Engineering away our natural defenses: an analysis of shoreline hardening in the US

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Rapid population growth and coastal development are primary drivers of marine habitat degradation. Although shoreline hardening or armoring (the addition of concrete structures such as seawalls, jetties, and groins), a byproduct of development, can accelerate erosion and loss of beaches and tidal wetlands, it is a common practice globally. Here, we provide the first estimate of shoreline hardening along US Pacific, Atlantic, and Gulf of Mexico coasts and predict where future armoring may result in tidal wetland loss if coastal management practices remain unchanged. Our analysis indicates that 22 842 km of continental US shoreline – approximately 14% of the total US coastline – has been armored. We also consider how socioeconomic and physical factors relate to the pervasiveness of shoreline armoring and show that housing density, gross domestic product, storms, and wave height are positively correlated with hardening. Over 50% of South Atlantic and Gulf of Mexico coasts are fringed with tidal wetlands that could be threatened by future hardening, based on projected population growth, storm frequency, and an absence of coastal development restrictions.

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Although coastal regions constitute less than 4% of the Earth's land area, coastal habitats (eg beaches and tidal wetlands; Figure 1) rank among the most valuable natural resources globally (MA 2005). Over one-third of the human population lives within 100 km of a coastline and development is increasing rapidly in most coastal regions of the world (MA 2005). Coastal development is vulnerable to damage and loss from erosion, including ambient waves, flooding, storms, and sea-level rise (SLR) (Peterson *et al.* 2008).

Historically, shoreline hardening has been a common response to coastal erosion, storm risks, and SLR, particularly in industrialized countries with large coastal populations, such as the US, the Netherlands, and Japan (Dugan *et al.* 2011). Shoreline hardening or armoring is defined as the construction or placement of vertical seawalls or bulkheads, sloped riprap (eg rocks) revetments, groins, jetties, or breakwaters along a shoreline (Figure 1). Although humans have been armoring coastlines for centuries, the extent and rate at which this occurs has increased markedly since 1900, and the effects of armoring on coastal ecosystem functions and services have only recently begun to be evaluated (NRC 2007).

Hardening of shorelines by means of seawalls or bulkheads can steepen and shorten shallow intertidal habitat over time (Dugan *et al.* 2008). The structures themselves also provide less physically complex habitat as compared with natural shorelines, so that hardened shorelines generally support fewer species (Figure 1; Seitz *et al.* 2006; Gittman *et al.* in press). When constructed landward of tidal wetlands, hard structures may also increase seaward scour during storm events and can prevent upslope migration of tidal wetlands as sea level rises, leading to their eventual loss (termed "coastal squeeze"; Doody 2004).

Despite its adverse ecological effects, efforts to understand the underlying causes and rates of shoreline armoring have been limited (Dugan *et al.* 2011). Filling these data gaps could help determine where and how much shoreline is at risk. More specifically, identifying shorelines with tidal wetlands that are threatened with hardening will help coastal managers to adopt more stringent regulations for shoreline armoring that could prevent future wetland losses. The purpose of this study was to: (1) catalog tidal shoreline hardening in all continental US coastal counties; (2) determine which physical and socioeconomic features of a coastal region may be more commonly associated with armoring; (3) identify regions of the US likely to experience continued hardening and subsequent coastal habitat loss; and (4) identify alternative management strategies for coastal protection.

Methods

We selected the US for our analysis because of its extensive coastline, high coastal population density (39% of the population lives in coastal counties), and data availability, as well as its vulnerability to shoreline erosion, flooding, and property damage (MA 2005; NOAA 2013). Furthermore, in the US, there is growing interest in developing a national coastal protection and adaptation

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Figure 1. *Types of natural and artificially hardened shorelines found in the US: (a) rocky shore; (b) beach; (c) tidal marsh; (d) mangrove; (e) seawall; (f) riprap revetment; (g) bulkhead; and (h) breakwater. For images of other shoreline types found in the US, refer to the NOAA ESI shoreline types image gallery (http://response.restoration.noaa.gov/esi-shoreline-types).*

framework in response to changing climatic conditions (Peterson *et al.* 2008; Arkema *et al.* 2013).

