Coastal wetlands reduce property damage during tropical cyclones

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Edited by Catherine L. Kling, Cornell University, Ithaca, NY, and approved January 24, 2020 (received for review September 4, 2019)

Coastal wetlands dampen the impact of storm surge and strong winds. Studies on the economic valuation of this protective service provided by wetland ecosystems are, however, rare. Here, we analyze property damage caused by 88 tropical storms and hurricanes hitting the United States between 1996 and 2016 and show that counties with more wetland coverage experienced significantly less property damage. The expected economic value of the protective effects of wetlands varies widely across coastal US counties with an average value of about \$1.8 million/km^2 per year and a median value of \$91,000/km^2. Wetlands confer relatively more protection against weaker storms and in states with weaker building codes. Recent wetland losses are estimated to have increased property damage from Hurricane Irma by \$430 million. Our results suggest the importance of considering both natural and human factors in coastal zone defense policy.

ecosystem services | economic valuation | climate change

Traditional defensive measures against storm surge include building levees and sea walls. However, such structures can fail (1), and there are concerns about negative impacts of such structures on the local environment (2). Planners are looking at coastal wetlands as potential natural levees for storms due to their ability to reduce water velocity and wave turbulence (3). Moreover, wetlands accumulate sediments providing protection against rising sea levels and local subsidence (4, 5).

Policymakers are often skeptical about employing wetlands as storm buffers, and hesitant to preserve or restore wetland systems as part of a storm defense strategy. Previous work has focused on mechanisms by which wetland plants attenuate storm surge (3–7). Surprisingly few studies address the economic value of this protective service. These studies, which we build on, tend to be limited to a particular type of wetland, such as mangrove forests (8–11), a few specific disasters (8–10), or specific regions [i.e., certain tropical countries (8–11) and Louisiana (12–15)]. The exception is the influential US national study (16), which finds that 1 km^2 of wetlands produce on average \$3.3 million annually in storm protection services. However, this study is limited by the coarse data employed and imprecise measure of the storm impact region.

Here, we estimate the economic value of coastal wetlands in storm protection by analyzing all 88 tropical cyclones (of which 34 made landfall as hurricanes) impacting the counties along the entire Atlantic and Gulf Coasts of the United States between 1996 and 2016 (*SI Appendix*, Figs. S1 and S2). Tropical storms are defined as tropical cyclones with maximum sustained winds of 34 to 63 kt, while hurricanes are those with at least 64 kt (17). Among the 232 coastal counties experiencing at least tropical-storm–level winds, 203 experienced property damage at least once, and 38% of counties suffered damage when hit by tropical-cyclone winds (*SI Appendix*, Tables S1 and S2). Many tropical cyclones hitting the United States are below hurricane strength—the focus of most previous work (8–16). We show wetlands reduce property damage proportionately more at the lower end of the tropical cyclone classification scale, although the absolute magnitude of damage reduction is larger at the high end of the scale.

By using all of the tropical storms and hurricanes affecting the United States since 1996, when consistently defined county estimates of property damage become available, we avoid sample selection bias issues, whereby damage data were generally available earlier only for more destructive storms. Areas subject to flood risk in a county are more accurately estimated, based on local elevation data and detailed information on individual storm trajectories that more precisely spatially delineate storm paths and wind speeds at different distances and directions from the eye (see Fig. 1 for the example of Hurricane Katrina). Wetland coverage varies over time and space within a county due to natural or anthropogenic factors (2). It also effectively varies because each storm's flooding area is a function of 1) storm path and 2) wind intensity. State characteristics remaining unchanged over time and year-level economic shocks potentially influencing property damage are controlled by using a fixed-effects statistical framework.

Annual expected property damage caused by tropical cyclones depends on the following: first, the probability that a county experiences tropical cyclones of different wind velocities—the wind velocity, in turn, determines the area likely to be flooded by storm surge; second, the probability that, on experiencing a given wind speed, damage is nonzero. These relationships are described by the following:

$$\mathrm{E}(\mathrm{D}|X_{-v}) = \int P(D>0|v,X_{-v})E\left(D|v,X_{-v},D>0\right)f(v)dv,$$

where D represents a county's property damage when experiencing wind speed v during a tropical cyclone, $f(v)$ represents the

Significance

With rising sea levels and increasingly intense storms associated with climate change, there is substantial interest in alternative defensive measures for protecting low-lying coastal communities against coastal flooding. Coastal wetlands are known to dampen storm surge and wind impacts, but policymakers have doubts about employing wetlands as natural levees due to lack of empirical evidence of effectiveness. Using detailed geospatial data, we explore a comprehensive set of natural and human factors to examine the role of coastal wetlands in reducing tropical-cyclone–related property damage. Using all 88 tropical storms and hurricanes hitting the United States between 1996 and 2016, the expected economic value of the protective effects of wetlands is estimated for all counties along the Atlantic and Gulf Coasts.

Author contributions: F.S. and R.T.C. designed research, performed research, contributed new reagents/analytic tools, analyzed data, and wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

Data deposition: All data and code (csv files and Stata code) necessary for replication of the results in this paper have been deposited at GitHub, https://github.com/fangsun/wetland/tree/master/PNAS_wetland.

