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The value of China's coastal wetlands and seawalls for storm protection

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ABSTRACT

China has relied on seawalls for storm protection along its coasts for decades. In contrast, the storm protection functions of coastal wetlands are often ignored by decision makers in China. We examined 127 historical storms with consequent economic loss to China from 1989 to 2016 and estimated the value of coastal wetlands with controlling for seawalls for storm protection. A regression model with the natural log of damage per unit gross domestic product in the storm swath as the dependent variable and explanatory variables including the length of existing seawalls in the storm swath and the natural logs of wind speed, storm duration and wetland area in the storm swath was highly significant and explained 59.2% of the variation in relative damages. Results show that a gain of 1 km^2 of wetlands corresponds to an average CNY 83.90 million (median = CNY 11.87 million) decrease in storm damage from specific storms. Coastal wetlands are gifts of nature and self-maintaining so they have zero construction and maintenance costs. They also provide many other valuable ecosystem services that hard seawalls do not.

1. Introduction

Storms, including typhoons, cyclones, tropical storms, hurricanes, tornadoes, winter storms, and tropical depressions, can result in human fatalities, economic losses, and ecological damages (IPCC, 2013). China has been hit by the most storms out of any country since 1970, the time when modern global satellite surveillance became available (NOAA's Hurricane Research Division, 2010). For example, when the 2016 typhoon Mujigae made landfall in the China coastal provinces, it killed approximately 5 people due to flooding and had a total economic cost to China of CNY 2.67 billion (Marine Disaster Bulletin, 2016). Low-lying sedimentary coasts are generally much less resilient to flooding (Woodruff et al., 2013). Storm impacts are likely to increase in the future partly due to an increase in storm frequency driven by climate change (IPCC, 2013; Rahmstorf, 2017; Garner et al., 2017) and partly as population and cities expand along the coast (Dinan, 2017).

Storm damages are mainly attributed to flooding from storm-tidal surge and rainfall, but are also caused by high winds (Farber, 1987). Coastal wetlands are a good example of natural buffers against storms. A wetland between uplands terrain and the storm surge is likely to diminish storm intensity (Costanza et al., 2008; Simpson and Riehl, 1981). Examining the role of wetlands in mitigating storms generally falls into two classes: numerical simulations and empirical observations.

A burgeoning pool of research has quantified the effect of wetlands on storm surge and flooding using numerical simulations. Multiple of factors such as size of wetlands, vegetation species, marsh elevation and bottom friction have been shown to have a definite and wide ranging effect on storm peak surge levels (Loder et al., 2009; Barbier et al., 2013; Wamsley et al., 2010; Narayan et al., 2017). Barbier et al. (2013) simulated four storms to show that storm surge levels decline with wetland continuity and vegetation roughness. Loder et al. (2009) confirmed that storm surge is parameterized in terms of marsh elevation and bottom friction. In addition, storm related parameters including intensity, duration, forward speed and maximum wind radius can be affected by wetlands to attenuate storm surges (Deng et al., 2010; Hu

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Table 1
An overview of data obtained in this study.

Data	Descriptions	Sources	Websites
Historical typhoons in china	All major typhoons caused economic damages in China from 1991 to 2016 were detailed.	Marine Disaster Bulletin (MDB)	http://www.soa.gov.cn/zwgk/hygb/zghyzhgb/index.html
Hurricane tracking data	Hurricane/tropical data with wind speeds and trajectories	Unisys Weather	http://weather.unisys.com/hurricane
Global disasters	International disaster database recording individual cases for countries	EM-DAT	http://www.emdat.be
Herbaceous coastal wetlands	Data were extracted from Landsat satellite images	Geospatial Data Cloud	http://www.gscloud.cn
Hard engineered defence	Data were retrieved from Landsat satellite images	U.S. Geological Survey	http://www.usgs.gov
Census data	Raster data showing the distribution of Chinese population	SEDAC RESDC	http://sedac.ciesin.columbia.edu/data/colection/gpw-v3 http://www.resdc.cn
GDP	Temporal statistical GDP data for Chinese coastal provinces	National Bureau of Statistics of China	http://data.stats.gov.cn/easyquery.htm?cn=E0103

et al., 2015; Marsooli, et al., 2016; Zhang et al., 2012).

