% White	0.42	0.15	7.55	0.0060
Mean age	0.0096	0.15	0.004	0.95
% Homeowner	0.42	0.15	7.22	0.0072
% homes built after 1989	−0.19	0.16	1.50	0.22
Population (hundreds)	0.14	0.14	1.05	0.31
Shore length (km)	0.26	0.15	3.38	0.069
County	—	—	45.82	<0.0001
Random effects				
Level		Variance		
Census tract		0.42		
CBG		1.46×10^{-8}		

SE standard error, χ^2 chi-squared value from likelihood ratio test

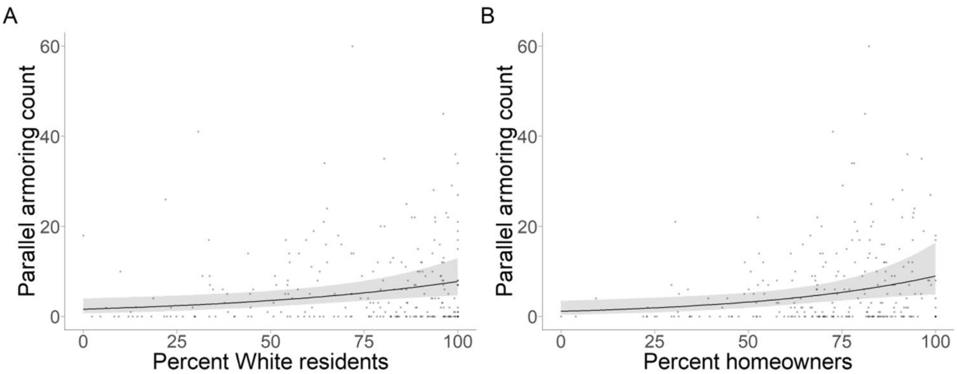

Fig. 5 Marginal effects plots for percentage White (**A**) and percentage homeowners (**B**) in the negative binomial model of shore-parallel armoring count. Both terms showed a positive correlation with armoring count and a similar magnitude of effect (percentage White, $\beta=0.42$, χ^2 $(1)=7.55$, $p=0.0060$; percentage homeowner, $\beta=0.42$, χ^2 $(1)=7.22$, $p=0.0072$). Solid line represents the marginal effect estimate, and the gray areas show 95% confidence intervals around each estimate. Points plot the raw data, and darker points indicate the overlap of two or more points

from 1.61 to 7.77 between CBGs that were 0 and 100% White (Fig. 5A and 95% confidence interval of 0.65–3.96 to 4.66–12.97) and from 1.14 to 8.97 between CBGs that were 0 to 100% homeowners (Fig. 5B and 95% confidence interval of 0.37–3.47 to 4.90–16.42).

Shoreline length was positively correlated with armoring count ($\beta=0.26$, χ^2 $(1)=3.38$, $p=0.069$). The number of armoring structures in a CBG was predicted to increase from 4.40 to 12.06 between CBGs with 1 km to 125 km of shoreline (95% confidence interval of 2.74–7.05 to 4.55–23.82). Given how few CBGs contained shorelines over 100 km and the wide confidence intervals around the upper estimate for shoreline length, we interpret this result with caution. Lastly, the county results (χ^2 $(5)=45.82$, $p<0.0001$) led us to conduct a Tukey HSD post hoc test, which revealed higher armoring counts between Beaufort, Charleston, Georgetown, and Jasper counties relative to Horry County (Fig. 6). Marginalizing over the other variables in the model, armoring counts were predicted to be higher in a CBG located in Beaufort (10.19 more structures, $z=6.65$, $p<0.0001$), Charleston (4.64 more structures, $z=5.24$, $p<0.0001$), Georgetown (3.34 more structures, $z=3.32$, $p=0.014$), and Jasper counties (7.45 more structures, $z=3.36$, $p=0.012$) than in Horry County. Due to the small number of CBGs in Jasper and Colleton and the large confidence intervals around those marginal estimates, readers should make inferences about county-level effects for these two counties with caution. All county predictions and pairwise comparisons are available in the electronic supplemental material (Tables S3 and S4).

Discussion

Question 1—How is Armoring Clustered?

As predicted, the more urban counties of Beaufort and Charleston contained nearly all the identified hot spots in

