

1           **How does the removal of federal subsidies affect investment in coastal protection**  
2           **infrastructure?**

3  
4           Jordan Branham  
5           Kyle Onda  
6           Nikhil Kaza  
7           Todd K. BenDor  
8

9           <sup>1</sup>Department of City and Regional Planning and UNC Institute for the Environment  
10           University of North Carolina at Chapel Hill  
11           New East Building, Campus Box #3140  
12           Chapel Hill, NC 27599-3140

13           \*Corresponding Author – email: [jbranham@live.unc.edu](mailto:jbranham@live.unc.edu), phone: 919.283.3579

14  
15           David Salvesen  
16

17           Institute for the Environment  
18           University of North Carolina at Chapel Hill  
19           New East Building, Campus Box 1105  
20           Chapel Hill, NC 27517  
21  
22  
23

24           **Journal:** Land Use Policy

25  
26           **Keywords:** Coastal Barrier Resources Act (CBRA); natural hazards; coastal protection; shoreline  
27           armoring; climate adaptation; coastal ecology  
28  
29  
30  
31

32 **Abstract**

33 Shoreline armoring, which involves the installation of hardened structures to protect coastal  
34 property, dramatically alters shoreline composition and resulting ecological functions. Accelerating  
35 hazard threats to growing coastal communities compounds this problem, creating demand for more  
36 armoring. We examine whether designation by the U.S. Coastal Barrier Resources Act (CBRA) –  
37 enacted to disincentivize urban development on hazardous coastal barriers – is associated with lower  
38 propensities to armor shorelines. In designated areas, CBRA removes access to federally-subsidized  
39 flood insurance, infrastructure subsidies, and disaster assistance. Using logistic regression modeling,  
40 we examine armoring at the parcel scale across the State of Florida (USA), controlling for CBRA  
41 designation, land use, and local population density. Our findings reveal a significant negative  
42 relationship between CBRA designation and the odds of armoring, particularly for residential and  
43 vacant properties. As coastal areas grapple with increasing impacts from coastal hazards, removal of  
44 public subsidies may be an effective non-regulatory method for maintaining the ecological and  
45 protective benefits of natural shorelines.

46

47 **Introduction**

48 Despite exposure to hurricanes and other hazards, low lying U.S. coastal areas have experienced  
49 explosive growth in population and development; the Atlantic and Gulf coasts are home to 51  
50 percent of all new housing units built in the U.S. from 1970-2016 (Klotzbach et al. 2018). This  
51 building boom has placed more people and assets in the path of hurricanes and tropical storms,  
52 resulting in escalating storm-related damage along the U.S. coastline. Nine of the ten most costly  
53 U.S. hurricanes have occurred since 2005 (NOAA 2019), culminating in the costliest hurricane  
54 season in U.S. history in 2017 (Halverson 2018).

55

56 Efforts to shield development along the coast through the placement of coastal protection  
57 infrastructure have changed the composition of shorelines along the U.S. coast (Gittman et al. 2015).  
58 Coastal protection infrastructure, also called shoreline armoring or hardening, is composed of  
59 physical structures that are placed along open and sheltered coastlines in order to offer protection  
60 from storm surges and flooding, or stabilize coastal land and halt erosion. Examples of these types  
61 of structures include seawalls, bulkheads, rock revetments, and retaining structures (Titus et al.  
62 2009a).

63

64 By the early 2000s, 14 percent of the total U.S. shoreline was armored, with much of the armoring in  
65 the sheltered (i.e., a bay, sound, or tidal river) coasts of major metropolitan areas (Gittman et al.  
66 2015). Today, continued development in low-lying coastal areas is expected to result in increasing  
67 investments in coastal protection infrastructure (Titus et al. 2009b); indeed, along with retreat,  
68 protection is a primary adaptation strategy available to coastal communities to address risks from  
69 hurricanes and sea level rise (Woodruff et al. 2018; Bedsworth and Hanak 2010). Despite their  
70 protective intent, a growing body of literature has questioned the effectiveness of armored

71 shorelines in reducing storm and erosion damage, finding armored structures increase property  
72 damages (Smith et al. 2017) or that natural shorelines offer equivalent protection (Feagin et al. 2015;  
73 Arkema et al. 2013; Narayan et al. 2016). Furthermore, the placement of protective structures with  
74 the intent to enhance safety can produce a paradox that increases risk of disaster by inducing further  
75 development behind these structures and disincentivizing relocation away from hazardous coastal  
76 areas (Armstrong et al. 2016; Burby 2006; Kittinger and Ayers 2010).

77

78 While armored shorelines are a popular method for addressing shoreline erosion, these structures  
79 can have a number of negative ecological effects. Replacing natural shorelines with armored  
80 structures can lead to a loss of marine habitat that fragments and reduces the abundance of marine  
81 life and shorebird populations (Bulleri and Chapman 2010; Dugan et al. 2008); seawalls in particular  
82 can reduce biodiversity by 23 percent and marine organisms by 45 percent (Gittman et al. 2016a). As  
83 the development of coastal areas coincides with increases in sea levels and erosion, the placement of  
84 armored structures impedes inland migration of wetlands and reduces the area available for natural  
85 shoreline habitats (Gittman et al. 2016b). Still, given the expectation that demand for erosion control  
86 measures will continue with increases in sea level (Titus et al. 2009b), a growing body of work  
87 supports the use of living shorelines (using native vegetation and natural features to stabilize  
88 shorelines) in order to provide protective benefits, maintain important ecosystem services, and  
89 accommodate future shoreline migration (Davis et al. 2015; Bilkovic et al. 2016; Currin, Chappell,  
90 and Deaton 2010).