Estimation of shoreline hardening along the US coast

We used the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration's Environmental Sensitivity Index (ESI) geodatabases to calculate the linear kilometers of total shoreline and kilometers of hardened shoreline for each coastal county within the continental US (NOAA 2005). The ESI identifies 15 shoreline types (eg Type 1: exposed rocky shore or seawall) that are further subdivided into more specific shoreline types (eg Type 1A: exposed rocky shores; Type 1B: exposed, solid, man-made structures [seawalls]; Figure 1; WebTable 1). We grouped all man-made structures (seawalls, bulkheads, riprap structures [revetments, breakwaters, groins/jetties], and hybrid seawall/bulkheads with riprap) to calculate the cumulative lengths of hardened shoreline (Figure 1; WebTable 1). We divided each state's ESI shoreline by coastal county and, for the Pacific and Atlantic coasts, by whether the shoreline was "open" (ie directly exposed to the ocean) or "sheltered" (ie located in a bay, sound, lagoon, or tidally influenced river). We did not divide the Gulf of Mexico coast into "open" or "sheltered" categories because much of the Gulf coastline (eg the Louisiana coastline, the Big Bend region of Florida) consists of reticulated wetlands that cannot be easily classified in this way. We then calculated the length (in kilometers) of tidal shoreline (total and armored), as well as the percentage of hardened shore for each county. Additionally, we calculated the length of tidal wetland shoreline (total and armored).

Regression tree analyses

To evaluate the relationship between potential drivers and the percentage of hardened shoreline in each US coastal county, we considered the following factors: 2010 housing density (units per square kilometer), 2010 gross domestic product (GDP, expressed in US dollars), coastal slope (%), accretion/erosion rates (meters per year [m yr^{-1}]), geomorphology, mean tidal range (m), mean wave height (m), relative SLR (millimeters per year [mm yr^{-1}]), storm frequency between the years 1970–2010, relative county shoreline position (north to south or west to east along the coast), and years since a ban on shoreline hardening was passed (sources included: the US Census Bureau, the National Ocean Economics Program, the US Geological Survey Coastal Vulnerability Index [USGS CVI] [for a description of the variables, see Hammer-Klose and Thiehler 2001], the Federal Emergency Management Agency's US Presidential Major Disaster and/or Emergency Declarations [FEMA 2014], and federal and state legislation and permitting procedures).

We ran separate regression trees for the Atlantic open and sheltered coasts, the Pacific open and sheltered coasts, and the Gulf of Mexico coast, to describe differences among county-level shoreline hardening patterns, vis-à-vis repeated partitioning of county armoring percentages into increasingly homogeneous groups based on serial, bimodal splits among potential drivers of hardening (De'ath and Fabricius 2000). Because USGS CVI data were not available for the Pacific sheltered coastal counties, the regression tree for the Pacific sheltered coast does not include these factors. We developed regression trees using the analysis of variance (ANOVA) method of recursive partitioning and we pruned over-fitted trees using *k*-fold cross-validation. We ran all regression tree analyses using R version 3.1.0 and rpart (Therneau *et al.* 2014).