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This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1915169117/-/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.1915169117

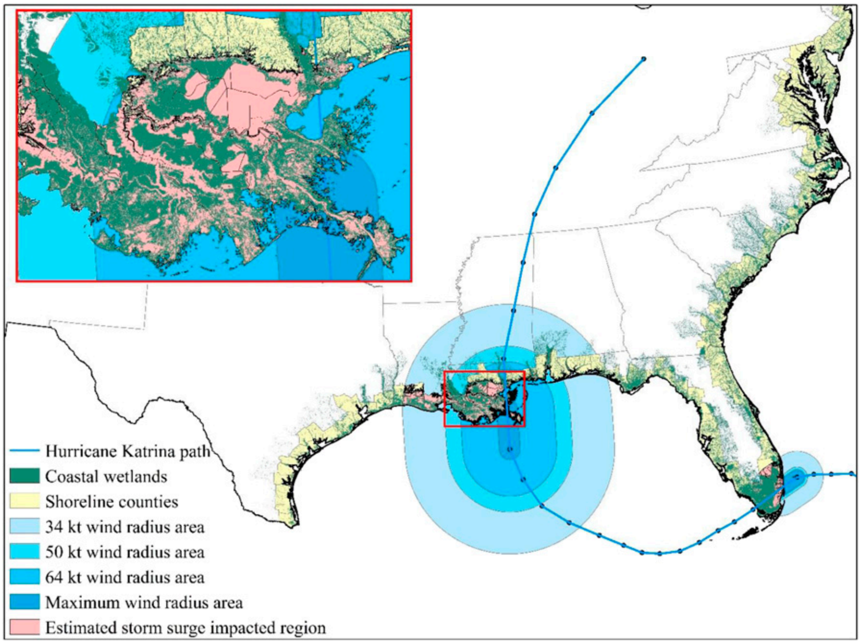

Fig. 1. Coastal wetland distribution and estimated storm surge area near Hurricane Katrina landfall.

annual probability of experiencing wind speed v, and X_{-v} represents other factors affecting property damage besides wind intensities. Applying the damage function approach developed by Barbier (11), coastal wetlands may influence property damage during storms in two ways: first, through the likelihood of a county experiencing damage in a storm surge; second, if damage occurs, the amount.

Results

Coastal wetland coverage is associated with statistically significant reductions in cyclone-related property damage. A loss of 1 km^2 of wetland coverage increases the predicted probability of experiencing property damage during storms by 0.02% ($P < 0.05$) in a county with the average wetland coverage, wind speed, and flooding area (*SI Appendix*, Table S3). For coastal communities suffering from property damage from a storm, a 1% loss of coastal wetlands is associated with a 0.6% increase in property damage ($P < 0.01$), controlling for storm-specific characteristics, property value under flooding risk, state-specific time-invariant determinants of property damage, and year-level shocks (Table 1 and *SI Appendix*, Fig. S3). Coefficient estimates of wind, potential storm surge area, property value under flooding risk, and being located to the right-hand of the storm path are positive and significant. The wind effect is particularly large (a 1% increase increases damage by 7%) and counties on the storm path's right side experience 140% ($P < 0.01$) more property damage than those on the left.

Coastal wetlands' protective effects are nonlinear in wind intensity, conditional on damage. This may be because once wetland vegetation is fully saturated with water, wave dissipation effects are weaker (18, 19). To detect this type of nonlinearity, wetland effects are decomposed by the wind speeds experienced by a county. Wetlands are effective against storms of all different magnitudes. The elasticity of property damage with respect to wetlands is −0.58 for a tropical storm (a 1% decrease in wetlands is associated with a 0.58% reduction in property damages), −0.55 for a category 1 hurricane, −0.40 for a category 2 hurricane, and −0.35 for a category 3 to 5 hurricane (Fig. 2*A* and *SI Appendix*, Table S4). This pattern is consistent with laboratory experiments (6). The preventative effect is especially strong for tropical storms, which happen twice as often as hurricanes. However, because property damage is rapidly increasing in storm strength, the absolute magnitude of damages prevented is predicted to be largest for major hurricanes.

Saltwater wetlands are located closer to the shore than freshwater wetlands (*SI Appendix*, Fig. S4), providing the first line of defense against storm surges. Nevertheless, freshwater wetlands typically have more coverage than saltwater wetlands, providing a wider buffer zone, as freshwater wetlands constitute about 85% of total coastal wetland coverage. We find significant reductions in property damage for both freshwater and saltwater wetlands. The difference between their contributions is small and not significantly different from zero (Fig. 2*B*; column 3 of Table 1). This is not surprising since storm surge can extend miles inland and encompass both types of wetlands.

