Potential for Error in Valuing Ecosystem Services Using the Expected Damage Function Approach

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Selected Paper prepared for presentation at the Southern Agricultural Economics Association's 2015 Annual Meeting, Atlanta, Georgia, January 31-February 3, 2015

ABSTRACT

Communities along the US coast are highly vulnerable to coastal storms. Trends in population growth, climatic events and land use are likely to exacerbate future damages. Coastal management entities are faced with decisions about how to manage resources in a manner that improves environmental quality and provides the maximum benefit for coastal populations. This is particularly true along the coast of the Gulf of Mexico, where coastal storms are common, land loss is rapid and billions of dollars are allotted for coastal restoration projects. Many of these projects are intended to mitigate hurricane damages by using wetlands as storm buffers. The physical science literature shows that wetlands do provide situational protection from storm surge. However, little economic analysis has explored the effect of wetlands on economic losses. This analysis uses hurricane simulation data to estimate county- or parish-level damages based on observed damages from coastal storms making landfall in Louisiana from 1995-2008. A model describing these damages as a function of wetland area, socio-economic conditions and storm intensity allows the estimation of the value of wetlands for their protective ecosystem services under various contexts and future scenarios. Potential sources of error are discussed and examples are analyzed. The implications of these finding are significant for coastal restoration decisions in a changing environment.

Key Words: wetlands, hurricanes, economic damage, resilience, expected damage function

JEL Classifications: Q24, Q54, Q56, Q57

INTRODUCTION

Wetland ecosystems are valuable resources for coastal populations. Increasingly, research has focused on valuing the benefits, or ecosystem services, provided by wetlands so that environmental costs and benefits can be more directly considered along with financial costs and benefits of policy decisions. Among the most valuable ecosystem services provided by coastal wetlands is their capacity to attenuate wave energy, which makes them valuable for erosion control and storm damage mitigation (Augustine, et al. 2009). Despite many large scale wetland construction and restoration projects currently ongoing or being planned in order to provide these benefits (CPRA 2012), very little research has been conducted that describes the value of wetlands for their damage mitigating functions, so the benefits that can be expected from many of these projects in terms of reduced economic damages are unknown.

There are several factors that have limited the feasibility or validity of economic analyses that attempt to value the damage mitigation provided by coastal wetlands. Reliable estimates of economic damage from hurricanes and tropical storms are scarce and have the potential to be inflated, particularly when estimates are generated for insurance claims or disaster relief. The consistent damage data that does exist is generally provided at a scale that does not permit the analysis of the effect of local wetland processes on local damages. Analysis of these local processes requires extensive physical science modeling of the effect of wetlands on surge inundation in order to estimate the monetary damage that was (or would be) avoided due to wetland presence. This can be done (Barbier et al. 2013), and it is a valid approach for valuing specific projects. But, the resources required for such analysis are not always available and value estimates are of this type are not applicable beyond the local focus of the research.

Recent research has made promising improvements in the practice of valuing environmental features for their damage mitigation potential. Referred to as the expected damage function approach (EDF), this method measures the effect of wetlands on economic damages by valuing wetlands as an input in the production of damages (Barbier, 2007). First used by Farber (1987), this method has reemerged as a more viable methodological option because of increased data quality and availability. Additionally, recent highly damaging natural disasters, including the 2004 Indian Ocean tsunami, the 2005 Atlantic hurricane season and Hurricane Sandy, have renewed interest in utilizing natural coastal features that provide protection against flooding.

Three notable attempts have been made to value wetlands using the EDF approach. Barbier (2007) measured the effects of mangrove forests on tsunami damages in Thailand. In that research, the estimated annual cost (in terms of increased vulnerability to damage) of mangrove deforestation was estimated to be $3.4 million (1996 USD) across the Thai coast (Barbier, 2007). Similarly, Costanza et al. (2008) created a hurricane damage function that describes damages as a function of wind speed and wetland area and monetize the coefficient estimate for the wetland variable to estimate the mitigation potential for a unit of wetland. This research estimated the average annual per hectare (ha) value of coastal wetlands to be $1,700 across the East and Gulf coasts, with a large range of $126 (Louisiana)- $586,000 (New York) (2004 USD). This large range is a result of differences in the effect of wetlands depending on the frequency with which storms impact an area, the value of assets that are vulnerable to damage and the degree to which wetlands protect those assets (Costanza et al. 2008).