Several empirical studies have found evidence of the effectiveness of wetlands in reducing death tolls and in protecting property (Das et al., 2009; Koch et al., 2009; Seriño et al., 2017). Some studies have attempted to value the protection service of coastal wetlands against the storms. For example, a regional study by Narayan et al. (2017) showed that wetlands avoided USD 0.6 billion in direct flood damages to properties during Hurricane Sandy. Seriño et al. (2017) found that the estimated average cost of saving life by retaining a hectare mangrove area was USD 301,811 in Visayas, Philippines during the super typhoon HAIYAN. However, some of these studies have been criticized for focusing on a regional scale, using small samples, or inadequately controlling for confounding factors such as protective structures. Literature reviewed by Seriño et al. (2017) indicated that long-term empirical evidence that coastal wetlands provide significant protection against storms is scarce (Das et al., 2009). Recently, wetlands as ecosystem-based hazard protection measures have challenged traditional hard engineering in terms of sustainability and cost-effectiveness (Temmerman et al., 2013; Smith et al., 2017). To support such an argument, evidence of the value of storm protection services by wetlands based on large samples collected at the national scale, controlling for confounding factors is necessary. Our analysis is one of the few (another is Costanza et al., 2008) that synthesizes historical cases at a national scale, in this case for China.

China has responded to storm strikes by establishing hard engineered defences since 1970. The positive role of hard engineered defences in mitigating economic loss caused by storms has been addressed by the Chinese State of Ocean Administration (Liu et al., 2019). China is an ideal case to analyse because its coastline is approximately 34,000 km with 13,830 km of hard engineering structures (Luo et al., 2015). China's coastal population was approximately 595 million by 2015, it has been hit by the most storms since 1970, and nearly 58% of coastal wetlands have been lost since 1950 due to land reclamation and infrastructure development (Yang et al., 2017; Bi et al., 2012).

Coastal wetlands in China are mainly distributed within nine provinces including Liaoning, Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, Hainan, Guangxi, and two municipalities (Shanghai and Tianjin). There are 12 types of natural barriers along the China's coast: permanent shallow marine waters, marine subtidal aquatic beds, coral reefs, rocky marine shores, intertidal sand/shingle/pebble beaches, intertidal mud/sand flats, intertidal marshes, mangroves, coastal brackish lagoons, coastal freshwater lagoons, permanent estuarine waters, and estuarine systems of deltas (Jiang et al., 2015). In this paper, we focus on herbaceous and woody coastal wetlands including intertidal marshes and mangroves. On one hand, China's coastal wetlands have been critically degraded. Yang et al. (2017) noted the importance of coastal wetlands and that the shortage of protected coastal sites is underappreciated in China. Only 14.7% of current coastal wetlands are covered by protected area status, although China has drawn a "red line" to conserve at least 53.33 million ha of wetlands in the country (Bai et al., 2016). On the other hand, no work has been done to estimate the storm protection value by coastal wetlands in China, although coastal wetlands have been identified widely in literature to provide storm protection.

2. Data and methods

This paper provides an estimate of the value of coastal wetlands for storm protection with controlling for seawalls. To estimate the storm protection value of coastal wetlands, we used a regression model in which the dependent variable was the natural log of storm damage (TD) per unit gross domestic product (GDP) in the swath of the storm (ln(TD/GDP)) and the explanatory variables included the length of seawalls in the storm swath and the natural logs of the wind speed at landfall, storm duration and the wetlands area in the storm swath.

To determine the storm protection value provided by coastal wetlands, available data were collected from a variety of sources. Details can be seen in Table 1 as follows:

Since 1989, the State of Ocean Administration (SOA), China has issued an annual Marine Disaster Bulletin to the public to provide official statistics about maritime disasters and their impacts. The International Disaster Database, from EM-DAT, provided individual records of typhoons worldwide including Chinese cases since 1900. We mainly collected the total economic damage (TD) data for typhoons from Marine Disaster Bulletin (MDB) and the international EM-DAT complemented several cases. In summary, 127 typhoons with economic loss over 28 years from 1989 to 2016 were sampled and coded in the regression model. The total economic damage (TD) from MDB is comprehensive including properties, roads, bridges, fishing ships, human lives, agriculture and mari-aquaculture that were damaged by the storms.