Results

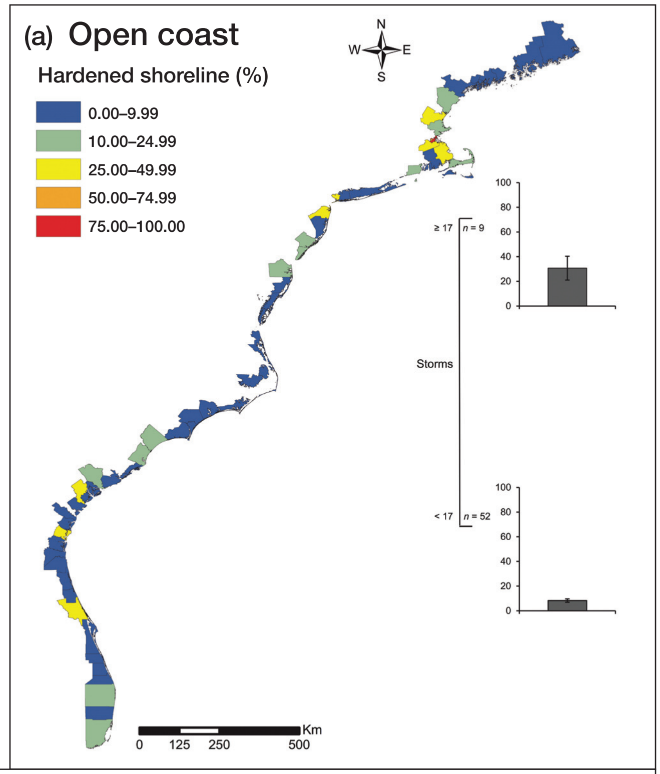
The continental US was estimated to have 160 168 km of tidal shoreline, of which 22 842 km (14%) was hardened (WebTable 2). Brackish and salt marsh were the dominant types of tidal wetland found along US coasts, making up 48% of the total US shoreline (WebTable 3). Approximately 1% (886 km) of existing tidal marsh shoreline has been armored (eg a hard structure has been built along and typically landward of the marsh) (WebTable 3), although this does not account for marsh already lost on the seaward side of man-made structures.

Shoreline hardening along US open coasts

Along the open coasts of the Atlantic and Pacific, 846 km (9%) of the shoreline has been hardened (Figures 2a and 3a). Atlantic coastal counties that experienced 17 or more storm events between 1970 and 2010 (in Massachusetts, Maine, and New Hampshire) had a higher percentage of hardened shoreline (μ = 30.7 ± 9.6%) than counties that experienced fewer than 17 storms (μ = 8.3 ± 1.4%, R^2 = 0.25; Figure 2a). The percentage of armoring along the Pacific open coast was higher (μ = 24.1 ± 2.8%) in counties where the mean wave height was <1.3 m (ie counties in southern California) (Figure 3a). Counties with mean wave heights ≥1.3 m and located south of San Francisco County, California, had more hardening (μ = 11.0 ± 2.7%) than counties north of San Mateo County, California (μ = 2.4 ± 0.9%). Mean wave height accounted for 70% of the variance in hardened shoreline along the open Pacific coast (R^2 = 0.80, full tree).