A similar result was found by Boutwell and Westra (2015), who found that wetlands were more valuable where they are most scarce, suggesting that wetlands, as a damage mitigation measure, exhibit diminishing marginal productivity. Those results showed that the average value of wetlands across the northern Gulf coast to be approximately $26,000 (2010 USD) per hectare per kilometer of coast for a given storm, which corresponds to an annual value of approximately $200 per hectare. Subsequent analysis noted that, for counties/parishes with fewer wetlands, the estimated per unit value of those wetlands is significantly greater than the value estimated for wetlands in areas with extensive wetlands. For counties/parishes with less than the median relative area of wetlands, the estimated average reduction in damages was $194,000/ha/km of coast for a given storm (corresponding to an annual value of nearly $1,500 per hectare). The estimated value of wetlands for the subset of data greater than the median relative wetland area was not statistically different from zero. This does not indicate that wetlands do not mitigate damage, but additional wetlands do not further mitigate damages in the subsample with extensive wetlands. In this case, diminishing marginal productivity refers to the notion that increasing the size of a wetland increases the protection provided, but that each additional increase in wetlands adds less protection than the increase before until there is no additional protection provided. While changes in wetland area seriously impact the vulnerability of some communities, others would not be significantly impacted by the same change because the wetland system is already providing protection at the capacity of that system (Boutwell and Westra, 2015).

These results suggests that there are extreme differences in the potential benefits that are provided by wetlands in terms of damage mitigation. An important consideration is that coastal wetland systems vary greatly across the country. It may not be appropriate, for example, to include data from North Carolina and Louisiana in the same analysis of the impacts of wetlands on economic damage because the coastal systems are very different in these states. Even along the northern Gulf coast, there exists a high degree of heterogeneity across the coastal landscape.

This paper demonstrates the potential of the EDF approach for valuing the damage mitigation ecosystem services provided by coastal wetlands. This analysis improves on previous analyses by significantly reducing the spatial resolution of analysis by deriving county- and parish- level damage estimates using hurricane model simulation data. This research also explores how coastal systems differ in how they utilize wetlands to mitigate damages and the implications of those differences for ecosystem valuation. To illustrate the potential for dissimilarities in the relationship between wetland systems and damages between one region and another, models are generated using varying constructs of wetlands for the northern Gulf coast and for Louisiana alone. The differences in the coefficient estimates between these models highlight the importance of local considerations in modeling coastal systems.

METHODOLOGY

Using data that describe population, wind speed, wetland size and economic damages, an expected damage function is estimated using nonlinear least squares estimation. The data include all counties/parishes in the geographic area from Matagorda County, Texas to Okaloosa County, Florida that were impacted by a tropical storm or hurricane between 1995 and 2008. The model is estimated a total of four times using different measurement approaches and different geographical areas. Each model is estimated using the identical functional form. The model used is

$$\log(y) = \alpha\, x_1^{\beta 1}\, x_2^{\beta 2}\, x_3^{\beta 3}$$

where y is economic damages in a county or parish, x_1 is maximum sustained winds in the event for a county/parish, x_2 is the relative area of wetlands in a county or parish, x_3 is a population variable, the βs are coefficients of their respective variables and α is a constant intercept term.

The advantage of this form over a simple linear model is that the marginal effects can vary throughout the data. Because the effect of wetlands on storm surge or damages has been shown to differ under storms of varying intensity (Wamsley et al. 2010; Boutwell and Westra, 2014), for varying coastal population sizes (Costanza et al. 2008) and for varying wetland characteristics (Barbier, 2013; Boutwell and Westra, 2015) allowing the relationships between variables to vary accordingly improves the fit of the model. Additionally, including a single coefficient for each variable produces results that are simple to interpret and compare between models.

Data for economic damages were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC). These data include reported damage estimates for infrastructure (utilities, roads, etc), buildings (residential and commercial) and agriculture (row crops only and livestock only). Damage estimates are typically reported at a regional scale, so each damage estimate encompasses multiple counties/parishes. Damage estimates were estimated at the county scale using hazus (hazards US) model simulations. The hazus model is a model used by the US Federal Emergency Management Agency (FEMA) to predict hurricane damages based on the physical characteristics that influence storm surge inundation and the composition of vulnerable assets within a potentially inundated area. Data used for this analysis are available from the FEMA region IV coastal flood loss atlas (Longnecker, 2011). The raw damage estimates were applied to the county/parish scale according to the proportion of damages incurred by that parish in hazus model simulations for comparable storms. Data for population and wind speed were obtained from the US Census Bureau and the National Hurricane Center (NHC), respectively.