91

92 Studies of drivers of shoreline armoring in the U.S. have characterized these landscape  
93 transformations as the result of macro-scale influences, such as increasing urban development, or as  
94 the result of individual-level social dynamics. For example, Gittman et al. (2015) found that

95 shoreline armoring is correlated with county-level housing density, GDP, and past storm frequency,  
96 while Siders and Keenan (2020) similarly found protection to be the preferred adaptation strategy in  
97 areas correlated with high housing values, incomes, and population density at the Census block  
98 group-level. On the other hand, Scyphers et al. (2015) found that many coastal homeowners install  
99 armored structures in response to the negative impacts resulting from neighbors' armored  
100 shorelines. Yet, despite an array of local, state, and federal government roles in permitting and  
101 funding these structures, research into the relative impact of public funding on the propensity to  
102 install coastal protection infrastructure is limited or outdated (Titus et al. 2009a). In this paper, we  
103 examine how land use characteristics and access to public subsidies are associated with an owner's  
104 propensity to armor their shoreline. Drawing on the work of Armstrong et al. (2016), we focus on  
105 individual characteristics and decision-making by assessing this relationship at the parcel-level.

106

107 This study explores the role of public subsidies in the development of coastal protection through the  
108 lens of the 1982 U.S. Coastal Barrier Resources Act (CBRA; 16 USC §3501), which aims to  
109 disincentivize development in high-hazard areas by removing federal funding for infrastructure,  
110 flood insurance, and disaster assistance on undeveloped coastal barriers. Considered a subsidy  
111 removal policy approach, CBRA functions similarly to urban service boundaries (USBs), which  
112 restrict development subsidies (e.g., funding for transportation, water, and sewer infrastructure)  
113 without directly prohibiting development. Thus, in the case of CBRA, some of the cost of  
114 development is transferred from the federal government to private developers or state and local  
115 governments. Property owners also face increased long-term costs due to a lack of access to the  
116 subsidized National Flood Insurance Program (NFIP). As a result, CBRA is an excellent vehicle for  
117 studying the role of federal subsidies in stimulating investment in coastal protection, allowing us to

118 explore how the transfer of development costs to other public and private entities affects investment  
119 in shoreline armoring and whether this impact is moderated by land use.

120

121 In this paper, we ask, what are the relationships between federal infrastructure and flood insurance  
122 subsidies and the prevalence and placement of coastal protection infrastructure? How are these  
123 relationships moderated by land use? We examine these questions at the parcel level within the State  
124 of Florida (USA), which has an extensive shoreline (2,276 miles), substantial amount of land in  
125 CBRA, and a complete, contemporary set of shoreline composition data<sup>1</sup> (NOAA 2018).

126

127 Given the increased cost and difficulty of urban development, we expect land located within CBRA  
128 to be associated with a lower likelihood of shoreline armoring relative to non-CBRA areas; however,  
129 we also anticipate that this relationship will be moderated by land use, with more intense land uses  
130 (e.g., industrial, commercial, multi-family residential) exhibiting higher likelihoods of armoring both  
131 inside and outside of CBRA. Specifically, given the land use categories utilized in this analysis (see  
132 Table S1, Supp. Material 2), we hypothesize that commercial/institutional and industrial land uses  
133 will exhibit the highest likelihood of shoreline armoring, followed by multi-family residential, single-  
134 family residential, and military lands. Conversely, we expect armoring to be substantially less likely  
135 for government, recreational, and agricultural/vacant lands.

136

137 Our findings demonstrate that CBRA designation has a substantial negative relationship with the  
138 probability that a parcel is armored; however, this relationship is moderated by land use, with land  
139 utilized by federal and state governments, as well as industrial, commercial, and recreational uses,

---

<sup>1</sup> This dataset represents the most detailed categorization of the location and composition of U.S. shorelines, however the fractal nature of shorelines means that any length measurements will be a product of the spatial accuracy of the given dataset.

140 counteracting this trend. Given the federal government's historically supportive role towards coastal  
141 development (Bagstad, Stapleton, and D'Agostino 2007), along with the increasingly erosive forces  
142 from sea level rise and more intense coastal storms, this study's findings are particularly relevant for  
143 coastal policymaking for climate adaptation and habitat conservation.