Forested wetlands, having rougher woody vegetation, may provide a more effective buffer than emergent or scrub/shrub wetlands (5, 11, 14, 15). Costanza et al. (16) did not find significant evidence that forested wetlands reduced economic losses, perhaps due to data limitations. We find forested and nonforested wetlands play similarly protective roles (estimated elasticities are −0.58 and −0.56, respectively). We cannot reject the hypothesis that forested wetland reduces damage more than nonforested wetlands, as suggested by simulation studies (14, 15), although our result is consistent with that of Gedan et al. (5), who survey field observation studies and find mangroves and marshes confer comparable wave attenuation.

Coastal states take different strategies in terms of disaster relief and preparedness. Some adopt more stringent building codes, e.g., requiring building on stilts or setting a minimum construction elevation, while others do not. To investigate whether state-level policy factors induce heterogeneity in wetland protective effects, coastal states were separated into two groups based on being above or below the median assessment score for strictness of the residential building code and enforcement system (*Materials and Methods*). Virginia, Florida, South Carolina, and New Jersey rank as the top four states, while Texas, Mississippi, Alabama, and Delaware have no mandatory statewide building code directed toward storm damage prevention. Wetland effects on property damage reduction are significantly lower in states with

Table 1. Conditional damage model estimates

	(1)	(2)	(3)	(4)	(5)
	Log(damage)	Log(damage)	Log(damage)	Log(damage)	Log(damage)
Log(wetland)	−0.5756***	−0.5752***	−0.5805***	−0.5598***	−0.8055***
	(0.1840)	(0.1718)	(0.1836)	(0.1805)	(0.2029)
C1 hurricanes × log(wetland)		0.0261			
		(0.0769)			
C2 hurricanes × log(wetland)		0.1724*			
		(0.1029)			
C3-C5 hurricanes × log(wetland)		0.2251*			
		(0.1208)			
Saltwater wetlands × log(wetland)			0.0073		
			(0.0409)		
Forested wetlands × log(wetland)				−0.0198	
				(0.0390)	
Strict building code × log(wetland)					0.3011*
					(0.1545)
Log(wind)	7.1885***	6.4122***	7.1928***	7.1953***	7.1929***
	(0.5653)	(0.9744)	(0.5683)	(0.5668)	(0.5668)
Right	0.8821***	0.8749***	0.8828***	0.8880***	0.8825***
	(0.3129)	(0.3200)	(0.3147)	(0.3183)	(0.3128)
Log(storm area)	0.4793**	0.4767**	0.4811**	0.4595**	0.4558*
	(0.2249)	(0.2180)	(0.2248)	(0.2235)	(0.2293)
Log(property at risk)	0.3205***	0.3135***	0.3190***	0.3194***	0.3179***
	(0.0622)	(0.0599)	(0.0638)	(0.0624)	(0.0617)
Adjusted R^2	0.52	0.53	0.52	0.52	0.52

SEs (in parentheses) are clustered two ways at the county and storm levels. $n = 946$. All models include state and year fixed effects. $^*P < 0.10$, $^{**}P < 0.05$, and $^{***}P < 0.01$.

more stringent building codes and enforcement systems, suggesting that building codes are a partial substitute for wetlands in terms of storm protection (stricter code estimate, −0.50; less strict code estimate, −0.81), although wetlands still have a sizable effect even with stricter building codes (Fig. 2*D* and *SI Appendix*, Table S4).

The estimated storm protection effects of wetlands are broadly robust to the statistical model used (*SI Appendix*, Alternative Specifications; *SI Appendix*, Tables S5–S8) and do not change substantially when time trends are included instead of year fixed effects or whether the two largest disasters, Hurricanes Katrina and Sandy, are excluded. As additional robustness checks, we examine models that include different types of manmade storm defenses (levees, hard structures such as sea walls, and beach nourishment); different treatments of the property value at risk, which might be important due to the collapse of real estate markets during the Great Recession; and different substate regional indicator variables instead of state fixed effects. The

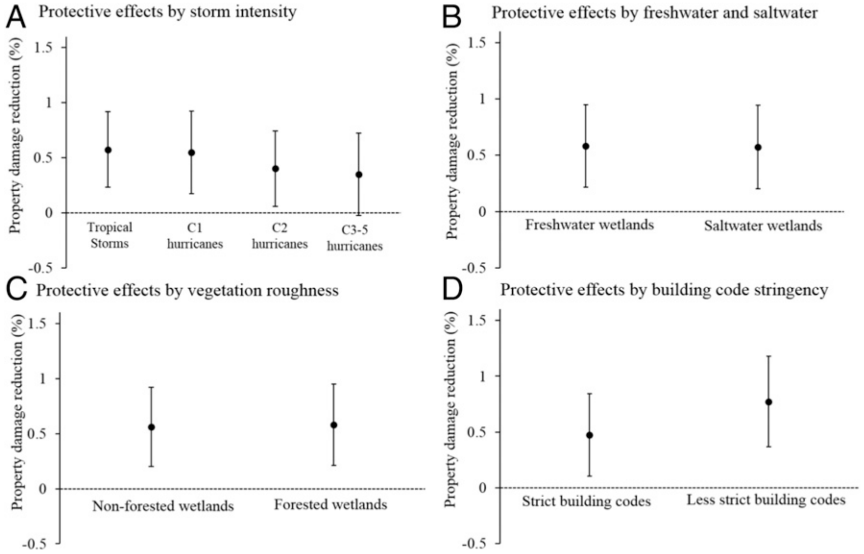

Fig. 2. Elasticity of property damage with respect to coastal wetland coverage by (*A*) storm intensity, (*B*) wetland type, (*C*) vegetation roughness, and (*D*) building code stringency. Each panel shows percent reduction (with 95% confidence interval) in property damage per 1% increase in wetland coverage. Regression coefficients correspond to models estimated in *SI Appendix*, Table S4, columns 2 to 5.

results of these models have estimated wetland impacts that are not statistically different from that of our primary specification.