Hurricane tracking data from Unisys Weather was used to estimate the size of swath for each storm in a parametric model as follows (Willoughby and Rahn, 2004),

$$R_i = 51.5\exp(-0.0223V_i + 0.0281\varphi_i) \quad (1)$$

We defined a more realistic varied swath instead of a constant swath. The impact distance from the storm center to the region of wind speed was denoted as the maximum wind radius R_i (Takagi and Wu, 2016). Therefore, wind radius changes with wind speed and latitude, and is not left as a constant value. We proposed a varied storm swath, which is a belt area with a central line along the trajectory of the storm approaching land and a wind radiusR_i. There is a general tendency for more intense storms or those in lower latitudes to have smaller eyes (Shea and Gray, 1973). The wind radius, R_i, is a function of combining wind forward speed V_i and the latitude position φ_i at a specific time i. Sustained wind speed and the latitude position were updated every 6 hours in the hurricane tracking dataset. The wind radius derived for all

127 typhoons ranges from 13.94 km to 154.57 km with an average of 50.90 km and a median of 49.39 km. Unisys Weather also provided the storm duration data, which is one of independent variables in the regression model.

All population data has a resolution of 1 km by 1 km. Population data from 1990 to 2015 were found at SEDAC (Socioeconomic Data and Applications Center, at Columbia University), while population data for 1995, 2000, 2005 and 2010 were obtained from RESDC (Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences). Population data for other years were interpolated based on data at the specific years available. Temporal statistical GDP per capita data at the provincial-level were obtained from the National Bureau of Statistics of China. The storm swaths were then overlaid on the spatially explicit population to obtain the affected population, then multiplied by the GDP per capita to generate the spatially explicit gross domestic product (GDP) exposed within each storm's swath. The ratio of TD/GDP represented the relative economic damage of each storm, whose logarithmic transformation (i.e., ln(TD/GDP)) was used as the dependent variable in the regression model.

A variety of Landsat data with 30 m or 60 m resolution for 1980, 1990, 2000, 2010 and 2015 covering the entire china's coast were downloaded from U.S. Geological Survey and were then used to retrieve the spatiotemporal distribution of hard engineered defence (i.e., seawalls) along the China's coast by utilizing remote sensing and GIS technologies. More details can be seen in the work by Xu et al. (2016). For example, the coastline were delineated and classified via visual interpretation by the same person at the same scale to ensure accuracy from the color composite TM/ETM +543 and MSS 432 pseudo-color image (Xu et al., 2016). Storm swaths were overlaid on map of hard engineered defence to obtain the involved length of seawalls in each storm swath.

Temporal spatial distribution data for herbaceous coastal wetlands was extracted from a multiple of Landsat satellite images with a resolution of 30 m by 30 m downloaded from Geospatial Data Cloud for 28 years from 1989 to 2016 using GIS technology combined with visual interpretation method. Storm swaths were also overlaid on herbaceous coastal wetland cover to obtain the affected wetlands in each swath. There is a descriptive statistics for all data used in the regression model, as shown at the Table S1 in the supplementary information.

We ran a multiple regression model using the natural logs of area of coastal herbaceous wetland, wind speed at storm' landfall and storm duration as the independent variables and a logarithm transformed *TD*/GDP as the dependent variable as described below:

$$\ln(TD_i/GDP_i) = \alpha + \beta_1 \ln(wetland_i) + \beta_2 seawall_i + \beta_3 \ln(wind_i) + \beta_4 \ln(duration_i) \quad (2)$$

where TD_i was the total economic loss observed from storm i, GDP_i represented gross domestic product exposed in the swath of storm i, $wind_i$ was the wind speed of the specific storm i at landfall in m/s, $wetland_i$ and $seawall_i$ referred to the wetlands area and the length of seawalls in the swath of the storm$i$, respectively and $duration_i$ denoted storm i's duration in hours.