144

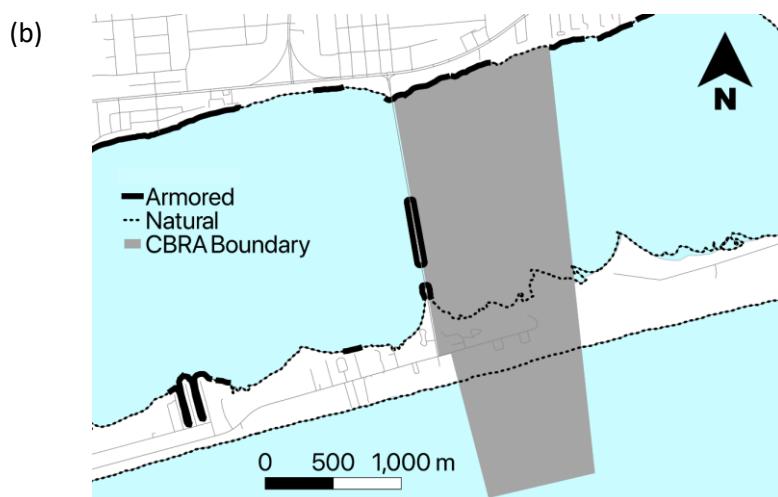
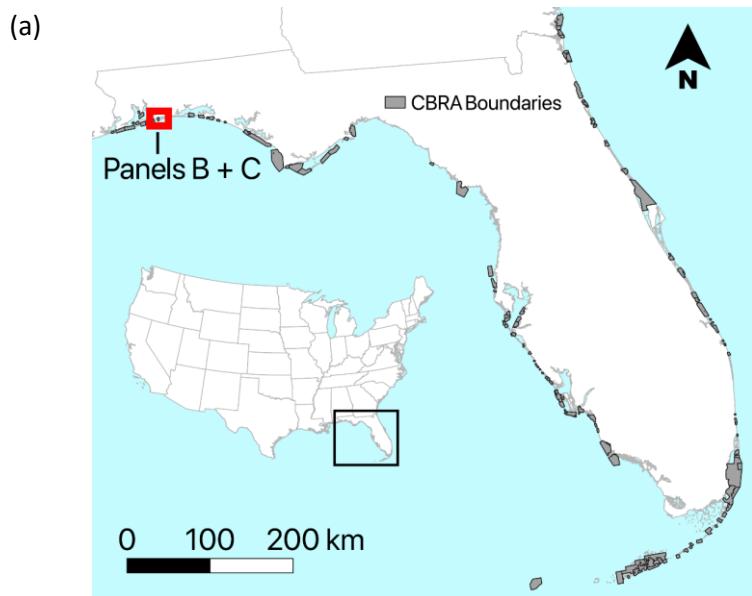
## 145 **Methods**

### 146 Data

147 Geospatial parcel boundary data, along with the land use information for all thirty-five coastal  
148 counties in Florida was acquired from the Florida Geographic Data Library (FGDL; 2017). Detailed  
149 geospatial shoreline location and composition data for the Florida coast was acquired from NOAA's  
150 Environmental Sensitivity Index (ESI; NOAA 2018); this dataset also includes hydrology polygons  
151 that were used to identify and extract those parcels that share a boundary with the coastline (which  
152 we refer to as "coastal parcels"). Finally, geographic boundary data of CBRA areas were obtained  
153 from the U.S. Fish and Wildlife Service (2019).

154

155 Figure 1: A) CBRA units along Florida shoreline; B) Example of CBRA unit boundary and shoreline  
156 classification; C) Extracted parcels with land use and shoreline classification.



158 Substantial pre-processing efforts were required to prepare data for analysis; please refer to Supp.  
159 Material 1 and 2 for more details on these efforts.

160

## 161 Analytical Techniques

162 This analysis assesses the relationship of land use and CBRA on the propensity of armoring on  
163 individual property using binary logistic regression. We do *not* seek to comprehensively describe all  
164 of the underlying environmental, political, and economic factors affecting the propensity to armor  
165 the coastline; instead, we explore how the relationship between CBRA and armoring is moderated  
166 by coastal land use through an interaction term.

167

168 Pre-processing of parcels produced a final dataset of 313,152 coastal parcels, complete with  
169 shoreline attributes, land use, and location in CBRA. We also control for whether a parcel is located  
170 in a municipality, given that local policies and development practices can impact armoring  
171 prevalence (e.g., Kittinger and Ayers 2010), and include the population density of the Census tract in  
172 which the parcel is located, as local population density and resulting infrastructure needs tend to be  
173 correlated with armoring (Siders and Keenan 2020).

174

175 To model the relationship of shoreline armoring and designation in CBRA, we use a logit model  
176 with the following specification:

$$177 \ln\left(\frac{p}{1-p}\right) = \beta_0 + \beta_1\gamma + \beta_2C + \beta_3(CBRA) + \boldsymbol{\beta}\mathbf{L} + \boldsymbol{\beta}(\mathbf{L} * CBRA)$$

178 where,  $p$  = probability of shoreline armoring in parcel,  $\gamma$  = dummy indicating a municipality,  $C$  =  
179 US Census tract population density (in 1000s), CBRA = dummy indicating whether a parcel is within

180 a CBRA unit,  $\mathbf{L}$  = a vector of land use dummy variables (with agricultural as the base case),  $\boldsymbol{\beta}$  =  
181 vector of regression coefficients.

182  
183 In their assessment of development in CBRA, Onda et al. (2020) found that land located within  
184 CBRA exhibits less development than land outside CBRA; however, the development that occurs  
185 within CBRA is characterized by bigger houses, larger parcels, and higher land values. As a result, we  
186 do not include controls for land value or parcel size, since this would introduce multicollinearity  
187 issues in our model. Furthermore, while the approach we use in this analysis facilitates exploration  
188 of CBRA's direct relationship with shoreline armoring, its cross-sectional nature is unable to account  
189 for the causal reasons underpinning armoring due to endogeneity. Regardless of cause, this analysis  
190 will allow us to determine the relationships between CBRA designation and the propensity to armor  
191 different coastal land uses.