We estimate the marginal value of coastal wetlands for storm protection for each shoreline county along the Atlantic and Gulf Coasts. Assuming the local probability of experiencing different tropical cyclone intensities provided in ref. 20 follows a gamma distribution, estimated annual marginal values range from less than \$800 to \$100 million per km^2, with an average of about \$1.8 million and a median value of \$91,000 (Fig. 3 and *SI Appendix*, Table S9). The heterogeneity in the storm protection value of wetlands (*SI Appendix*, Figs. S5 and S6) across counties is due to the property values at risk, local wetland coverage, coastline shape, local elevation, building codes, and the probability of experiencing different wind intensities. The low valued wetlands tend to be located in more rural, less populated counties, while the converse is true for more highly valued wetlands.

The marginal value of coastal wetlands for storm protection over a fixed time period, the relevant quantity for benefit–cost assessments involving development projects, can be estimated by discounting the future annual value of wetlands over the desired time frame assuming the current annual marginal value remains constant. Using a discount rate of 2.8% (21), expected storm protection services provided by 1 km^2 of coastal wetlands over a 30-y (100-y) period are on average worth about \$36 million (\$60 million). The median value is \$2 million (\$3 million).

Discussion

Estimates of the marginal economic value of wetland services in protecting property value can serve many purposes. Federal, state, and local agencies responsible for wetland management could employ our estimated expected marginal value when determining the amount and the optimal site of required compensatory mitigation. To achieve the goal of "no net loss" in both wetland acreage and function, section 404 of the Clean Water Act requires development projects that could have adverse impacts on wetlands to offset wetland loss by restoring, creating, enhancing, or preserving wetlands within the same watershed (22). To determine the amount of compensatory mitigation for each project, the Army Corps of Engineers conducts a case-by-case evaluation and sets a compensatory mitigation ratio. The expected marginal value of wetlands in reducing storm damages estimated in this study should be useful to a federal agency making such assessments, as well as serving as an input to risk models of the National Flood Insurance Program. One of our main findings is that location is a crucial factor in the storm protection services provided by wetlands. This should be accounted