Shoreline hardening along US sheltered coasts

Despite a considerable amount of hardening along open coast-



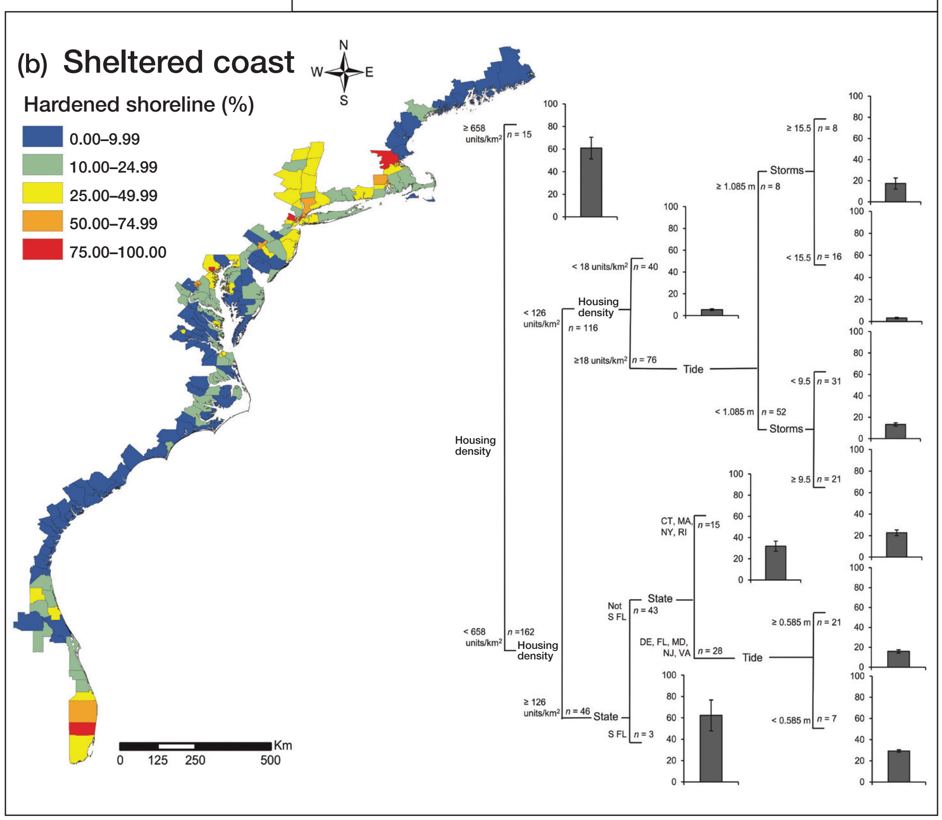
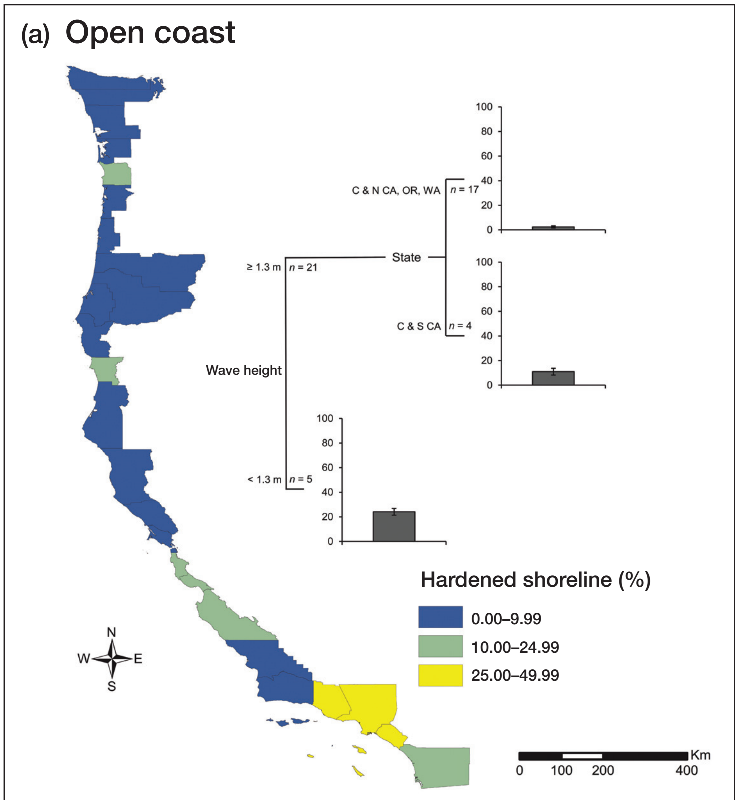


Figure 2. The percentage of total tidal shoreline hardened by county and the regression tree results for (a) the Atlantic open coast and (b) the Atlantic sheltered coast. "Housing density" is the number of individual housing units per square kilometer (as defined by the US Census Bureau), "Storms" are the total number of storms that resulted in a US Presidential Major Disaster and/or Emergency Declaration from 1970 to 2010 (FEMA 2014), "Tide" is the mean tide range (m), "State" is the state in which the shoreline is found, and "n" is the number of counties split into each node and used to calculate the percentage of hardened shoreline. Error bars represent one standard error.