The data used to characterize the degree of protection provided by wetlands were collected using a geographic information system (GIS), ArcGIS. Data describing wetland type, as classified by Cowardin, et al (1979), were downloaded from the US Fish and Wildlife Service (FWS) and overlaid with US county/parish maps. The FWS data files were developed between 2002 and 2007 (Stout et al. 2007). Consistent land cover data are not available for each of the years necessary to provide each sample with the data from the year of the respective storm. Raw area estimates were obtained by manually delineating boundaries for each parish using U.S. Census Bureau parish shapefiles and extracting all data features that are identified by FWS code as either "marine deepwater wetland" or "estuarine marine wetland". The acre values for these features were then independently summed to yield an estimate for each wetland classification within each county/parish (including marine wetlands immediately seaward of a respective political boundary).

Because these wetlands occur exclusively along the coast, parishes with longer coastlines are expected to have a larger area of coastal wetlands. It can also be expected that parishes with longer coastlines have greater geographic exposure to waves and storm surge. This transitively implies that areas with larger areas of coastal wetlands should experience more exposure to waves and storm surge and, therefore, more storm damage. Such an implication is an artifact of the nature of the political boundaries used in this analysis. To account for this, the wetland variable is divided by the length of coastline for each county/parish. This variable is referred to as "relative wetland size" here forth.

The wetland classifications are summarized, according to Cowardin et al. (1979), as:

Estuarine Marine Wetlands:

> "…consists of deepwater tidal habitats and adjacent tidal wetlands that are usually semi enclosed by land but have open, partly obstructed or sporadic access to the open ocean, and in which ocean water is at least occasionally diluted by freshwater runoff from the land. The salinity may be periodically increased above that of the open ocean by evaporation. Along some low-energy coastlines there is appreciable dilution of sea water. Offshore areas with typical estuarine plants and animals, such mangroves and oysters are also included in the estuarine system."

Marine Deepwater Wetlands:

> "…consists of the open ocean overlying the continental shelf and its associated high-energy coastline. Marine habitats are exposed to the waves and currents of the open ocean and the water regimes are determined primarily by the ebb and flow of oceanic tides. Salinities are high, with little or no dilution except outside the mouths of estuaries. Shallow coastal indentations or bays without appreciable freshwater inflow, and coasts with exposed rocky islands that provide the mainland with little or no shelter from wind and waves are also considered part of the marine system because they generally support typical marine biota."

Using this data, four damage functions are estimated. The first and second models, model 1 and model 2, will be derived from data that include all counties/parishes in the data along the northern Gulf coast. Model 1 is estimated using a relative wetland size variable that includes only the estuarine marine wetland classification and model 2 is estimated using a variable that includes both the estuarine marine classification and the marine deepwater wetland classification.

Model 3 and model 4 are estimated in a similar fashion with model 4 including both classifications and model 3 including only the estuarine classification, but using data from parishes in Louisiana only. Comparing results from these models will illustrate how the EDF approach is vulnerable to error stemming from imperfectly constructed measurements of the ecosystem feature of interest – in this case, coastal wetlands.

RESULTS

The results from model 1 (which includes the entire dataset and the estuarine classification) are shown in Table 1. All variables have coefficient estimates that are statistically different from zero. Notably, the wetlands coefficient is negative, implying that increases in relative wetland area can be expected to reduce damages. The coefficient estimate corresponds to a marginal value (MV) estimate of approximately $7,420/ha/km (2010 USD) for a single storm. Table 2 shows the results from model 2 (which is the same as model 1, but includes both classification of wetlands in the relative wetland size variable). The coefficient estimates are roughly equivalent with the exception of the wetland coefficient, which has a larger standard error and is not statistically different from zero. While the coefficient estimate for the wetland variable was larger in model 2, it cannot be stated that wetlands, as defined by the wetland variable used here, are valuable for damage mitigation because the t-statistic is does not meet the threshold of statistical significance.