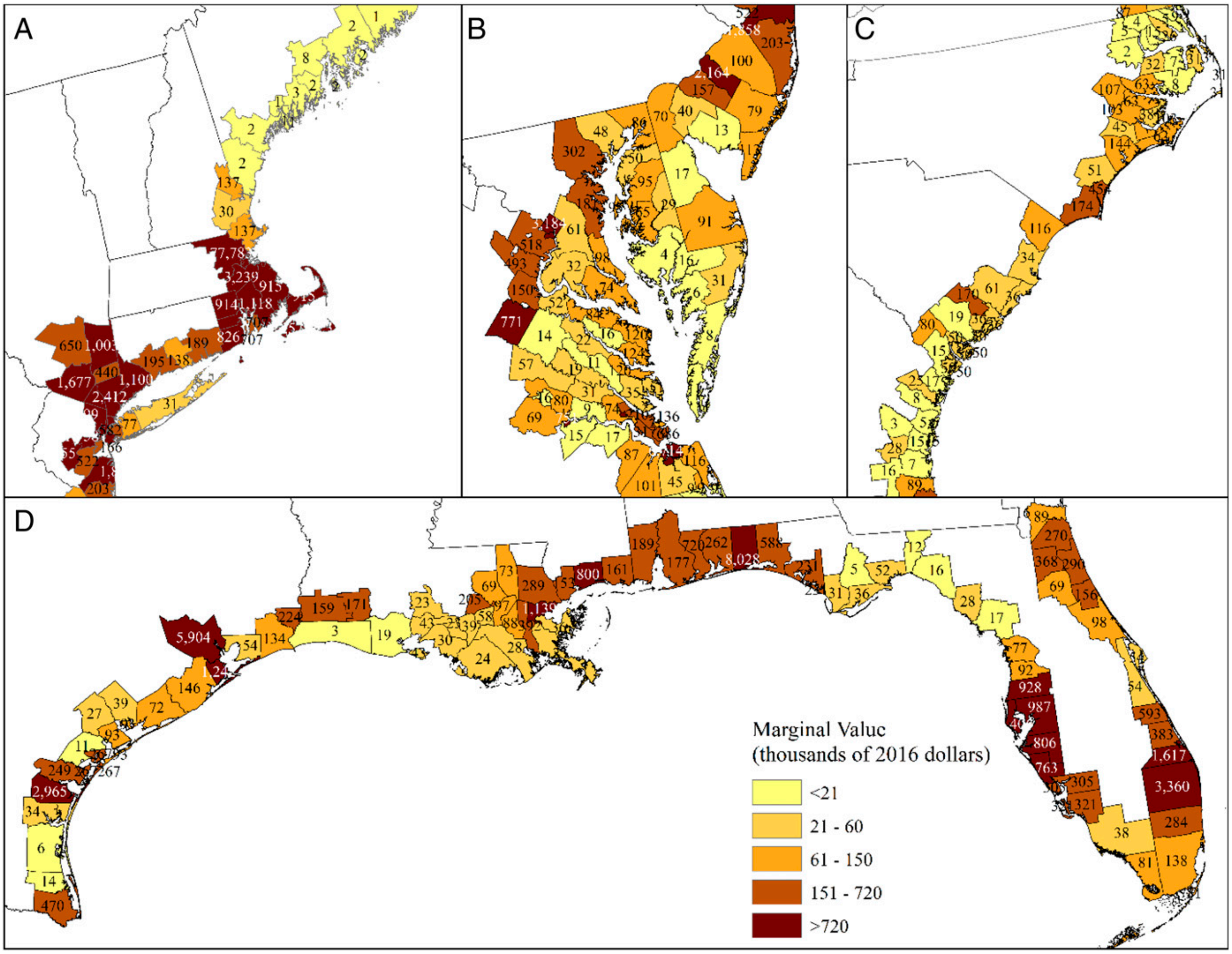

Fig. 3. Annual county-level marginal value of coastal wetlands for storm protection in (*A*) northeastern coastal counties, (*B* and *C*) eastern and southeastern coastal counties, and (*D*) coastal counties from Texas to Florida.

for when evaluating off-site compensatory mitigations since even relatively small differences in location between the wetlands lost and the new wetlands created can substantively influence the storm protection services provided. Furthermore, a replacement wetland may take decades to fully develop the functions provided by the original wetlands. The approach developed here, for a given discount rate, can be used to obtain a consistent estimate of the economic value of the storm protection service lost during the time it takes for the new wetland to fully reach the capacity of the lost wetland.

Our model can be used to estimate property damage under different wetland loss scenarios. To illustrate this use, we consider the question of how much property damage from Hurricane Irma, in 2017, which occurred just outside of our sample period, might have been prevented if there had been no loss of wetlands in Florida between 1996 and 2016. In the 19 coastal counties that experienced tropical-storm–level wind speeds when Hurricane Irma made landfall, wetland coverage was reduced by 2.8% between 1996 and 2016. Absent this reduction in wetlands, we estimate property damage in these counties would have been lower by about $430 million (*Materials and Methods*). This is substantial for a single storm. For comparison, the Federal Emergency Management Agency spent $10 billion on preventative hurricane, storm, and flood mitigation programs from 1989 to 2017 (23). This suggests that wetland preservation is likely to be a comparatively effective way of protecting coastal communities against tropical cyclones. Restoring wetlands may also be a cost-effective policy, but that action needs to consider the time path noted earlier for such wetlands to provide storm protection services. The interaction between building codes, restrictions on building in high-risk locations, and wetland coverage locations deserves further attention from a policy perspective.

Our model can also be used to predict the storm protection value of coastal wetlands in the context of different climate change scenarios. This can be done in a straightforward manner for the winds associated with tropical cyclone activity by simply replacing the actual wind distribution at each location with the forecast wind distribution based on a particular climate change scenario and reintegrating property damages estimates over the desired spatial locations and time frame. It is also possible to use our model to look at the interaction between changing sea levels and wetlands in coastal counties by holding the estimated parameters constant and substituting in a new detailed topographic map of areas at risk under different storm conditions. With projections of rising sea levels and increasingly intense storms associated with climate change (24), low-lying coastal communities are likely to become more vulnerable to flooding. Model-based estimates can be calculated for the economic value of preventing future property damage under specific climate change and mitigation scenarios under different assumptions about wetland coverage.

It is important to recognize storm protection for property is just one of the ecological services that wetlands provide. Other ecosystem services delivered by wetlands include habitat for fish and wildlife; filtration of industrial, residential, and agricultural runoff; outdoor recreational opportunities; and carbon sequestration—all of which we do not value here. These services are at the heart of the current controversy over the US Clean Water Act (22, 25). While we have provided comprehensive estimates for a major component of wetland services, having values for the entire suite of these services is needed for effective policy decisions (26), particularly when unmonetized benefits of wetland services are likely to be ignored.

Materials and Methods

Data. Information on data sources can be found in *SI Appendix*, *Data*.

Data Availability. All data and code necessary for replication of the results in this paper are available for download at GitHub.