192

## 193 **Results**

### 194 Descriptive statistics

195 Parcels in CBRA account for 2.64 percent ( $n = 8,280$ ) of the total number of parcels we analyzed.  
196 These parcels tend to be larger than non-CBRA parcels, averaging 10.47 ha compared to 2.61 ha,  
197 respectively. CBRA covers 9.84 percent (86,692 ha) of the total land area of coastal parcels analyzed  
198 (880,736 ha); this difference is mostly due to the greater prevalence of subdivided parcels outside  
199 CBRA. We find substantial differences in total shoreline armoring on parcels inside (10.47 percent)  
200 and outside (70.14 percent) of CBRA, with considerable variation across land uses.

201

202 Outside of CBRA, several land uses exhibit armoring in more than half of all parcels and  
203 substantially more than other land uses: single-family residential (78.9 percent), multi-family

204 residential (69.7 percent), commercial/institutional (65.2 percent), and industrial (50.4 percent; Table  
205 1). The prevalence of armoring inside CBRA is substantially lower across all categories with the  
206 exception of industrial (53.9 percent) and federal government (11.7 percent) land uses. For instance,  
207 vacant parcels experience 84 percent less armoring in CBRA than outside CBRA, while multi-family  
208 residential (75 percent) and single-family residential (72 percent) land uses exhibit similar trends.

209

210 Table 1: Armoring statistics by CBRA and land use

Land Use Category	% Armored		Parcels (count)		Area (ha)	
	CBRA	Non-CBRA	CBRA	Non-CBRA	CBRA	Non-CBRA
Agricultural	2.7	12.3	849	4,161	4,136	97,456
Commercial/Institutional	38.3	65.2	81	6,601	618	16,408
Federal Government	11.7.	7.1	103	969	7,934	35,774
Industrial	53.9	50.4	13	1,122	221	9,158
Local Government	16.7	50.3	261	2,820	3,306	21,674
Military	7.7	27.4	13	175	1,746	51,718
Recreational	10.7	20.9	731	3,125	15,415	215,015
Residential, multi-family	17.5	69.7	217	30,761	356	15,217
Residential, single-family	22.2	78.9	1,254	203,722	812	37,363
State/Regional Government	8.2	13.6	1,802	2,719	27,309	88,122
Vacant	7.8	48.7	3,724	48,697	34,759	206,138

211

212 Vacant land uses comprise a substantial portion of the parcels within CBRA (45.0 percent) and have  
213 armored shorelines on only 7.8 percent of those parcels; outside CBRA, vacant parcels exhibit  
214 considerably higher rates of armoring (48.7 percent). State and regional government parcels are the  
215 next most prevalent within CBRA (21.8 percent) and experience similarly low rates of armoring (8.2  
216 percent). Amongst the public sector, local government parcels have the most prevalent coastal  
217 protection infrastructure, with 50.3 percent armored outside CBRA and 16.7 percent inside CBRA.

218

219 Regression analyses

220 Overall, parcels within CBRA have 78 percent lower odds of being armored than parcels located  
221 outside CBRA (Table 2). Single-family residential (50 percent), vacant (49 percent), and multi-family  
222 residential (45 percent) land uses all have significantly lower odds of being armored than their  
223 counterparts outside CBRA. The odds of federal government (663 percent) and industrial (525  
224 percent) land uses being armored, however, are substantially higher inside CBRA. Similarly,  
225 recreational (175 percent), state and regional government (105 percent), and  
226 commercial/institutional (117 percent) lands have higher odds of being protected inside CBRA.  
227 Coastal lands used by local governments or the military exhibit no significant difference in armoring  
228 expectations from agricultural lands.

229

230 Most coastal parcels outside of CBRA have substantially higher odds of having protected shorelines  
231 than agricultural parcels outside of CBRA; parcels owned by the federal government is the notable  
232 exception, with odds of armoring reduced by 40 percent. Local government parcels, on the other  
233 hand, have odds of armoring 463 percent higher than agricultural lands. Several land uses have  
234 considerably higher odds of protection, with single-family residential land having the highest  
235 increase (1,900 percent), followed by multi-family residential (1,198 percent),  
236 commercial/institutional (865 percent), vacant (484 percent), and industrial (456 percent) land uses.  
237 Location within a municipality has a small but positive effect (25 percent) on the odds that a parcel's  
238 shoreline is protected, while a 1000-person increase in Census tract population density increases the  
239 odds of armoring by 15 percent.

240

241

242 Table 2: Binary logistic regression of armoring in parcel, controlled by land use and CBRA  
 243 designation. \*p < 0.05, \*\*p < 0.01, \*\*\*p < 0.001. n = 313,152. AUROC indicates “area under Receiver  
 244 Operator Characteristic” (Fawcett 2006), which indicates how model estimates improved on those  
 245 of a random (empty) model.

246

		Odds ratio [95% interval]
Land Use	In CBRA (yes/no)	0.22 [0.14; 0.32]***
	Parcel is in municipality (yes/no)	1.25 [1.23; 1.28]***
	Tract population density per sq. mile (in 1000s)	1.15 [1.15; 1.16]***
	Commercial/Institutional	9.65 [8.69; 10.75]***
	Federal Government	0.60 [0.46; 0.78]***
	Industrial	5.56 [4.78; 6.47]***
	Local Government	5.63 [5.00; 6.35]***
	Military	2.70 [1.89; 3.79]***
	Recreational	1.49 [1.31; 1.70]***
	Residential, multi-family	12.98 [11.80; 14.30]***
Land Use * CBRA interactions	Residential, single-family	20.00 [18.23; 21.99]***
	State/Regional Government	1.17 [1.01; 1.35]*
	Vacant	5.84 [5.32; 6.43]***
	Commercial/Institutional	2.17 [1.18; 4.08]*
	Federal Government	7.63 [3.42; 16.36]***
	Industrial	6.25 [1.91; 21.14]**
	Local Government	1.17 [0.69; 2.04]
	Military	1.15 [0.06; 6.47]
	Recreational	2.75 [1.71; 4.60]***
	Residential, multi-family	0.55 [0.32; 0.97]*
	Residential, single-family	0.50 [0.33; 0.80]**
	State/Regional Government	2.05 [1.25; 3.45]**
	Vacant	0.51 [0.34; 0.82]**
	Intercept	0.12 [0.11; 0.13]***
Log Likelihood		-168,534.08
AIC		337,116.15
AUROC		0.727