Table 3 shows the results from model 3 (which is the same as model 1, but includes only Louisiana storm impacts). The coefficient estimate for the wetland variable is not statistically significant. The results from model 4 (which is the same as model 3, but includes both wetland classifications) are shown in table 4. All coefficients are highly significant for this model, including the wetland coefficient. The monetized marginal effect for this model yields a MV of approximately $320/ha/km for a single storm.

DISCUSSION

Wetlands reduce wave energy by several processes that can be categorized as direct mechanisms or indirect mechanisms. Direct mechanisms are those in which wetland vegetation physically interacts with waves and dampens their effect (Gedan, 2011). As water flows through the vegetated structure of wetlands, drag and friction cause wave energy and turbulence to decrease (Nepf et al. 2007). The most effective wetlands at attenuating wave energy and turbulence are partially submerged and emergent wetlands (Neumeier and Ciavola, 2004). In coastal Louisiana, these wetlands are those included in the estuarine marine wetland category including salt marsh, intertidal bottomland forest and oyster reefs (Cowerdin et al. 1979).

There are other manners in which wetland ecosystems attenuate surge and wave energy. Indirect mechanisms are those that propagate changes in the underlying bathymetric conditions and coastal morphology (Gedan et al. 2011). As wetland ecosystems develop, decaying plant matter and living root structures fortify the underlying sediment. This is because organic soils generally resist erosion resulting from wave energy more effectively than less organic soils in wetlands (Feagin et al. 2009). Because wave height is proportional to water depth (Le Hir et al. 2000), the development of a coastal bathymetry that reduces the destructive energy in waves and storm surges is a valuable function of wetlands. These types of interactions are most are facilitated primarily by off shore high salinity ecosystems where vegetation may not be abundant. Nevertheless, considering the effects of these ecosystem features is critical for refining value estimates, as is shown in the results above.

Table 5 shows the values used for the alternative relative wetland area variables. Counties/parishes are listed in order from largest marine deepwater wetland area to smallest. Note the far right column, which shows the proportion of total wetlands that are classified as estuarine marine wetlands. The results of the analysis show that marine deepwater wetlands play a significant role in storm damage mitigation in Louisiana, but were not as influential for the Gulf region. Additionally, estuarine marine wetlands explain a great deal of the variance in damages for the model using the regional dataset, but did not have a strong influence on damages in Louisiana.

The physical mechanisms facilitated by equivalent ecosystems will perform the same way across the coast. It is the difference in the composition of wetlands that may be driving the discrepancy in the results. Parishes in Louisiana on average have larger relative areas of both wetland classifications. The samples in the gulf dataset (excluding Louisiana) have significantly smaller variation than the data from Louisiana for the relative marine deepwater wetlands category which could explain why the coefficient of the total wetland variable was not significant for the model using the regional dataset. Also, the extent of marine wetlands in Louisiana may be limiting the potential for estuarine wetlands to markedly reduce economic damages. Because storm waves would be smaller after traversing larger expanses of marine wetlands, the physical effects of estuarine wetlands may be obscured by the influence of more seaward wetlands. All of these possibilities warrant further investigation and require consideration when modeling the effects of wetlands on community vulnerability and economic impacts.

CONCLUSION

It is clear that coastal wetland ecosystems have the potential to mitigate damages from coastal storms and hurricanes. The dynamics between human populations, coastal ecosystems and coastal storms still remain largely unexplored. From an economic analysis perspective, a major restraint is the availability of data regarding economic damages. This research shows how using computer simulations can help refine the scale of damage estimates. Improving the resolution of analysis will be critical for identifying wetland characteristics that are most valuable for the provision of protection.

The EDF approach is a valid approach for estimating lower bound estimates for the value of coastal features for damage mitigation. However, this paper has shown that the method is prone to potentially large error if the specific feature of interest is not well defined or is not well measured by the data. Considering the manner in which systems work is critical for the appropriate modeling of their interactions. This suggests the need for more sophisticated modeling of the interaction between variables in the model and how those interactions affect the value of wetlands and the vulnerability of communities.