Construction of Potential Flooding Area for Each Storm. For each tropical cyclone, the maximum sustained wind speed experienced by each affected county was estimated based on distance from the storm center and the radii of different wind intensities. Potential flooding areas for each tropical cyclone wind category are estimated based on local elevation since inland penetration of storm surge is highly dependent on local topography. For each county, we map the area below each elevation from 0 to 8 m in 0.5-m increments. We then compare the area with the Storm Surge Inundation Map developed by National Oceanic and Atmospheric Administration Map (27), which provides the flooding inland extent for different hurricane categories based on simulated storms, taking into account local topography, elevation, and other environmental features. We select the elevation for which these two maps coincide the closest. For tropical storms and category 1 hurricanes, we select locations with elevation below 1 to 1.5 m as the potential flooding areas. For category 2 to category 5 hurricanes, we choose elevations ranging from 2 to 8 m to create the flooding areas. The estimated storm surge impact region for a specific storm is the intersection of the potential flooding areas and the areas exposed to at least tropical storm strength wind. The property value at risk for flooding is the value of total housing, estimated based on US Census Bureau block group housing value data, within the flood risk area.

Regression Models. To estimate the marginal effects of coastal wetlands in storm protection along both the extensive and intensive margins, we employ a Cragg lognormal hurdle model (28, 29) that consists of two parts: a probit model estimating whether coastal wetlands reduce the likelihood that a county experiences damage in a storm, and a conditional damage model estimating to what extent coastal wetlands reduce property damage when damage occurs. The two models can be expressed as follows:

$$P(damage_{csht} > 0|X) = \Phi(\gamma_0 + \gamma_1 wetland_{csht} + \gamma_2 wind_{csht} + \gamma_3 stormarea_{csht} + \gamma_4 riskproperty_{csht} + \gamma_5 right_{csht} + \eta_{csht}), \quad [1]$$

$$\ln(damage)_{csht} = \beta_0 + \beta_1 \ln(wetland)_{csht} + \beta_2 \ln(wind)_{csht} + \beta_3 \ln(stormarea)_{csht} + \beta_4 \ln(riskproperty)_{csht} + \beta_5 right_{csht} + \gamma_s + \lambda_t + \varepsilon_{csht}, \quad [2]$$

where $damage_{csht}$ is the property damage caused by tropical cyclone h in year t in county c of state s, and X is a vector of all of the regressors in the probit model. $wetland_{csht}$ is the coastal wetland area in county c within the estimated storm surge impact region of storm h, $wind_{csht}$ is the maximum sustained wind speed experienced by the county, and $stormarea_{csht}$ is the area of each county within the potential storm surge impact zone. $riskproperty_{csht}$ controls for the total property value under the risk of coastal flooding for each county. Counties with more property value within the potential flooding areas are likely to experience greater losses because the property to be potentially destroyed is of greater value. To control for the location of a county relative to the storm track, an indicator variable, $right_{csht}$, is included in the model. $right_{csht}$ equals 1 if a county is located to the right of the storm path, and 0 otherwise. Coastal flooding impacts are expected to be greater on the right side of the storm path since tropical cyclones rotate counterclockwise in the Northern Hemisphere with strong winds pushing water onshore to the right of the storm path, while blowing water away from the coast to the left (30). γ_s is a state fixed effect, which captures state-specific characteristics that are fixed across time. One example is the shape of the coastline of each state, which is relatively stable over time—a state with a coastline curved inward may experience higher surge levels (thus, more damage) when a tropical cyclone makes landfall, compared to states with a convex coastline (31). γ_s also includes factors such as each state's historical exposure to storm surges and residents' culture and attitudes toward storms. λ_t is a year fixed effect, which mainly picks up year specific factors that affect all counties in the United States. η_{csht} and ε_{csht} are error terms, which capture random components with limited long-term forecast in advance such as tides, very specific storm track, wind gusts, and rainfall. β_1 is the coefficient of interest, which captures the elasticity of storm damage to existing wetland coverage when a county suffers from positive property damage.

Our model relies on estimation techniques designed for panel data. With panel data, one needs: a long enough time dimension; a large enough number of units along the individual unit or spatial dimension; and for the product of these two dimensions, the number of individual observations, to be reasonably large. When either dimension gets to be too small, key statistical quantities of interest, and particularly fixed effects, are unreliably estimated in the specific sense that they are not consistent estimates of quantities. Our number of individual observations is more than 900, and substantially larger than that used in past studies. Our number of time periods, 21 y, is also larger than that in many environmental impact studies using panel data. Less obvious is the fact that our panel dataset is unbalanced. In the conditional damage model, an observation is only generated if tropical storm winds hit a particular county. Because we have far more tropical storms than previously used and these storms often hit multiple states, there are plentiful observations to get consistent state-level fixed effects for all of the states hit except for New Hampshire, Maine, and Connecticut, which were not hit by many storms. However, this is not the case for individual counties. Forty counties were hit only once. Adding county-level fixed effects causes these counties to drop out of the sample because the fixed effect is effectively equal to the residual. There are another 64 counties that are hit twice. The county fixed-effect estimate for these counties is unreliable as it is simply the average of the two residuals for that county. It is only when the number of observations on which the fixed effect is based gets reasonably large that fixed-effect estimates become well defined with the signal clearly standing out from the noise of the error term. Alternative specifications using county-level and substate-level fixed effects defined in two different ways are explored in *SI Appendix*, Alternative Specifications, State-level and Sub-State-level Fixed Effect Models.