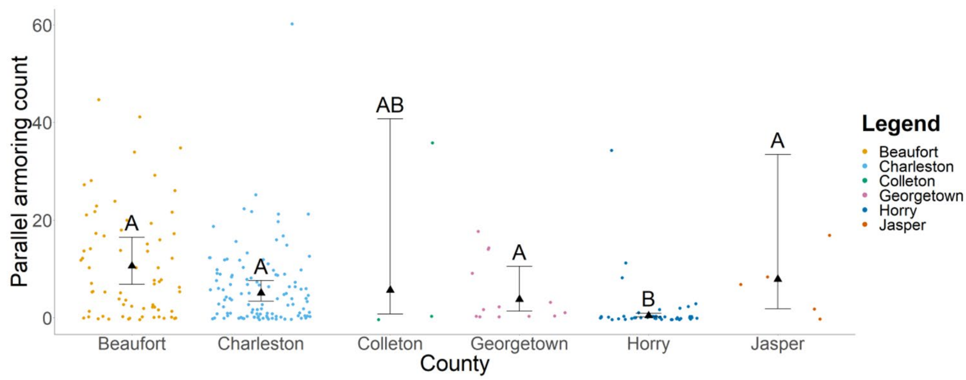

Fig. 6 The Tukey HSD post hoc analysis of county fixed effect in the negative binomial model of shore-parallel armoring count (χ^2 $(5)=45.82$, $p<0.001$). Letters represent pairwise contrasts with p-values adjusted for multiple comparisons using a Bonferroni correction. Black triangles represent individual county estimates with associated 95% confidence interval error bars. Circular points plot the raw data colored by county. Raw data points are jittered to avoid overlap and provide a better visualization of the number of observations per county

the study, regardless of whether we were examining the number or density of armoring structures. Urbanization, however, was not a uniform predictor of armoring hot spots. Cold spots occurred in parts of Charleston County and in areas around downtown Myrtle Beach. The presence of cold spots in Horry County is likely a consequence of the area's unique geography. Compared to other counties in the study, Horry County has little tidal marsh and most of the shoreline occurs along the highly channelized and maintained Intracoastal Waterway.

Many of the hot spots we identified were CBGs containing well-known and large gated communities and/or vacation resorts. For example, Fripp Island, the Sea Pines development on Hilton Head Island, and the Wild Dunes development on Isle of Palms are all gated communities that serve both permanent residents and vacation travelers. General associations between tourism development and armoring have been found in other areas of the world, particularly along sandy beaches (Phillips and Jones 2006; Calandra et al. 2022; García-Romero et al. 2023). In South Carolina, although many armoring hot spots appeared in beachfront communities, only 34 shore-parallel armoring structures were located along the beach. Examining the armoring polylines in the raw data reveals that in these instances, most of the armoring is built on the interior estuary side of these communities. Although we do not know the age of the 34 armoring structures located on the beach, this low level of armoring is almost certainly a consequence of amendments to the South Carolina state code in 1988 that prohibited most beachfront shore-parallel armoring (S.C. Code Ann. § 48-39-290(B)(2)(a-e)).

The differences in the identified hot/cold spots between the count and density analyses illustrate that either variable might be of value depending on management/research goals. For example, armoring counts might be more appropriate for identifying areas with lots of armoring and allocating greater resources for inspection/maintenance there. Alternatively, armoring density might be more appropriate for identifying areas at higher risk of coastal squeeze due to high concentrations of discrete armoring structures along a small amount of coastline. Thus, although hot spot analysis can be a valuable tool, future researchers and managers should be deliberate in their choice of what variables they consider, the spatial unit used in analysis (e.g., neighborhoods, Census blocks, special districts, or other units of government jurisdiction), and the way they model spatial relationships between units.

Question 2—To What Extent is Armoring Co-located with Infrastructure on Private Property?

We found a high degree of spatial overlap between armoring and docks with 898 armoring structures (of 1611, 55.74%) totaling 71.25 km (of 159.30 km, 44.73%) occurring within 50 m of a dock. In these areas, docks and shore-parallel armoring might interact in ways that augment or counteract their ecological and hydrological effects. For example, armoring has been shown to limit the deposition of detritus (wrack) in salt marsh (Gehman et al. 2018) and beach (Dugan and Hubbard 2006; Heerhartz et al. 2014) environments. In contrast, docks have been shown to trap large amounts of wrack along their length (Alexander and Robinson 2004; Alexander 2008). In salt marshes, the antagonistic interaction of these two types of infrastructure could have nuanced effects, as wrack can act as both a disturbance by smothering and killing vegetation (Gehman et al. 2018) while also providing structure and resources to various animal communities (Sobocinski et al. 2010; Smith et al. 2019). The frequent co-occurrence of docks and armoring shows that their collective ecological effects should be assessed frequently.

Other studies have focused on understanding what drives private property owners to armor their shorelines (Scyphers et al. 2015; Stafford and Guthrie 2020), but to our knowledge, our study is the first to attempt to quantify the amount of armoring occurring on private, personal property in the Southeastern USA. When compared to the 97 armoring structures totaling 14.18 km we removed from the study because they were located on military bases or the Port of Charleston (electronic supplemental material, Table S1), this finding suggests that private, personal property is likely the most substantial contributor to armoring along the South Carolina coast. The amount of armoring located on private property has important policy and management implications, especially as coastal populations continue to grow (Pew Charitable Trust 2024) and sea level rise heightens the inherent risk of building on the coastline. As some state and local agencies attempt to minimize the amount of hard erosion control structures within their jurisdictions, understanding where hard armoring currently exists and who owns these structures could help local, state, and federal partners identify landowners, communities, and homeowner associations with substantial levels of armoring. This in turn could help direct resources towards planning and implementing strategies to mitigate the negative externalities of armoring or convert existing armoring into nature-based erosion control when appropriate.

