The Value of Coastal Wetlands for Hurricane Protection

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Abstract

Coastal wetlands reduce the damaging effects of hurricanes on coastal communities. A regression model using 34 major US hurricanes since 1980 with the natural log of damage per unit gross domestic product in the hurricane swath as the dependent variable and the natural logs of wind speed and wetland area in the swath as the independent variables was highly significant and explained 60% of the variation in relative damages. A loss of 1 ha of wetland in the model corresponded to an average USD 33 000 (median = USD 5000) increase in storm damage from specific storms. Using this relationship, and taking into account the annual probability of hits by hurricanes of varying intensities, we mapped the annual value of coastal wetlands by 1km × 1km pixel and by state. The annual value ranged from USD 250 to USD 51 000 ha^{-1} yr^{-1}, with a mean of USD 8240 ha^{-1} yr^{-1} (median = USD 3230 ha^{-1} yr^{-1}) significantly larger than previous estimates. Coastal wetlands in the US were estimated to currently provide USD 23.2 billion yr^{-1} in storm protection services. Coastal wetlands function as valuable, selfmaintaining “horizontal levees” for storm protection, and also provide a host of other ecosystem services that vertical levees do not. Their restoration and preservation is an extremely cost-effective strategy for society.

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References and Notes

Emergency Events Database (http://www.emdat.be): this data set defined a hurricane to be a disaster if it satisfied at least one of the following criteria: *i)* 10 or more people killed; *ii)* 100 or more people affected, injured, or homeless; *iii)* declaration of a state of emergency and/or an appeal for international assistance.

Webster, P., J. Holland, G. J. Curry, and H. R. Chang. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309:1844–1846. CrossRef, PubMed

Emanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436:686–688. CrossRef, PubMed

Simpson, R. H. and H. Riehl. 1981. The Hurricane and Its Impact. Louisiana State University Press. Baton Rouge, LA. 398 pp.

Boesch, D. F., L. Shabman, L. G. Antle, J. W. Day Jr., R. G. Dean, G. E. Galloway, C. G. Groat, S. B. Laska, et al. 2006. A New Framework for Planning the Future of Coastal Louisiana after the Hurricanes of 2005. University of Maryland Center for Environmental Science. Cambridge, MD. 24 pp.

Costanza, R., W. J. Mitsch, and J. W. Day Jr.. 2006. A new vision for New Orleans and the Mississippi delta: applying ecological economics and ecological engineering. Front. Ecol. Env. 4:465–472. CrossRef

Cahoon, D. R., D. J. Reed, and J. W. Day Jr.. 1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States—Kaye and Barghoorn revisited. Marine Geol. 128:1–9. CrossRef, CSA

Harter, S. K. and W. J. Mitsch. 2003. Patterns of short-term sedimentation in a freshwater created marsh. J. Environ. Qual. 32:325–334. PubMed, CSA

Louisiana Coastal Wetlands Conservation Task Force and Wetlands Conservation and Restoration Authority.1998. Coast 2050: Toward a Sustainable Coastal Louisiana.. Louisiana Department of Natural Resources. Baton Rouge, LA. (http://eddyburg.it/index.php/filemanager/download/456/Coast_2050.pdf).

Barbier, E. B. 2007. Valuing ecosystem services as productive inputs. Econ. Policy 49:177–229. CrossRef

Danielsen, F., M. K. Sorensen, M. F. Olwig, V. Selvam, F. Parish, N. D. Burgess, T. Hiraishi, V. M. Karunagaran, et al. 2005. The Asian tsunami: a protective role for coastal vegetation. Science 310:643. CrossRef, PubMed

Kerr, A. M. and A. H. Baird. 2007. Natural barriers to natural disasters. BioScience 57:102–103. CrossRef

United Nations Environment Programme Division of Early Warning and Assessment Global Resource Information Database (http://www.grid.unep.ch/data/gnv199.php).

Elvidge, C. D., K. E. Baugh, J. B. Dietz, T. Bland, P. C. Sutton, and H. W. Kroehl. 1999. Radiance calibration of DMSP-OLS low-light imaging data of human settlements. Remote Sens. Environ. 68:77–88. CrossRef, CSA

Sutton, P. C. and R. Costanza. 2002. Global estimates of market and non-market values derived from nighttime satellite imagery, land use, and ecosystem service valuation. Ecol. Econ. 41:509–527. CrossRef

US Gross Domestic Product data from: http://www.bea.gov/national/xls/gdplev.xls

Vogelmann, J. E. and S. M. Howard. 2001. Completion of the 1990′s National Land Cover Dataset for the conterminous United States from Landsat Thematic Mapper Data and Ancillary Data Sources. Photogramm. Eng. Remote Sens. 64:45–57.

Pearson's coefficients showed insignificant collinearity between the analyzed variables. In addition no other land use areas covaried with either herbaceous or forested wetlands, which were also not correlated with each other.