247

248

249 **Discussion and Conclusions**

250 This analysis finds a substantial negative relationship between location in CBRA and the odds that a  
251 shoreline is protected, demonstrating that the removal of federal subsidies is associated with reduced  
252 investments in shoreline armoring. In particular, land uses that tend to be associated with private  
253 residential development are far less likely to be armored in CBRA, including the two land uses –  
254 single-family and multi-family residential – that exhibit the highest likelihoods of being armored  
255 outside CBRA. Similarly, vacant lands exhibit the second lowest odds of armoring inside CBRA  
256 despite high odds of armoring outside CBRA.

257

258 On the other hand, we find that commercial/institutional land uses are slightly more likely to be  
259 armored in CBRA, while industrial armoring is very similar both inside and outside CBRA. We also  
260 find federal and state/regional government, as well as recreational, lands are more likely to be  
261 armored in CBRA despite relatively low armoring outside of CBRA. These patterns suggest CBRA  
262 may be effective at deterring investments in shoreline protection of traditional residential  
263 development, yet less effective at reducing armoring for other land uses.

264

265 Our findings regarding armoring trends among land uses outside CBRA generally aligned with our  
266 expectations, with high armoring rates on multi-family and single-family residential as well as  
267 commercial/institutional lands. Perhaps the most unexpected result is the prevalence of armoring on  
268 vacant land outside CBRA. We hypothesize that this is due to the preponderance of dredge-and-fill  
269 residential developments along the coast of Florida, which tend to be characterized by armored  
270 shorelines for the entire development; many of these developments have a substantial number of  
271 parcels that remain undeveloped, yet nevertheless feature armored shorelines. We also find that local  
272 government land is more likely to be armored, suggesting that municipalities play a key role in the

273 development of shorelines not only as a side-effect of urban density but also through active  
274 development of government-owned property. Overall, our findings reveal that few types of land  
275 uses outside of CBRA are unlikely to be armored.

276

277 It is important to emphasize that this analysis is cross-sectional, and therefore unable to account for  
278 endogeneity in CBRA designation decisions or the prevalence of armoring *prior* to the creation of  
279 CBRA. For instance, lower prevalence of shoreline armoring in CBRA units may be attributable to  
280 land characteristics that pre-dated CBRA designation, and which make the installation of shoreline  
281 armoring infrastructure infeasible. Therefore, we must be careful not to attribute causality to these  
282 findings, which would only be possible using a time series analysis of changes in shoreline armoring,  
283 beginning prior to the enactment of CBRA.

284

285 While future work is needed to definitively understand the *causal effects* of CBRA's disincentives, we  
286 instead note the existence of a relationship between CBRA and the reduced odds of having coastal  
287 protection infrastructure. The notable lack of present-day armoring in CBRA of lands that  
288 experience significant armoring outside CBRA suggests that the removal of infrastructure, disaster  
289 assistance, and NFIP subsidies may reduce the likelihood of future coastal protection.

290

291 We offer three possible explanations for this trend, each of which may occur in combination with  
292 the others. One possible explanation is that the lack of access to post-disaster assistance inside  
293 CBRA makes it financially difficult to repair or replace protective infrastructure damaged during a  
294 storm (see Kunreuther 2006; Gallagher and Hartley 2017). Thus, over time, armored infrastructure  
295 might decrease in prevalence within CBRA as tropical storms and hurricanes inflict costly damages,  
296 necessitating either repair or removal.

297

298 A second possibility is that CBRA is associated with different types of development that are less  
299 reliant on shoreline armoring for viability or are built less proximate to water. For example, “dredge-  
300 and-fill” residential developments directly adjacent to the water are common throughout Florida,  
301 particularly outside CBRA (Cummings 2006; Johnston 1981); this type of development often uses  
302 bulkheads to retain the fill on which the house is placed, leading to high rates of protection. It is  
303 possible that dredge-and-fill developments are prohibitively expensive to develop inside CBRA or  
304 that reduced land scarcity within CBRA makes such operations unnecessary, leading to fewer of  
305 these types of development that necessitate armoring for their viability. The notable differences in  
306 armoring trends between residential and vacant lands located inside and outside of CBRA lends  
307 credence to this explanation.

308

309 Third, we theorize that CBRA may be associated with reductions in development rates on land  
310 designated by the Act, which in turn reduces the likelihood of armoring (given that there are fewer  
311 assets to be protected). In a similar fashion, CBRA was intended to reduce the incentive for private  
312 developers to purchase and improve land in designated units, which could lead to a different  
313 combination of actors and landowners inside CBRA. Recent research by Onda et al. (2020) finds  
314 that areas within CBRA tend to exhibit less development than surrounding areas, and the  
315 preponderance of vacant coastal parcels within CBRA reinforces this finding. However, while this  
316 explanation likely accounts for some of the reductions in shoreline armoring we observe, it does not  
317 account for the observed variability in armoring across land uses, particularly those that are *more*  
318 likely to be armored than their counterparts outside CBRA. More importantly, it does not explain  
319 the wide variation in armoring of vacant parcels, which are significantly less likely to be armored  
320 inside CBRA than vacant parcels outside CBRA.