One potential problem with this formulation is endogeneity (Costanza et al., 2008). For example, wetland area and GDP could be negatively correlated, which resulted in high wetland area correlates with lower GDP, if urban area and wetland area were "competing" for the same fixed area. We tested for the hypothesis that the reduction in economic damage was caused by an endogenous relationship with GDP. Actually, GDP and wetland area were examined to be positively correlated (r = 0.337). Controlling for the relationship between GDP and the wetland area demonstrates that the effect of wetland upon hurricane damage is not spurious (Costanza et al., 2008).

It is expected that$\beta_1 < 0$, $\beta_2 < 0$ and$\beta_3 > 0$, $\beta_4 > 0$. Once the coefficients in the Eq. (3) were estimated by using the ordinary least squares, Eq. (3) can be rearranged to hind-cast the total damages from storm i as:

$$TD_i = e^{\alpha} * wetland_i^{\beta_1} * e^{\beta_2 seawall_i} * wind_i^{\beta_3} * duration_i^{\beta_4} * GDP_i \quad (3)$$

Obviously, the total damage (TD) is expected to vary linearly with GDP. Also the total damage is expected to vary as the β_1 power of the area of wetland, β_3 power of the wind speed and β_4 power of the storm duration. The difference of TD with a gain of an area of Q of wetlands is then calculated as:

$$\Delta TD_i = e^{\alpha} * e^{\beta_2 seawall_i} * wind_i^{\beta_3} * (wetland_i^{\beta_1} - (wetland_i + Q)^{\beta_1}) * duration_i^{\beta_4} * GDP_i \quad (4)$$

If Q equals to 1 km^2, the Eq. (4) can be rewritten as:

$$\Delta TD_i = e^{\alpha} * e^{\beta_2 seawall_i} * wind_i^{\beta_3} * (wetland_i^{\beta_1} - (wetland_i + 1)^{\beta_1}) * duration_i^{\beta_4} * GDP_i \quad (5)$$

where ΔTD_i is also called the marginal protection value of the wetland under the storm i.

3. Hurricane frequencies, tracks and trends

There were 127 typhoons that caused economic losses that crossed the Chinese coast during the period 1989–2016. The frequency of typhoons hitting China with economic damage is estimated as the total number of storms (127) divided by the 28 years of record = 4.5 storms/yr. These typhoons' landfalls are spatially varied. At the regional scale, the Guangdong and the Fujian were listed as the most frequently hit provinces by these typhoons, with an annual landfall probability of 1.75 and 1.54 storms/yr on average for the past 28 years, respectively. Tracks of all these typhoons were mapped in Fig. S1. As anticipated, southern provinces received more storm hits historically than northern provinces.

It was observed that there were substantial changes in storm number and intensity for the Chinese coasts. As seen in Table 2, tropical storms and hurricanes in category 4 and 5 have increased significantly in frequency over the past 28 years. The number of hurricanes in

Table 2

Change in the number and percentage of hurricanes in all categories and the tropical storms for the 14 year periods 1989–2002 and 2003–2016 for the Chinese coasts. An increasing trend is highlighted by red and a decreasing trend is marked in green. Hurricanes are measured on the Saffir-Simpson Hurricane Wind Scale, which runs from Category 1 up to Category 5. Category 1: 33 m/s ≤ wind speed ≤ 42 m/s; Category 2: 43 m/s ≤ wind speed ≤ 49 m/s; Category 3: 50 m/s ≤ wind speed ≤ 58 m/s; Category 4: 59 m/s ≤ wind speed < 70 m/s; Category 5: 70 m/s ≤ wind speed; tropical storm: wind speed < 33 m/s.

Hurricane Intensity	Period			
	1989-2002 (14 years)		2003-2016 (14 years)	
	Number	Percent	Number	Percent
Tropical storm	4	8.5%	17	21.3%
Category 1	20	42.6%	17	25%
Category 2	9	19.1%	11	13.8%
Category 3	5	10.6%	6	7.5%
Category 4	5	10.6%	20	25%
Category 5	4	8.5%	9	11.3%

category 1, 2 and 3 has remained approximately constant, but has decreased as a percentage of the total number of storms throughout the 28-year period. In contrast, the sum of category 4 and 5 storms more than tripled in number (9 cases over the 1989–2002 period and 29 cases over the 2003–2016 period) and nearly doubled in percentage (19.1% over the 1989–2002 period and 36.3% over the 2003–2016 period). This finding was consistent with the previous study by Webster et al. (2005) in which the western Pacific Ocean was observed to receive more frequent and intensive hurricanes over a 30 years' period from 1975 to 2004. Although these changes may reflect long term patterns of storm intensity, we may also expect a trend toward more intense hurricanes hitting the Chinese coast in the future due to warming sea surface temperatures resulting from climate change.