We tested various log-log formulations using maximum likelihood and Akaike's Information Criterion (AIC) corrected for small sample size. Our theoretical assumption was that TD should be proportional to GDP and thus we used ln(TD/GDP) as the dependent variable. We did compare this to models with ln(TD) as the dependent variable and ln(GDP) as one of the independent variable. However, these models did not have a sufficient increase in likelihood to merit the additional degree of freedom as measured by AIC. The addition of forested wetlands to the model also did not improve the model, but the addition of herbaceous wetlands yielded the best model reducing the AIC_c by 2.91 versus a model with just wind speed. The AIC evidence ratio implies that the model with wetlands included has an 81% chance of being the correct model versus a model with wetlands omitted. We also tested the model using a recently available alternative data set for hurricane damages from Pielke et al. (20). This data set normalized damages for wealth and population by county. Using this data set gave us very similar results, however, so we decided to report our results using the original damage data set.

Pielke Jr., R. A., J. Gratz, C. W. Landsea, D. Collins, M. Saunders, and R. Musulin. 2008. Normalized hurricane damages in the United States:1900–2005. Nat. Hazards Rev. 9:29–42. CrossRef

A 95% confidence interval was generated for each of the parameter estimates as well as the adjusted R^2 measure using a 10 000 iteration bootstrap analysis. The adjusted R^2 interval was (0.342, 0.832). The intervals for the other parameters are listed in Table 1. The coefficient for wind speed (β_1) was significant 99.94% of the time, while the coefficient for wetlands (β_2) was significant 93.04% of the time.

One potential problem with this formulation is endogeneity. If wetland area and GDP are *negatively* correlated (as one might expect if urban area and wetland area were “competing” for the same fixed landscape area), then this could cause bias in the estimate of the coefficient for wetlands or spurious correlation. For example, it might be the case that high wetland area correlates with lower GDP, which correlates with less TD. We tested for the possibility that the reduction in damage attributable to herbaceous wetlands was spurious and caused by an endogenous relationship with GDP. GDP and herbaceous wetland area (all variables assumed log-transformed) were actually positively (and weakly) correlated ($r = 0.19$). However, as hypothesized, the partial correlation coefficient of total damage upon herbaceous wetlands controlling for GDP and wind speed was negative ($r = -0.34$, $p = 0.05$) (23). Controlling for the relationship with GDP demonstrates that the perceived effect of herbaceous wetlands upon hurricane damage is not spurious but rather is partially suppressed (statistically) because of the positive correlation between GDP and wetlands. Further, if an endogenous relationship with GDP were causing a spurious effect of herbaceous wetlands upon total damage, a similar relationship should have been seen with other undeveloped land covers. However, the addition of other land cover types (e.g., forested wetlands and forest) did not improve any of the models we tested.

Cramer, D. 2003. A cautionary tale of two statistics: partial correlation and standardized partial regression. J. Psychol. 137:507–511. PubMed

A second potential problem with the formulation used is selection bias. It might be the case that we are using data that is selectively gathered from locations where recorded damage is greater, probably due to a higher intensity of GDP. In these places, since storm protection services are proportional to total damage (more potential damage to mitigate), they could be disproportionately high leading to overestimates of the average values. However, unlike the case of selection bias in typical valuation studies (see 25) in damage mitigation studies we find that selection bias tends to cause underestimates of value. We tested this by creating a Monte Carlo simulated data set using a log-log formulation and comparing regression results when the data was restricted to samples with damages above a given percentile. The higher the percentile, the lower the estimated damage mitigation of wetlands implying our estimates are conservative.

Hoehn, J. P. 2006. Methods to address selection effects in the meta regression and transfer of ecosystem values. Ecol. Econ. 60:389–398. CrossRef

Blake, E. S., E. N. Rappaport, C. W. Landsea, and G. J. Jerry. 2005. Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2004 (NOAA Technical Memorandum NWS TPC-4). National Weather Service, National Hurricane Center, Tropical Prediction Center. Miami, FL. (http://www.aoml.noaa.gov/hrd/Landsea/dcmifinal2.pdf).

While residual analysis suggests little correlation between wetland area and model error and we have several data points with low wetland area, the log-log formulation makes marginal value calculations at low wetland areas problematic because values go to infinity as area goes to 0. For this reason, we capped increases in marginal value in our calculations for wetland areas below a certain number, k. In other words, in the integration we used the marginal value at k for all wetland areas less than k rather than allowing it to climb to infinity. Given model fit across the range of areas, we believe this yields a conservative value estimate. If the model diverges from reality at some lower threshold of wetlands, then for hurricanes with wetland area below that threshold, observed damage should have been below the predicted. However, of the four hurricanes with the least wetland area, three have observed damages higher than the model prediction, and the hurricane with the lowest amount of herbaceous wetland, Emily, is an outlier for which total damage was strongly underestimated. We used k = 5000 (The minimum area of wetlands in any state in our sample was 3638 ha for Rhode Island. 5000 ha is thus just within the range of our data.) but also report values in Table 3 using k = 10 000 and k = 1000 to demonstrate sensitivity to this assumption. TV increases as k decreases, but in all cases, limiting the integration in this way leads to conservative estimates.