321

322 This analysis finds that designation within CBRA coincides with reduced investments in shoreline  
323 armoring, which may increase the short-term risk of erosion for current residents. However, this is  
324 likely to have little effect on damages from hurricanes and tropical storms; strong evidence now  
325 demonstrates that maintaining natural shorelines can be more effective at reducing storm surge and  
326 flood risk, meaning fewer armored structures may decrease storm damages while also eliminating the  
327 need to repair damaged armored segments (Gittman et al. 2014; Arkema et al. 2013). Avoiding  
328 shoreline armoring can also reduce risk for potential future residents by eliminating the reinforcing  
329 feedbacks that incentivize rebuilding and further new development behind armored infrastructure  
330 after disasters (Woodruff et al. 2018; Burby 2006).

331

332 As climate change and sea level rise increase in severity, coastal cities and states will need to look for  
333 ways to manage landscapes that reduce future liabilities (e.g., deteriorating and ineffective  
334 infrastructure) and maintain the benefits and amenities of natural ecosystems. Broader efforts to  
335 shift investments towards uses of natural infrastructure, such as using oyster beds for storm surge  
336 protection (NYGOSR 2020) or adopting green infrastructure for flood management (Carter et al.  
337 2018; Liu and Jensen 2018; Soz et al. 2016), attempt to create pathways towards preserving valuable  
338 natural amenities while simultaneously offering practical benefits. Recently, the U.S. Army Corps of  
339 Engineers has shifted towards a policy promoting the use of living shorelines (e.g., using natural  
340 materials for protective purposes), approving a Nationwide Permit (allowing expedited  
341 establishment) for living shorelines in early 2017 (USACE 2017).

342

343 CBRA's subsidy removal appears to be an effective, non-regulatory method for avoiding further  
344 development of natural shorelines and helping to maintain their amenities and protective qualities.

345 While other policy prescriptions, such as coastal zone management programs implemented by US  
346 states, have demonstrated efficacy at reducing shoreline armoring (Kittinger and Ayers 2010), these  
347 regulatory approaches may be more difficult to implement. Future research is needed to understand  
348 how state and local policies, such as coastal management programs or development incentives,  
349 might interact with CBRA to influence shoreline armoring. Policy alignment on the part of state and  
350 local governments that can further disincentivize investments in shoreline armoring may help avoid  
351 continued degradation of marine habitats and wildlife (Dugan et al. 2008; Gittman et al. 2016a),  
352 allow for the natural inland migration of coastal ecosystems (Gittman et al. 2016b), and preserve the  
353 amenity values of natural shorelines and beaches, which are the dominant attraction of most coastal  
354 states.

355 **Acknowledgements**

356 This paper is based upon work supported by the U.S. National Science Foundation under  
357 Geography and Spatial Sciences Grant No. 1660450 and Coastal SEES Grant No. 1427188. We  
358 would like to thank Terri Fish, Katie Niemi, and Dana Wright (USFWS), as well as Laura Moore  
359 (UNC) for their support and advice with this project.

360

361 **Author contributions**

362 T.B., N.K., and D.S. conceptualized the research objectives and questions. J.B., K.O., N.K., and  
363 T.B. contributed to the research design. J.B and K.O. collected and prepared data for analysis. J.B.  
364 led data analysis with input from all authors. J.B. led the writing of the manuscript, with substantial  
365 input, additions, and revisions from T.B., N.K., and D.S.

366

367 **Competing Interests**

368 “The authors declare that no competing interests exist.”

369

370 **References**

371

372 Arkema, Katie K., Greg Guannel, Gregory Verutes, Spencer A. Wood, Anne Guerry, Mary

373 Ruckelshaus, Peter Kareiva, Martin Lacayo, and Jessica M. Silver. 2013. "Coastal Habitats

374 Shield People and Property from Sea-Level Rise and Storms." *Nature Climate Change* 3 (10):

375 913–918. <https://doi.org/10.1038/nclimate1944>.

376 Armstrong, Scott B., Eli D. Lazarus, Patrick W. Limber, Evan B. Goldstein, Curtis Thorpe, and

377 Rhoda C. Ballinger. 2016. "Indications of a Positive Feedback between Coastal

378 Development and Beach Nourishment." *Earth's Future* 4 (12): 626–35.

379 <https://doi.org/10.1002/2016EF000425>.

380 Bagstad, Kenneth J., Kevin Stapleton, and John R. D'Agostino. 2007. "Taxes, Subsidies, and

381 Insurance as Drivers of United States Coastal Development." *Ecological Economics* 63 (2–3):

382 285–98. <https://doi.org/10.1016/j.ecolecon.2006.09.019>.

383 Bedsworth, Louise W., and Ellen Hanak. 2010. "Adaptation to Climate Change: A Review of

384 Challenges and Tradeoffs in Six Areas." *Journal of the American Planning Association* 76 (4): 477–

385 95. <https://doi.org/10.1080/01944363.2010.502047>.