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TABLES

Table 1: Nonlinear least squares regression results for the Gulf dataset using the estuarine marine wetland classification for the relative wetland area variable. The marginal value of wetlands for storm protection implied by these results is approximately $7,420/ha/km/storm. Adjusted $R^2 = 0.964$, observations = 201

Ln(damage)	Coefficient	Standard Error	t	P>t
Alpha	2.287471	0.615051	3.72	<0.001
Wind	0.360538	0.035315	10.21	<0.001
Wetlands	-0.02763	0.013331	-2.07	0.04
Population	0.03928	0.014871	2.64	0.009

Table 2: Nonlinear least squares regression results for the Gulf dataset using the sum of the estuarine marine wetland and marine deepwater wetland classification for the relative wetland area variable. Adjusted $R^2 = 0.963$, observations = 201

Ln(damage)	Coefficient	Standard Error	t	P>t
Alpha	2.187756	0.617821	3.54	<0.001
Wind	0.36267	0.035516	10.21	<0.001
Wetlands	-0.03978	0.02757	-1.44	0.151
Population	0.059269	0.015181	3.9	<0.001

Table 3: Nonlinear least squares regression results for the Louisiana dataset using the estuarine marine wetland classification for the relative wetland area variable. Adjusted $R^2 = 0.956$, observations = 118

Ln(damage)	Coefficient	Standard Error	t	P>t
Alpha	2.425151	0.978645	2.48	0.015
Wind	0.313535	0.053538	5.86	0
Wetlands	0.003522	0.023064	0.15	0.879
Population	0.034262	0.019095	1.79	0.075

Table 4: Nonlinear least squares regression results for the Louisiana dataset using the sum of the estuarine marine wetland and marine deepwater wetland classification for the relative wetland area variable. The marginal value of wetlands for storm protection implied by these results is approximately $320/ha/km/storm. Adjusted $R^2 = 0.959$, observations = 118

Ln(damage)	Coefficient	Standard Error	t	P>t
Alpha	5.332384	2.214207	2.41	0.018
Wind	0.31175	0.051801	6.02	0
Wetlands	-0.11367	0.04015	-2.83	0.005
Population	0.057361	0.019613	2.92	0.004

Table 5: Wetland area data for each county/parish in the dataset listed from largest to smallest areas of marine deepwater wetland.

County/Parish	Marine Deepwater Wetlands (ha)	Estuarine Marine Wetlands (ha)	Total Coastal Wetlands (ha)	Length of Coast (km)	*Relative Wetland Area, Estuarine Wetlands (ha/km)	*Relative Wetland Area, Total Coastal Wetlands (ha/km)	Estuarine Share of Total Wetland Area
Harrison County	1004198	7966	1012164	130	61	7765	0.01
Cameron Parish	909944	7216	917160	72	100	12664	0.01
St. Bernard Parish	727445	87995	815439	84	1044	9672	0.11
Plaquemines Parish	706914	117379	824293	315	372	2613	0.14
St. Tammany Parish	606887	2927	609814	66	44	9242	0.00
Escambia County	606851	249	607100	61	4	9927	0.00
St. Mary Parish	606634	3352	609986	121	28	5054	0.01
Terrebonne Parish	560792	3361	564153	60	56	9474	0.01
Vermilion Parish	560764	13415	574179	53	253	10811	0.02
Okaloosa County	551384	11910	563295	83	143	6771	0.02
Harris County	533313	25651	558964	71	362	7894	0.05
Jackson County	526605	6670	533276	66	101	8082	0.01
Brazoria County	526459	10038	536497	69	145	7769	0.02
Baldwin County	504340	90675	595015	109	831	5452	0.15
Lafourche Parish	465790	25984	491775	92	283	5361	0.05
Orleans Parish	434984	125018	560002	116	1079	4833	0.22
Santa Rosa County	396979	10222	407202	40	254	10121	0.03
Matagorda County	273059	28775	301834	66	439	4607	0.10
Hancock County	222022	150229	372251	155	971	2406	0.40
Mobile County	153431	972	154404	51	19	2998	0.01
St. Charles Parish	152506	4695	157201	13	363	12164	0.03
Jefferson Parish	143003	66211	209214	117	564	1783	0.32
Iberia Parish	128176	4704	132880	34	137	3876	0.04
Galveston County	126142	5149	131291	119	43	1105	0.04
St. John the Baptist Parish	115568	18573	134141	48	390	2817	0.14

*Used as variable