4. Statistics of storm damages

Storms result in fatalities, wind, and flooding damages to properties and commercial harvests such as agriculture and mari-aquaculture. Damages in lives, properties, roads, bridges, fishery ships, agriculture and mari-aquaculture were captured for 127 typhoons from China's official reports (i.e., Marine Disaster Bulletin), which also documented a total economic loss for each of the 127 typhoons. All economic losses of 127 historical cases from 1989 to 2016 were then converted to 2016 CNY based on Consumer Price Index by Statistics of China. As shown in Fig. 1, annual economic losses caused by storms vary significantly from year to year, but have decreased over the past 10 years. This can be explained by: 1) the rapid improvement of weather forecasting and warning systems for natural disasters in China; 2) man-made engineered structures along the Chinese coasts; and 3) better construction of houses built recently in China making them more resistant to wind damage. However, climate change is likely to increase the frequencies of hurricanes in some parts of the world including the west Pacific Ocean (IPCC, 2013).

5. Model regression for coefficient estimation

For all 127 cases, we collected data for wind speed at landfall, total economic loss (TD), GDP exposed in the storm swath, storm duration, the length of existing seawalls and the wetland area traversed by storms to include in the regression analysis. The ordinary least square (OLS) estimate of the regression is summarized in Table 3 and is listed in Eq. (6). The model yielded a R^2 of 0.592. The associated sign of wetlands is negative and remains significant when other confounding variables were added progressively. The fact that the coefficient of wetlands remained negative and significant implies that coastal wetlands did play a protective role. The coefficient for wetlands of −0.1966 indicates that the total economic damage decreases rapidly with increasing wetlands area. Aside from the wetlands, the other significant determinants of economic damage by storm include wind speed at landfall, storm duration and the presence of seawalls. As expected, both wind speed and storm duration significantly affected the relative economic damage caused by storm. The relative economic damage increases as the 3.059 power of the wind speed at landfall during storm and the 1.0014 power of the storm duration. To control for the effect of protective structures along the China's coast, we included a variable capturing the presence of seawalls in the regression model. The negative sign of the seawalls suggests that the longer the seawalls in the storm swath the lower the storm damage. The coefficient is negative and significant implying that in areas where seawalls were present, coastal community suffered less economic damage. On average, the expected reduction in the log count of relative economic damage (TD/GDP) with a kilometre increase in seawall cover is 0.0035.

The relative damage (TD/GDP) predicted was compared with the TD/GDP observed (Fig. 2). The regression model can explain 59.2% of the variation in relative damages.