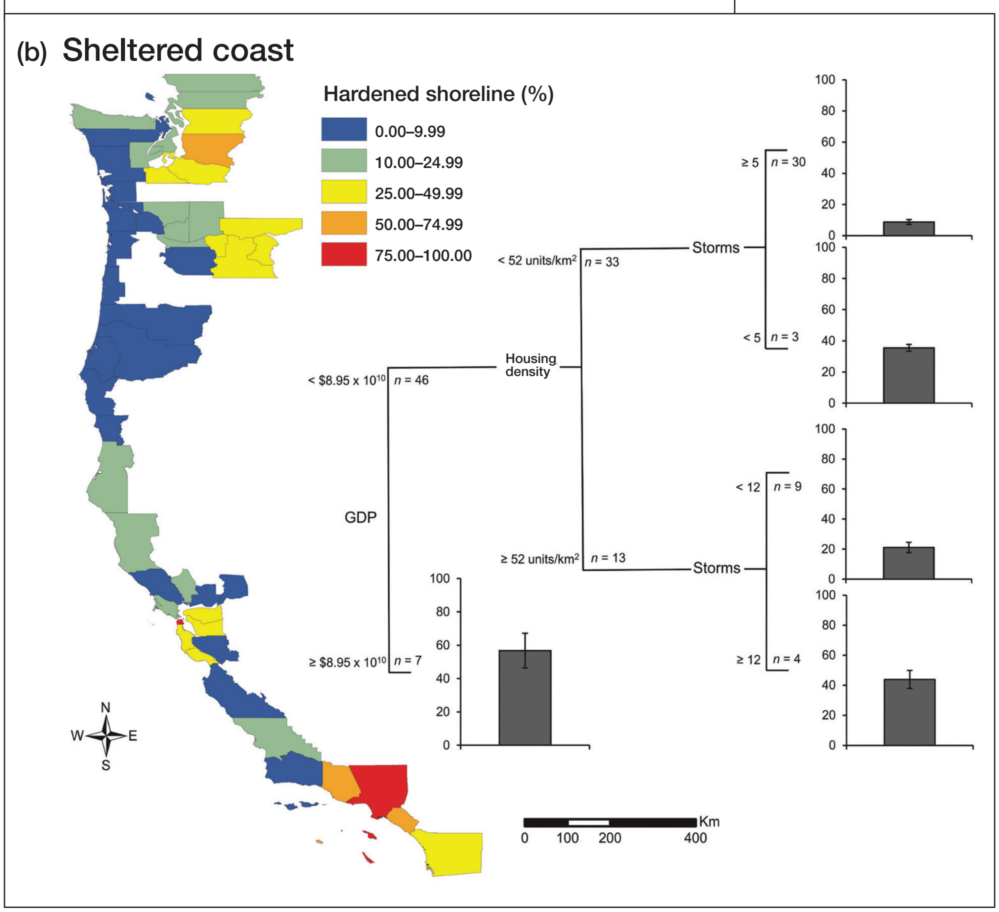


Figure 3. The percentage of total tidal shoreline hardened by county and the regression tree results for (a) the Pacific open coast and (b) the Pacific sheltered coast. "Wave height" is the mean wave height (m); "GDP" is the 2010 US gross domestic product (US\$, as defined by the US Bureau of Economic Analysis); and "Housing density", "Storms", "State", "n", and error bars are defined as in Figure 2.

lines, hardening was more prevalent on sheltered Atlantic and Pacific coasts (14% or 14 607 km; Figures 2b and 3b; WebTable 2). Atlantic coastal counties with housing densities ≥ 658 units km^{-2} and counties in southern Florida with housing densities ≥126 units km^{-2} had the highest percentages of shoreline armoring (μ = 60.9 ± 4.8% and μ = 62.3 ± 14.5%, respectively; Figure 2b). When housing densities were <126 units km^{-2} and in counties outside South Florida, fewer storms and a smaller mean tide range were associated with less hardening. Housing density accounted for 41% of the variation in hardened shoreline among Atlantic sheltered coastal counties (R^2 = 0.72, full tree). New Hampshire, Rhode Island, and Connecticut had the highest percentage of hardened marsh shoreline on the Atlantic coast (7%, 6%, and 4%, respectively; WebTable 3).