386 Bilkovic, Donna Marie, Molly Mitchell, Pam Mason, and Karen Duhring. 2016. "The Role of Living

387 Shorelines as Estuarine Habitat Conservation Strategies." *Coastal Management* 44 (3): 161–74.

388 <https://doi.org/10.1080/08920753.2016.1160201>.

389 Bulleri, Fabio, and Maura G. Chapman. 2010. "The Introduction of Coastal Infrastructure as a

390 Driver of Change in Marine Environments." *Journal of Applied Ecology* 47 (1): 26–35.

391 Burby, Raymond J. 2006. "Hurricane Katrina and the Paradoxes of Government Disaster Policy:

392 Bringing About Wise Governmental Decisions for Hazardous Areas." *The ANNALS of the*

393 *American Academy of Political and Social Science* 604 (1): 171–91.

394 <https://doi.org/10.1177/0002716205284676>.

395 Carter, Jeremy G., John Handley, Tom Butlin, and Susannah Gill. 2018. "Adapting Cities to Climate  
396 Change – Exploring the Flood Risk Management Role of Green Infrastructure Landscapes." "  
397 *Journal of Environmental Planning and Management* 61 (9): 1535–52.  
398 <https://doi.org/10.1080/09640568.2017.1355777>.

399 Cummings, J. Bruce. 2006. "A Brief Florida Real Estate History." Appraisal Institute of West Coast  
400 Florida.

401 Currin, C A, W S Chappell, and A Deaton. 2010. "Developing Alternative Shoreline Armoring  
402 Strategies: The Living Shoreline Approach in North Carolina." In *Puget Sound Shorelines and*  
403 *the Impacts of Armoring-Proceedings of a State of the Science Workshop, May 2009*, edited by H  
404 Shipman, M.N Dethier, G Gelfenbaum, K.L Fresh, and R.S Dinicola, 91–102. U.S.  
405 Geological Survey Scientific Investigations Report.

406 Davis, Jenny L., Carolyn A. Currin, Colleen O'Brien, Craig Raffenburg, and Amanda Davis. 2015.  
407 "Living Shorelines: Coastal Resilience with a Blue Carbon Benefit." *PLoS ONE* 10 (11).  
408 <https://doi.org/10.1371/journal.pone.0142595>.

409 Dugan, Jenifer E., David M. Hubbard, Iván F. Rodil, David L. Revell, and Stephen Schroeter. 2008.  
410 "Ecological Effects of Coastal Armoring on Sandy Beaches." *Marine Ecology* 29 (s1): 160–70.  
411 <https://doi.org/10.1111/j.1439-0485.2008.00231.x>.

412 Fawcett, Tom. 2006. "An Introduction to ROC Analysis." *Pattern Recognition Letters* 27 (8): 861–74.  
413 <https://doi.org/10.1016/j.patrec.2005.10.010>.

414 Florida Geographic Data Library (FGDL). 2017. "Florida Parcel Data Statewide." Florida:  
415 University of Florida GeoPlan Center.

416 Gallagher, Justin, and Daniel Hartley. 2017. "Household Finance after a Natural Disaster: The Case  
417 of Hurricane Katrina." *American Economic Journal: Economic Policy* 9 (3): 199–228.  
418 <https://doi.org/10.1257/pol.20140273>.

419 Gittman, Rachel K., F. Joel Fodrie, Alyssa M. Popowich, Danielle A. Keller, John F. Bruno, Carolyn  
420 A. Currin, Charles H. Peterson, and Michael F. Piehler. 2015. "Engineering Away Our  
421 Natural Defenses: An Analysis of Shoreline Hardening in the US." *Frontiers in Ecology and the*  
422 *Environment* 13 (6): 301–307. <https://doi.org/10.1890/150065>.

423 Gittman, Rachel K., Charles H. Peterson, Carolyn A. Currin, F. Joel Fodrie, Michael F. Piehler, and  
424 John F. Bruno. 2016b. "Living Shorelines Can Enhance the Nursery Role of Threatened  
425 Estuarine Habitats." *Ecological Applications* 26 (1): 249–63.

426 Gittman, Rachel K, Alyssa M Popowich, John F Bruno, and Charles H Peterson. 2014. "Marshes  
427 with and without Sills Protect Estuarine Shorelines from Erosion Better than Bulkheads  
428 during a Category 1 Hurricane." <https://doi.org/10.1016/j.ocecoaman.2014.09.016>.

429 Gittman, Rachel K, Steven B Scyphers, Carter S Smith, Isabelle P Neylan, and Jonathan H  
430 Grabowski. 2016a. "Ecological Consequences of Shoreline Hardening: A Meta-Analysis."  
431 *BioScience* 66 (9). <https://doi.org/10.1093/biosci/biw091>.

432 Glavovic, Bruce C., and Gavin P. Smith. 2014. "Introduction: Learning from Natural Hazards  
433 Experience to Adapt to Climate Change." In *Adapting to Climate Change: Lessons from Natural*  
434 *Hazards Planning*, 1–38. New York: Springer.

435 Halverson, Jeffrey B. 2018. "The Costliest Hurricane Season in U.S. History." *Weatherwise* 71 (2): 20–  
436 27. <https://doi.org/10.1080/00431672.2018.1416862>.

437 Johnston, Sam A. 1981. "Estuarine Dredge and Fill Activities: A Review of Impacts." *Environmental*  
438 *Management* 5 (5): 427–40. <https://doi.org/10.1007/BF01866820>.