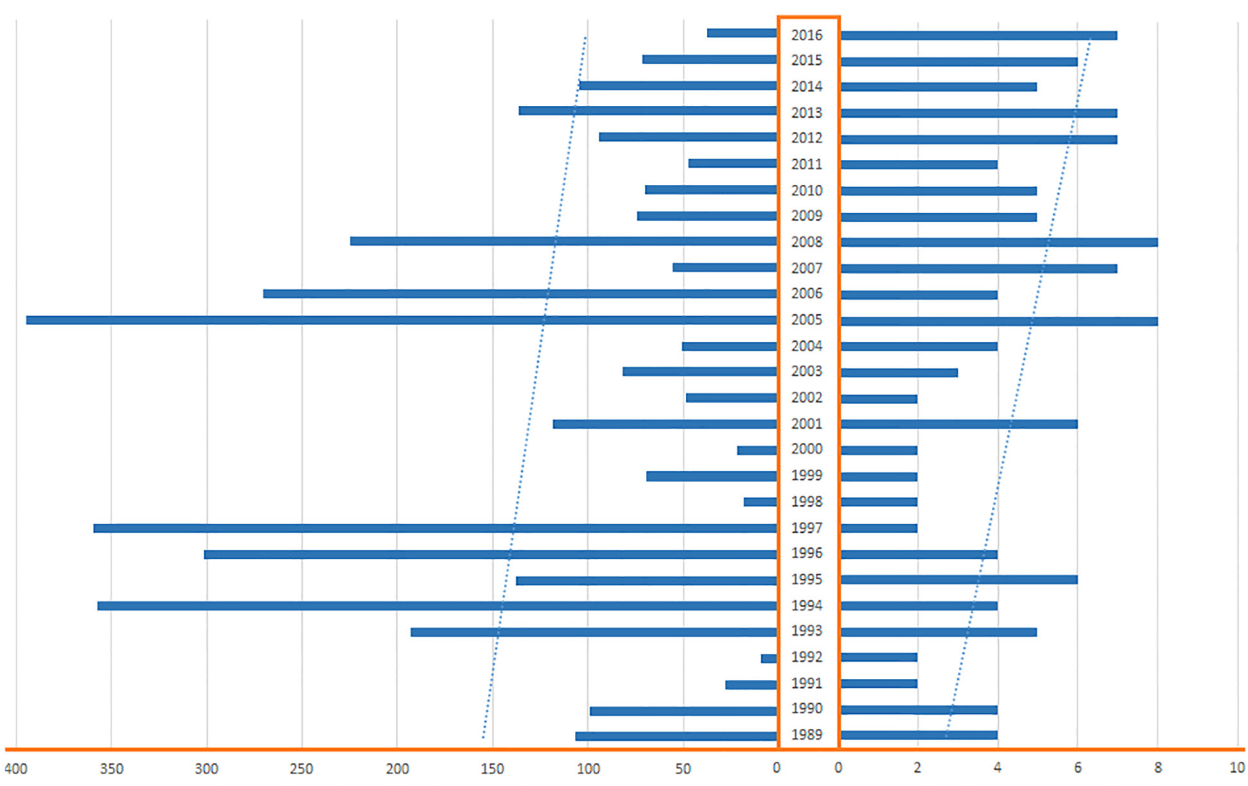

Fig. 1. Annual economic loss caused by these 127 typhoons and the estimated storm frequency per year along the Chinese coasts based on 127 cases for 28 years from 1989 to 2016.

Table 3
Regression model coefficients.

Variable Symbol	Definition	Coefficient	Std. Error	Prob.
α	constant	−19.7843**	1.5212	0.0000
wetland	The area of wetland in km^2 in the storm swath	−0.1966**	0.0937	0.0379
seawall	The length of seawall in km in the storm swath	−0.0035**	0.0014	0.0152
wind	The wind speed at landfall	3.0590***	0.3404	0.0000
duration	The storm duration in hours	1.0014***	0.2376	0.0000

Sample size N = 127.
*** Statistically significant at 1% level.
** Statistically significant at 5% level.

$$\ln(TD_i/GDP_i) = -19.7843 - 0.1966 * \ln(wetland_i) - 0.0035 * seawall_i + 3.0590 * \ln(wind_i) + 1.0014 * \ln(duration_i) \quad (6)$$

6. Marginal protection value of herbaceous coastal wetlands and seawalls for storms

We estimated marginal value per unit area of coastal herbaceous wetlands in preventing storm damage from a specific storm. The values ranged from a minimum of CNY 67,751/km^2 for Tropical storm HIGOS (2008) to a maximum of CNY 1785 million/km^2 for Typhoon SINLAKU (2002), with an average value of CNY 83.90 million/km^2. The median value was CNY 11.87 million/km^2, which implied a quite skewed distribution.

We also estimated marginal value per unit length of seawalls in preventing storm damage for all selected 127 storms. The values ranged from a minimum of CNY 38,886/km to a maximum of CNY 74.5 million/km with an average value of CNY 8.9 million/km and a median value of CNY 4.8 million/km.