Potential Endogeneity. The main source of random variation that statistically identifies the impact of wetlands in storm protection is the storm-specific track for each tropical hurricane. Each storm track (including specific path, radius, and intensity) puts a different set of wetlands, even within the same county in the same year, into play exogenously and at different intensity. This means that, even for the same property, if a storm of a specified intensity approaches from a different angle or the track shifts a mile or two in one direction, there might be a different set of wetlands providing protective services. Exogeneity follows from the assumption that, at the time a particular storm track becomes manifest, the structures at risk have already been built and any wetlands providing protective services are in place. The identifying assumption is that, unlike say a localized pressure zone in front of a storm, which can shift its track, the configuration of wetlands in front of a storm does not influences its exact path up until the time the storm hits that area. It is important to recognize that this source of identifying variation does not allow us to address the issue of how the structures came to be located where they are at the time a tropical storm threatens the area. Hence that question is not the subject of investigation in this paper.

In addition to exploiting random variation in storm tracks, there is also variation in $wetland_{csht}$ that comes from two other sources: 1) natural processes such as sunshine, precipitation, nutrition in the water, and coastal erosion, which all can influence wetland distributions; 2) human activities including constructing structures, dredging, filling wetland, and building canals and levees. These alterations to the hydrologic systems influence the amount of sediments and nutrition brought to wetlands, thus influencing wetland productivity. (1) is due to exogenous natural factors; endogeneity concerns are therefore focused on (2). There may be concern that there are places where wetlands are being drained on a large scale to build structures. While this did take place in the more distant past, it is not a major issue in the wake of the 1988 Bush Administration "no net loss" of wetland coverage and function policy. To achieve this goal, the Environmental Protection Agency (EPA) finalized the Clean Water Act section 404 and required permits for projects with potential negative impacts on wetlands. Furthermore, the 1990 Memorandum of Agreement between the EPA and the Department of the Army established a three-part process, the mitigation sequence, that must be followed to offset impacts to wetlands (32). The import of these regulations during our study period (1996 to 2016) is that while there is some amount of building of new structures on wetlands in coastal areas, they almost always involve at most a small number of structures and the restoration of a close-by wetland within the same watershed. Some states are better at enforcing laws with respect to wetland loss, but this is picked up in state fixed effects. National enforcement efforts have some variation over time, but this is picked up in year fixed effects.

The potential for endogeneity naturally arises in any consideration of property damage, due to moral hazard and other concerns. This is largely due to locational and insurance decisions. However, the housing units at risk have already been built at their particular location when a storm strikes; each tropical cyclone's path is exogenous, providing the randomly assigned wind treatment. In addition, our damage measure includes total losses, not just insured losses, and there are reasons to expect the two measures to be quite different—for example, the probability of households in areas at high risk of coastal flooding having flood insurance was found to be only about 63% (33). Furthermore, the government strongly favors an ex post response to property damage, even though ex ante actions are considerably more effective, a contradiction largely driven by political considerations (23).

Another possible source of possible endogeneity is that units in areas at high risk of being hit by tropical cyclones may be better built or located in areas that are better protected by wetlands and other natural defenses against storm surge and flooding, although ex ante the opposite scenario is also plausible. To a large extent, this should be captured by the property value at risk. Also, state fixed effects capture time-invariant state-level factors influencing damages. The model results shown in *SI Appendix*, Table S6, column 2, go even further by including county level fixed, suggesting that, if anything, our main estimates for the marginal value of wetlands may be underestimated.

Marginal Value of Wetlands in Storm Protection. Let D_{csht}, W_{csht}, V_{csht}, S_{csht}, P_{csht}, and R_{csht} refer to $damage_{csht}$, $wetland_{csht}$, $wind_{csht}$, $stormarea_{csht}$, $riskproperty_{csht}$, and $right_{csht}$, and let α stand for $\beta_0 + \gamma_s + \lambda_t$. Based on the conditional damage model, the expected damage to a county when the wind speed is v, conditional on experiencing property damage, will be (omitting subscripts):

$$\mathrm{E}(\mathrm{D}|\mathrm{v}, X_{-v}, \mathrm{D}>0) = W^{\beta_1} v^{\beta_2} S^{\beta_3} P^{\beta_4} \mathrm{e}^{\alpha} E(\mathrm{e}^{\varepsilon}). \qquad [3]$$