California had the highest percentage of sheltered armored shoreline on the Pacific coast (28%) and possessed four of the five counties with the greatest amounts of hardening (Figure 3b; WebTable 3). California was also characterized by the highest percentage of hardened marsh shoreline (2%) on the Pacific Coast; in San Francisco County, for instance, 71% of marsh shoreline had been armored (WebTable 3). Counties with the highest GDP (≥ \$8.95 × 10^{10}) along the Pacific sheltered coast also had the highest percentages of hardened sheltered shorelines (μ = 56.7 ± 10.4%; Figure 3b). When GDP was < \$8.95 × 10^{10}, and housing density was ≥ 52 units km^{-2}, counties with more frequent storms also had higher percentages of armoring (μ = 43.9 ± 6.0%) than counties with the same housing densities but with fewer than 12 storms (Figure 3b). GDP and housing density accounted for 53% of the variance in hardened shoreline percentages along the sheltered Pacific coast (R^2 = 0.69, full tree).

Shoreline hardening along the US Gulf of Mexico coast

The Gulf of Mexico coast had the same percentage of

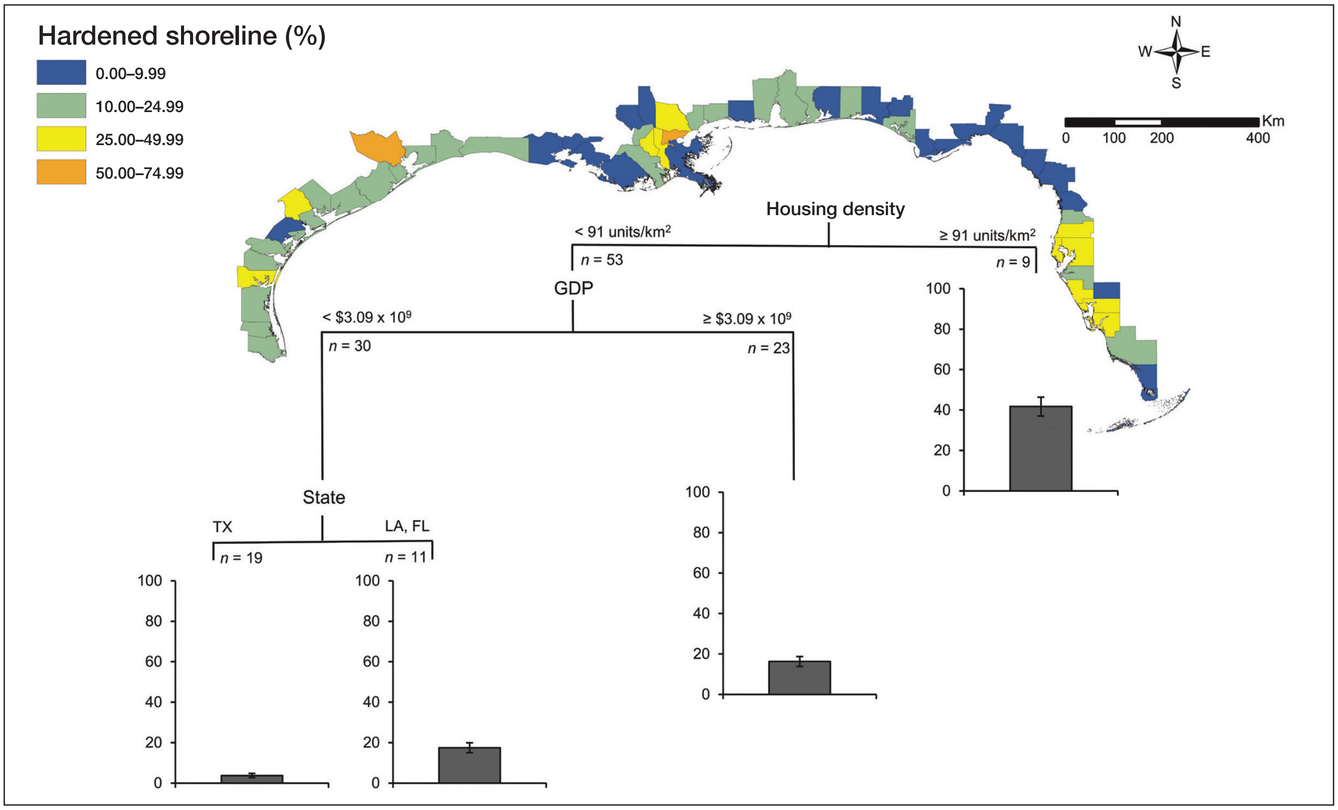


Figure 4. *The percentage of total tidal shoreline hardened by county and the regression tree results for the Gulf of Mexico coast. "Housing density", "GDP", "State", "*n*", and error bars are defined as in Figures 2 and 3.*