7. Discussion

The estimates in this paper have both similarities and differences to previous studies on the valuation of coastal wetlands. Costanza et al. (2008) estimated an average value of CNY 28.3 million/km^2 and a median CNY 4.3 million/km^2 (converted to 2016 CNY) protection value of U.S. coastal wetlands from storm damage. Our current estimate for marginal unit value was consistent with the US estimate but somewhat larger. This is to be expected since more built capital and population was present in the Chinese coastal areas compared with the U.S. coastal areas. Developing countries like China have been converting coastal wetlands to other land uses at high rates over the last decade (Coleman et al., 2008; Kirwan and Megonigal, 2013). This paper represents the first attempt to provide a monetary estimate for the storm protection values of coastal wetlands and seawalls in China. Compared with human made seawalls, coastal wetlands have many benefits. Firstly, wetlands are a less costly alternative for storm protection. Existing coastal wetlands are free, self-maintaining gifts of nature. If we had to construct the wetlands, the average annual costs of one acre of constructed wetlands plus maintenance would be approximately USD 1000 (i.e., USD 256,000/km^2) per year when the wetlands were analysed over a 40-year time period, although wetlands have indefinite lifespans and are expected to be permanent parts of the landscape (Iowa Learning Farm, 2015). By contrast, human made seawalls require extensive time to build and a large budget. Construction expenditure of seawalls was estimated to be up to CNY 6,397,500/km with an annual maintenance bill ranging from CNY 15,622/km to CNY 74,216/km in China by “Standard of Budget Quota for Maintenance on Water Resource Project” (MWR, 2004). Therefore, seawall construction and maintenance costs CNY 172,969 $km^{-1}\,yr^{-1}$ on average, further comparing with the

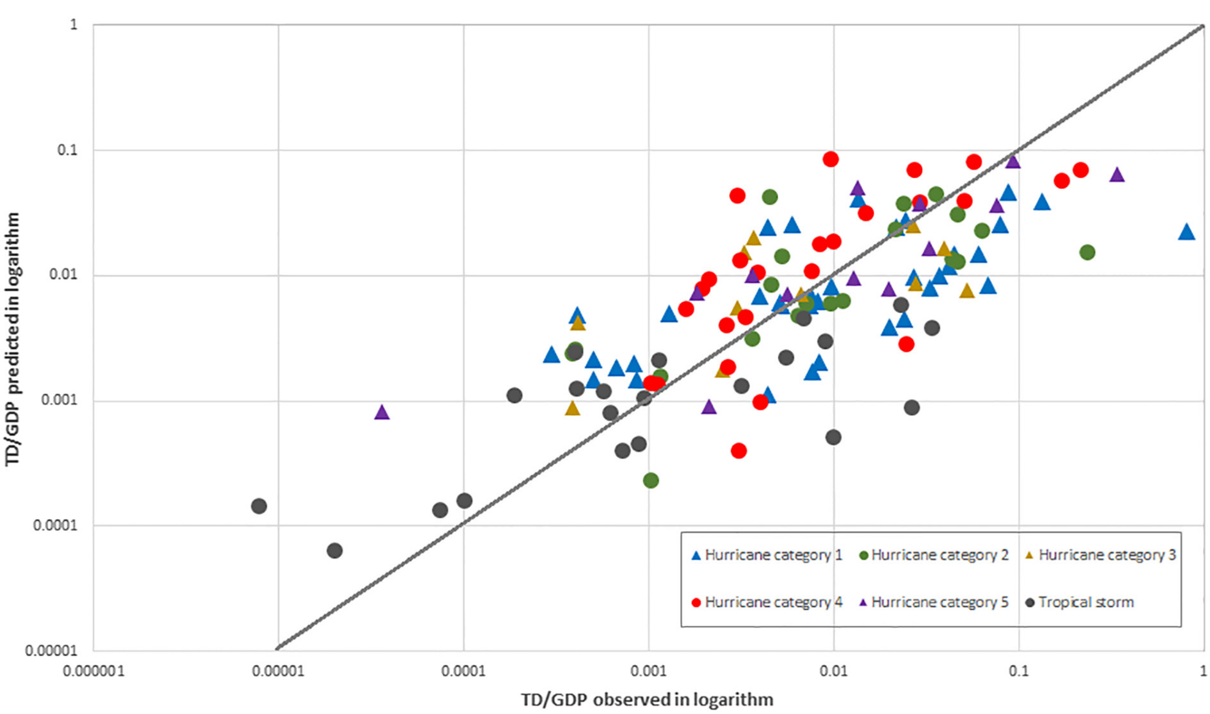

Fig. 2. Observed vs. predicted relative (TD/GDP) damage for 127 storms included in the analysis.