The underlying statistical framework here is a survival model where the expected value depends on both the estimated regression parameters and the estimated variance. There are two standard approaches to obtaining the estimate of $\mathrm{E}(e^{\varepsilon})$. First, we can assume the residuals are normally distributed, effectively treating the regression model as the maximum-likelihood estimator, which can be sensitive to outliers. Second, we can estimate this quantity by bootstrapping the empirical residual distribution of the observed data. This latter approach is more flexible and, in this instance, more conservative. It produces an estimated value of 10.81 for $\mathrm{E}(e^{\varepsilon})$, and estimates of marginal wetland values that are 17% lower than those obtained under the assumption that the error terms are normally distributed. We report the more conservative estimates. The annual expected property damage due to tropical cyclones to a shoreline county can be calculated by integrating the expected property damage over all of the possible storm wind speeds that could affect the county:

$$\mathrm{E}(\mathrm{D}|X_{-v}) = \int E\left(D\middle|v, X_{-v,} D>0\right) P\left(D>0\middle|v, X_{-v,}\right) f(v) dv. \qquad [4]$$

The marginal value of wetlands in storm protection will be $\partial \mathrm{E}(\mathrm{D}|X_{-v})/\partial W$, which can be expressed as follows:

$$\int \left[\frac{\partial E(D|v, X_{-v}, D>0)}{\partial W} P(D>0|v, X_{-v}) + \frac{\partial P(D>0|v, X_{-v})}{\partial W} E(D|v, X_{-v}, D>0)\right] f(v) dv. \qquad [5]$$

This can be estimated using the expression:

$$\int \hat{D}\left(\frac{\widehat{\beta_1}}{W} P\left(\widehat{D>0}|v, X_{-v}\right) + \frac{\partial P\left(\widehat{D>0}|v, X_{-v}\right)}{\partial W}\right) f(v) dv, \qquad [6]$$

where $\hat{D}$ is the predicted property damage when county c experiences a storm with wind speed v based on the estimation results of the model in Eq. **2**. In a few instances, the predicted value exceeds total property value under risk. To control the overprediction problem, $\hat{D}$ is capped by the total property value under flooding risk for each wind category. $P(\widehat{D>0}|v, X_{-v})$ and $\partial P(\widehat{D>0}|v, X_{-v})/\partial W$ are the predicted likelihood of a county experiencing damage when hit by wind velocity v and the estimated marginal effect of wetlands in reducing the probability of suffering property damage based on the estimation results of the model in Eq. **1**.

The annual distribution of wind speeds projected for each county from ref. 20 is assumed to follow a gamma distribution, and we impose 152 kt as the upper bound wind force (strongest wind speed recorded post World War II in the United States, which was during Hurricane Camille in 1969). The Landfalling Hurricane Probability Project estimated the probability of one or more events bringing three wind intensities, i.e., $P(v \geq 34\ \mathrm{kt})$, $P(v \geq 65\ \mathrm{kt})$, and $P(v \geq 100\ \mathrm{kt})$, for 11 coastal regions covering all counties in our analysis. These 11 coastal regions group counties based on the frequency of major hurricane landfalls from 1900 to 1999. For each region, using these points on the cumulative distribution function of wind speeds, the parameters of the best fit gamma probability distribution function of wind speeds are backed out using the minimum distance estimation method (34). The *R*-squared reported is the average over regressions from 11 different wind regions (20). As a robustness check, Weibull and log-normal distributions are fit for each county as well. These have slightly lower R^2 compared with that of the gamma distribution and generate similar estimates for the marginal value of wetlands (*SI Appendix*, Table S10).

The annual expected property damage due to tropical cyclones to a shoreline county can be calculated by integrating the expected property damage over all of the possible storm wind speeds that could affect the county. It would be straightforward to use alternative projections for future wind intensities in the modeling framework put forward here.

The marginal value of coastal wetlands across time is estimated by discounting the future annual value of wetlands to the current period. Assuming that the annual marginal value of wetlands for storm protection stays the same in the future, then the formula can be expressed as follows:

$$\sum\nolimits_{t=0}^{T}\frac{1}{(1+r)^{t}}\frac{\partial E(D|X_{-v})}{\partial W}, \qquad [7]$$

where *r* is the discount rate and *t* refers to year.

Wetland Loss in Florida and Hurricane Irma. The expected change in property damage can be forecasted under different wetland loss scenarios for a given storm. Hurricane Irma made landfall in Florida on September 10, 2017, as a category 4 hurricane (35) and influenced 19 coastal counties at its landfall locations (*SI Appendix*, Fig. S7). Since the storm path and wind speed radius data from refs. 36 and 37 have not been updated, we estimated wind intensity experienced by each affected county using Hurricane Irma Advisory Archive data from the National Hurricane Center (35). We used our usual methodology for the remaining explanatory variables. Total property damage caused by Hurricane Irma is also not yet known; therefore, we predict it using the model for two different scenarios: first, using 2010 coastal wetland coverage; second, using coverage in 1996, that is, assuming no loss. From 1996 to 2010, the total wetland coverage within the potential flooding area was reduced by about 500 km^2 (from 17,900 to 17,400 km^2), a loss about 2.8% of wetland coverage in 1996. The forecasted property damage is \$19.07 billion based on the wetland coverage in 1996 and \$19.50 billion based on the wetland coverage in 2010. Thus, our model predicts that property damage caused by Irma would have been reduced by \$430 million, if the 500 km^2 of wetlands lost between 1996 and 2010 had been maintained.

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