Costanza, R., S. C. Farber, and J. Maxwell. 1989. The valuation and management of wetland ecosystems. Ecol. Econ. 1:335–361. CrossRef

Woodward, R. T. and Y-S. Wui. 2001. The economic value of wetland services: a meta-analysis. Ecol. Econ. 37:257–270. CrossRef, CSA

Brander, L. M., R. J. G. M. Florax, and J. E. Vermaat. 2006. The empirics of wetland valuation: a comprehensive summary and a meta-analysis of the literature. Environ. Resour. Econ. 33:223–250. CrossRef

Farber, S. 1987. The value of coastal wetlands for protection of property against hurricane wind damage. J. Environ. Econ. Manag. 14:143–151. CrossRef, CSA

Costanza, R., R. d'Arge, R. de Groot, S. Farber, S. M. Grasso, B. Hannon, S. Naeem, K. Limburg, et al. 1997. The value of the world's ecosystem services and natural capital. Nature 387:253–260. CrossRef, CSA

Cited by

Xavier López-Medellín, Exequiel Ezcurra, Charlotte González-Abraham, Jon Hak, Louis S. Santiago, James O. Sickman. (2011) Oceanographic anomalies and sea-level rise drive mangroves inland in the Pacific coast of Mexico. *Journal of Vegetation Science* **22**:1, 143-151
Online publication date: 1-Feb-2011.
CrossRef
Shari Clare, Naomi Krogman, Lee Foote, Nathan Lemphers. (2011) Where is the avoidance in the implementation of wetland law and policy?. *Wetlands Ecology and Management*
Online publication date: 20-Jan-2011.
CrossRef
Virginia D. Engle. (2011) Estimating the Provision of Ecosystem Services by Gulf of Mexico Coastal Wetlands. *Wetlands*
Online publication date: 12-Jan-2011.
CrossRef
Keryn B. Gedan, Matthew L. Kirwan, Eric Wolanski, Edward B. Barbier, Brian R. Silliman. (2010) The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic Change*
Online publication date: 14-Dec-2010.
CrossRef
Ian J. Bateman, Georgina M. Mace, Carlo Fezzi, Giles Atkinson, Kerry Turner. (2010) Economic Analysis for Ecosystem Service Assessments. *Environmental and Resource Economics*
Online publication date: 13-Oct-2010.
CrossRef
R. Eugene Turner. (2010) Beneath the Salt Marsh Canopy: Loss of Soil Strength with Increasing Nutrient Loads. *Estuaries and Coasts*
Online publication date: 17-Sep-2010.
CrossRef
Shuang Liu, Robert Costanza, Austin Troy, John D’Aagostino, Willam Mates. (2010) Valuing New Jersey’s Ecosystem Services and Natural Capital: A Spatially Explicit Benefit Transfer Approach. *Environmental Management* **45**:6, 1271-1285
Online publication date: 1-Jun-2010.
CrossRef
Kazimierz Więski, Hongyu Guo, Christopher B. Craft, Steven C. Pennings. (2010) Ecosystem Functions of Tidal Fresh, Brackish, and Salt Marshes on the Georgia Coast. *Estuaries and Coasts* **33**:1, 161-169
Online publication date: 1-Jan-2010.
CrossRef
R. Kerry Turner, Sian Morse-Jones, Brendan Fisher. (2010) Ecosystem valuation. *Annals of the New York Academy of Sciences* **1185**:1, 79-101
Online publication date: 1-Jan-2010.
CrossRef

Dario Pumo, Stefania Tamea, Leonardo Valerio Noto, Fernando Miralles-Wilhem, Ignacio Rodriguez-Iturbe. (2010) Modeling belowground water table fluctuations in the Everglades. *Water Resources Research* **46**:11,
Online publication date: 1-Jan-2010.
CrossRef
Will R. Turner, Michael Oppenheimer, David S. Wilcove. (2009) A force to fight global warming. *Nature* **462**:7271, 278-279
Online publication date: 19-Nov-2009.
CrossRef
Torbjörn E. Törnqvist, Douglas J. Meffert. (2008) Sustaining coastal urban ecosystems. *Nature Geoscience* **1**:12, 805-807
Online publication date: 1-Dec-2008.
CrossRef

AMBIO: A Journal of the Human Environment 37(4):241-248. 2008
doi: 10.1579/0044-7447(2008)37[241:TVOCWF]2.0.CO;2