estimated storm protection value of CNY 848,312 $km^{-1} yr^{-1}$ by seawalls, which leads to a benefit/cost ratio of seawalls for storm protection is 4.9. According to the recent "National Plan for Coastal Dykes" issued on August, 2017, thirty-seven projects, constructing 500 km of new coastal dykes, will be carried out in the next 10 years (Ministry of Water Resources, 2017). This implies that approximately CNY 31.99 billion of investment for new seawalls, which creates an excessive financial burden for local governments. Secondly, the averaged life-span of dykes is limited to 50 years. Thirdly, unlike hard engineering, coastal wetlands naturally adapt to changes in sea levels, if they are not severely affected by human activities such as coastal engineering. Coastal wetlands have the capacity to adjust accretion rates to sea-level rise (Duarte et al., 2013; Kirwan and Mudd, 2012). Lastly, coastal wetlands provide additional valuable ecosystem services besides storm protection, including habitat for fish, and migratory birds, water purification, recreation and research (Aburto-Oropeza et al., 2008).

Studies reflected that green infrastructure performs equally, or better, than the man-made infrastructure for flood protection (Cao et al., 2016; Liquete et al., 2016). Some researchers documented that coastal concrete structures altered physical, chemical, and biological processes of habitats while also driving habitat loss (Perkins, et al., 2015; Raffaelli and Hawkins, 1996; Pennings et al, 2005; Defeo and McLachlan, 2013). We are not arguing to replace the existing seawalls with wetlands, but to transfer focus from man-made seawalls to a nature-based option using wetlands for storm protection under the umbrella of China's 13th five-year plan. We suggest that Chinese policymakers consider coastal wetlands instead of 500 km of new man-made seawalls.

8. Limitations and caveats

Our attempt to quantify the storm protection value of coastal wetlands and seawalls is limited for a number of reasons, including:

- Although we have included significant variables as much as possible, but our regression model leaves out many factors including elevation, sea-level, distance to coast and vegetation roughness that were found in previous studies (Barbier et al., 2013; Loder et al., 2009) to have an influence on damage reduction of wetlands. As more information becomes available we expect to be able to include some of these variables and improve the estimated value.
- The R^2 of the model is 0.59, which implies that 41% of the variation in the relative damage (ln(TD/GDP)) are not explained by the model. The model over-predicts the storms with very low economic damage and under-predicts the storms with very high economic damage as shown in Fig. 2. This could be attributed to a combination of a large variance of the relative damage (ln(TD/GDP)) up to 4.05 in a log-transformed version and imprecise geographic information on coastal wetlands, which were extracted from a number of Landsat satellite images.
- China has had a rapid economic development recently with a long history of building seawalls and other built infrastructures. This infrastructure consists of seawalls, groynes, harbours, ports and man-made embankments for transportation. We incorporated this "infrastructure" as a unique confounding variable in regression model, which actually also play a role of mitigating storms.
- We applied a varied storm swath rather than a constant one, which amplifies the difference of the relative economic damage caused by storms with different forward wind speeds. That means, a higher wind speed results in a smaller swath, which implies a smaller GDP exposed and a higher relative economic damage (TD/GDP). This is a better approximation than assuming a constant swath width.

Despite uncertainties and limitations mentioned above, our results highlight the economic benefits of storm protection services of coastal wetlands to China. Failure to value the services provided by ecosystems leads to degradation of the wetlands (Neebele and Forgie, 2017). Degradation of current coastal wetland in China is exacerbated by ignoring the benefits generated by ecosystems and over-valuing conventional coastal protection projects. Our results provide a conservative estimation of CNY 11.87 million per km^2 for the storm protection value of coastal wetland. This information can help decision makers to allocate coastal wetlands efficiently in future agendas.

9. Conclusion

China is currently facing environmental damages driven by economic expansion over the past 30 years. China is trying to balance its economic development and environmental degradation. Our study initially estimates the storm protection services of coastal wetlands with controlling for seawalls. Clarifying the value of coastal wetlands for storm protections provides decision makers with a way to compare them to man-made seawalls for this service. Conserving and restoring coastal wetlands, instead of building another 500 km of seawalls is more likely to help China to secure a sustainable 'ecological civilization' in the future.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2019.100905.

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