hardened shoreline (16%) as the entire Pacific coast (this percentage drops to 9% when all of the highly reticulated marsh shoreline of Louisiana is included) (WebTable 2; Figure 4). Counties with higher housing densities (≥91 units km^{-2}, eg Orleans Parish, Louisiana; Harris County, Texas) had higher percentages of armoring (μ = 41.7 ± 4.7%) than counties with lower housing densities (Figure 4). When GDP was < $3.09 × 10^9, Gulf counties in Texas had more hardening (μ = 16.3 ± 2.5%) than Gulf counties outside of Texas (μ = 3.7 ± 1.1%; Figure 4). Housing density alone partitioned 46% of the variation in the percentage of hardened shoreline along the Gulf coast (R^2 = 0.56, full tree). Texas had more than five times as much armored marsh shoreline (6%) than other Gulf states (0.4–1.4%) (WebTable 3).

Discussion

Our analysis indicates that 14% of the contiguous US shoreline is hardened and that 64% of armoring has occurred along Atlantic and Pacific sheltered shorelines, such as estuaries, lagoons, and tidally influenced rivers (WebTable 2; Figures 2b and 3b). Thus, shoreline hardening is likely a substantial yet largely understudied means by which humans modify and degrade coastal ecosystems in the US.

Potential drivers of shoreline hardening

Understanding the potential drivers of shoreline hardening could help identify where and how much shoreline and associated habitats are at risk of being lost to this process in the near future. Our analyses revealed that housing density and GDP, respectively, were the best predictors of armoring on US Atlantic and Pacific sheltered coasts, as well as along the Gulf of Mexico coast (Figures 2–4). Globally, man-made shoreline structures are associated with densely populated coastlines (eg around the Mediterranean), and have been used to protect both commercial and residential development and infrastructure for generations (Dugan *et al.* 2011). Most major US coastal metropolitan areas are located on sheltered coasts and tend to be heavily armored (eg New York, Los Angeles, New Orleans), regardless of other physical shoreline characteristics or processes.

Coastal metropolitan areas also support development in neighboring coastal counties (eg for the purposes of industry and tourism); this likely contributes to the spread of shoreline hardening, despite relatively low housing densities in these adjacent areas (Figures 2b, 3b, and 4; NOAA 2013). Specifically, these regions have a history of coastal modification that includes dredging of canals, to support shipping traffic from major ports (eg New York, Corpus Christi, Miami) and for flood control (eg South Florida canal systems), that probably contributed to hardening (US Census Bureau 2010).

Outside of metropolitan areas, the addition of man-made structures is more closely related to the vulnerability of coastal developments to damage from physical processes (eg storms, erosion). Along the Pacific open coast, the rocky shorelines of northern California, Oregon, and

Washington are associated with wave heights greater than 1.3 m, and are therefore not suitable for most types of development; this may be the reason for the lesser degree of armoring in these regions (Figure 3a). The regression tree selected a single variable that reduced the most variance in shoreline hardening; however, wave height was also strongly positively correlated with both county location (R^2 = 0.82) and the number of years since a ban on shoreline hardening was implemented (R^2 = 0.67).

Greater storm frequency was the most important predictor of armoring on the Atlantic open coast (Figure 2a). Hard structures are often built along coastlines in response to damage and erosion from major storm events (eg seawall construction in Galveston, Texas, following a major hurricane; Hansen 2007); areas prone to major storms would therefore be expected to have more hardened shoreline. However, there is evidence that natural beach dune and marsh shorelines experience less erosion and damage than hardened shorelines during single storm events (Thieler and Young 1991; Gittman *et al.* 2014). Given the uncertainty associated with the performance of bulkheads and seawalls during these storm events, the use of hard structures in response to storms should be evaluated further.