439 Kittinger, John N., and Adam L. Ayers. 2010. "Shoreline Armoring, Risk Management, and Coastal  
440 Resilience Under Rising Seas." *Coastal Management* 38 (6): 634–53.  
441 <https://doi.org/10.1080/08920753.2010.529038>.

442 Klotzbach, Philip J, Steven G Bowen, Roger Pielke, and Michael Bell. 2018. “Continental U.S.  
443 Hurricane Landfall Frequency and Associated Damage.” *American Meteorlogical Society*, 1359–  
444 1377. <https://doi.org/10.1175/BAMS-D-17-0184.1>.

445 Kunreuther, Howard. 2006. “Disaster Mitigation and Insurance: Learning from Katrina.” *The  
446 ANNALS of the American Academy of Political and Social Science* 604 (1): 208–27.  
447 <https://doi.org/10.1177/0002716205285685>.

448 Liu, Li, and Marina Bergen Jensen. 2018. “Green Infrastructure for Sustainable Urban Water  
449 Management: Practices of Five Forerunner Cities.” *Cities* 74 (April): 126–33.  
450 <https://doi.org/10.1016/j.cities.2017.11.013>.

451 NOAA. 2019. “Costliest U.S. Tropical Cyclones (Addendum).” Asheville, NC: NOAA National  
452 Centers for Environmental Information (NCEI).  
453 <https://www.ncdc.noaa.gov/billions/dcmi.pdf>.

454 NOAA (National Oceanic and Atmospheric Administration). 2018. “Environmental Sensitivity  
455 Index Maps and Data.” Silver Spring, MD: NOAA.  
456 <https://response.restoration.noaa.gov/resources/environmental-sensitivity-index-esi-maps>.

457 NYGOSR. 2020. “Learn More About the Living Breakwaters Project.” Governor’s Office of  
458 Storm Recovery. 2020. <https://stormrecovery.ny.gov/learn-more-about-living-breakwaters-project>.

460 Onda, Kyle, Jordan Branham, Todd K. BenDor, Nikhil Kaza, and David Salvesen. 2020. “Does  
461 Removal of Federal Subsidies Discourage Urban Development? An Evaluation of the US  
462 Coastal Barrier Resources Act.” *PLOS ONE* 15 (6).  
463 <https://doi.org/10.1371/journal.pone.0233888>.

464 Scyphers, Steven B., J. Steven Picou, and Sean P. Powers. 2015. “Participatory Conservation of  
465 Coastal Habitats: The Importance of Understanding Homeowner Decision Making to

466 Mitigate Cascading Shoreline Degradation.” *Conservation Letters* 8 (1): 41–49.

467 <https://doi.org/10.1111/conl.12114>.

468 Siders, A.R., and Jesse M. Keenan. 2020. “Variables Shaping Coastal Adaptation Decisions to

469 Armor, Nourish, and Retreat in North Carolina.” *Ocean & Coastal Management* 183 (January):

470 105023. <https://doi.org/10.1016/j.ocecoaman.2019.105023>.

471 Smith, Carter S, Rachel K Gittman, Isabelle P Neylan, Steven B Scyphers, Joseph P Morton, F Joel

472 Fodrie, Jonathan H Grabowski, and Charles H Peterson. 2017. “Hurricane Damage along

473 Natural and Hardened Estuarine Shorelines: Using Homeowner Experiences to Promote

474 Nature-Based Coastal Protection.” *Marine Policy* 81: 350–358.

475 <https://doi.org/10.1016/j.marpol.2017.04.013>.

476 Soz, Salman Anees, Jolanta Kryspin-Watson, and Zuzana Stanton-Geddes. 2016. “The Role of

477 Green Infrastructure Solutions in Urban Flood Risk Management.” Washington D.C: World

478 Bank. <https://openknowledge.worldbank.org/handle/10986/25112>.

479 Titus, J G, D E Hudgens, D L Trescott, M Craghan, W H Nuckols, C H Hershner, J M Kassakian,

480 et al. 2009b. “State and Local Governments Plan for Development of Most Land Vulnerable

481 to Rising Sea Level along the US Atlantic Coast\*.” *Environmental Research Letters* 4: 44008–

482 44015. <https://doi.org/10.1088/1748-9326/4/4/044008>.

483 Titus, James G., K. Eric Anderson, Donald R. Cahoon, Dean B. Gesch, Stephen K. Gill, Benjamin

484 T. Gutierrez, E Robert Thieler, and S. Jeffress Williams. 2009a. “Coastal Sensitivity to Sea-

485 Level Rise: A Focus on the Mid-Atlantic Region.” U.S. Climate Change Science Program.

486 U.S. Fish and Wildlife Service. 2019. “Digital CBRS Boundaries.” Coastal Barrier Resources System.

487 <https://www.fws.gov/cbra/maps/boundaries.html>.

488 USACE. 2017. "Nationwide Permit (54) Living Shorelines." US Army Corps of Engineers.

489 <https://www.nao.usace.army.mil/Portals/31/docs/regulatory/nationwidepermits/Nationwi>

490 de%20Permit%2054.pdf.

491 Woodruff, Sierra, Todd K. BenDor, and Aaron L. Strong. 2018. "Fighting the Inevitable:

492 Infrastructure Investment and Coastal Community Adaptation to Sea Level Rise: S.

493 Woodruff *et al.* : Coastal Community Trajectories and Sea Level Rise Adaptation." *System*

494 *Dynamics Review* 34 (1–2): 48–77. <https://doi.org/10.1002/sdr.1597>.

495