Question 3—What Demographic and Housing Characteristics Correlate with Armoring?

Our analysis of demographic and housing correlates of armoring partially conformed to our predictions. We did not find evidence that median household income was a meaningful predictor of armoring count, contrary to our expectations (Table 2). For most homeowners, their home is by far their single largest investment, which could make them more willing to pay for shoreline protection. The perceived effectiveness of armoring by homeowners in the Southeastern USA (Scyphers et al. 2015; Smith et al. 2017; Stafford and Guthrie 2020) might make them more tolerant of high installation costs (Scyphers et al. 2015; Gittman and Scyphers 2017), weakening the relationship between income and overall armoring count.

The percentage of a CBG that identified as White and the percentage homeowners were both positively correlated with armoring count and demonstrated a roughly equivalent magnitude of effect. Although the marginal effects for racial composition and homeownership appear small (e.g., an estimated difference of approximately six armoring structures between CBGs that are 0 and 100% White), these are notable increases when considered on the scale of the data. In our 246 CBG study area, 91 CBGs had no armoring, while 99 had 1–10 armoring structures. Thus, even six or seven more armoring structures would constitute a sizeable increase in most CBGs. The positive correlation between homeownership and armoring might again be explained by the pressure homeowners feel to protect their single largest asset. Additionally, renters might be living in larger apartment units/condominiums in which they do not have direct control over the adjacent waterfront and therefore have more attenuated influence over armoring decisions. Likewise, renters of single-family housing units do not have the authority to apply for the necessary permits to install armoring themselves. That said, the actual owners of rental units also have substantial financial interest in their properties and should feel pressure to protect their investments. Further work is needed to understand the mechanisms driving the correlation between armoring count and homeownership versus rentals.

Our results for the relationship between armoring and racial composition align with a comparable study conducted in the neighboring state of North Carolina (Siders and Keenan 2020), who found a negative correlation between the percentage of the population that was not White and percentage of the shoreline that was armored. This finding also aligns with prior research we conducted on another prominent type of coastal infrastructure: docks. Docks also show a strong, positive correlation with the percentage of a CBG population that identifies as White, with the predicted number of docks roughly tripling between CBGs that are 0 and 100% White (Beauvais et al. 2022). Coupled with the high degree of spatial overlap between docks and armoring, these findings clearly indicate that race is an important variable to consider when understanding the distribution of armoring and other forms of coastal infrastructure in the Southeastern USA.

We have argued in our prior work that this distribution of coastal infrastructure is a consequence of historic (and contemporary) Black land loss in the coastal Southeast (Beauvais et al. 2022), which has fueled subsequent large-scale development of residential communities and resorts along the water that predominantly cater to White migrants from other parts of the US (Rivers 2007; Kahrl 2012a; Dean 2013; Goodwine 2015; Hargrove 2020). We recognize, however, the inherent limitations of large-scale, observational studies in assigning causality, and alternative mechanisms might explain the correlation between racial composition and armoring. Survey instruments that collect information on a broad set of demographic characteristics of property owners and the armoring status of their parcels could help determine if these patterns hold at finer spatial scales and identify if White landowners overwhelmingly own shore adjacent properties. As we noted in the introduction, however, none of the studies we have cited that used surveys reported data on the relationship between the racial identity of respondents and armoring (Scyphers et al. 2015; Smith et al. 2017; Stafford and Guthrie 2020; Gittman et al. 2021). Interviews with a diverse range of coastal property owners or detailed analysis of property records could also help speak to our proposed mechanism. These approaches, however, quickly run into scalability issues as they are extremely time-consuming and require building meaningful relationships in communities.

Conclusion

Coastal armoring is an extensive form of infrastructure that is distributed unevenly along the South Carolina coast. Armoring hot spots tended to occur in CBGs associated with large-scale planned developments that often include both residential and vacation properties. We conservatively estimate that a little more than half of the 1611 armoring structures along the South Carolina coast occur on private, personal property and that both high rates of homeownership and White residents are positively correlated with the number of armoring structures in a CBG. These findings show that demographic and housing factors indicate where armoring is located on the South Carolina coast and specifically suggest that race and home ownership are two important factors to be considered explicitly in studies of coastal infrastructure, especially in the US Southeast. Examination of these factors can elucidate the historical and contemporary forces that drive armoring and associated coastal development. Given the impact of armoring on the estuarine environment, it is important to know what governs its distribution on the landscape, especially as coastal populations continue to grow and local and state officials contend with increasing pressure to develop the shoreline.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12237-024-01373-4.

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Declarations

Conflict of Interest The authors declare no conflict of interest.

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