Given the strong relationships between both housing density and GDP and shoreline hardening, other socioeconomic factors we did not include – such as commercial and recreational shoreline uses, coastal land ownership (public versus private), and coastal property values – may provide additional insights into the patterns of observed shoreline hardening in the US. Further refinement of the relationship between socioeconomic factors and armoring will allow policy makers and coastal-resource managers to develop targeted strategies (eg tax breaks for waterfront property owners that choose not to build a bulkhead or seawall) for reducing shoreline hardening in areas with vulnerable coastal habitats. These approaches may become increasingly fine-tuned as we learn more about how construction/repair costs or the cascading effects of neighboring shoreline hardening (Scyphers *et al.* 2015) drive decisions regarding shoreline maintenance.

Predictions for future hardening and habitat loss

Although European countries have been adding manmade structures to their shorelines for centuries, in the US, most of this construction likely occurred after 1900 (Dugan *et al.* 2011), making the rate of shoreline hardening in the US about 200 km yr^{-1}. If this rate remains constant and coastal populations continue to increase according to NOAA projections (NOAA 2013), the percentage of hardened shoreline will double by 2100, resulting in nearly one-third of the contiguous US coastline being armored. This projected rate is probably conservative but assumes that no additional restrictions are placed on shoreline hardening (only eight states have implemented total or partial bans on construction of hard structures along the shore).

Some of the largest increases in population density are predicted to occur along the South Atlantic and Gulf coasts, where most of the US's remaining tidal salt marshes (> 50%) and mangrove forests (100%) are currently found (WebTable 3; Kennish 2001). As much as 50% of US salt marsh has been lost over the past century, largely as a result of human activities (Kennish 2001). Although only a small percentage (1%) of existing tidal wetlands is currently hardened, this percentage does not account for the wetlands likely lost in the past to hardening (WebTable 3). On the Atlantic coast, 60% of the land between 0–1 m above current sea level is expected to be developed and hardened, thereby resulting in a large-scale coastal squeeze on tidal wetlands (Titus *et al.* 2009). Given the prevalence and ecological consequences of shoreline hardening, steps should be taken to reduce the rate of armoring and to implement alternative stabilization strategies (eg submerged sills, marsh planting; see Gittman *et al.* in press).

Conclusions

Our assessment demonstrates that much of the US shoreline is vulnerable to future habitat loss if actions are not taken to revise current coastal management strategies. Our estimate – that 14% of US tidal shoreline is hardened – is conservative, as all types of tidal shoreline were included in our analysis. When shorelines that are not likely to be armored (eg naturally rocky shores) are excluded, the majority of the natural shoreline most vulnerable to future hardening (eg beaches, wetlands) is found along the Gulf of Mexico and South Atlantic coasts. Given the projected increases in population for these two regions, these coasts will likely experience the highest rates of future hardening and the associated loss of marsh and other vegetated intertidal habitat to coastal squeeze (Doody 2004). This, in turn, will result in the loss of critical coastal ecosystem services such as provision of nursery habitat for commercially and recreationally valuable fish and crustaceans, filtration of nutrients and pollutants from terrestrial runoff, carbon burial, and erosion protection (Peterson *et al.* 2008).

Further analyses of the socioeconomic drivers of shoreline hardening are needed to determine how to prevent or reduce further destruction of sensitive habitats such as tidal wetlands. Although our analysis provides baseline estimates of armoring, continued updates will be required to calculate region-specific rates. Coastal managers could use these rates to assess the cumulative impacts on coastal habitats and to assess the risk of future habitat loss. Policy makers should also use these assessments to develop informed legislation and regulations, including a revision of the US Army Corps of Engineers' policy on nationwide permits to account for the future loss of habitat as a result of coastal squeeze, which will likely extend well beyond the construction footprint of a hard structure. Finally, we recommend that new management guidelines be developed to incorporate green infrastructure and planning for shoreline migration (eg rolling easements, bulkhead removal) with SLR. Without substantial changes to coastal management policies and development practices, the US coastlines will likely lose their natural defenses.

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