Assessing Hazard Vulnerability, Habitat Conservation, and Restoration for the Enhancement of mainland China’s Coastal Resilience

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Assessing Hazard Vulnerability, Habitat Conservation, and Restoration for the Enhancement of mainland China’s Coastal Resilience

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Abstract Worldwide, humans are facing high risks from natural hazards, especially in coastal regions with high population densities. Rising sea levels due to global warming are making coastal communities’ infrastructure vulnerable to natural disasters. The present study aims to provide a coupling approach of vulnerability and resilience through restoration and conservation of lost or degraded coastal natural habitats toclamation under different climate change scenarios. The integrated valuation of ecosystems and tradeoffs model is used to assess the current and future vulnerability of coastal communities. The model employed is based on seven different biogeophysical variables to calculate a natural hazard index and to highlight the criticality of the restoration of natural habitats. The results show that roughly 25% of the coastline and more than 5 million residents are in highly vulnerable coastal areas of mainland China, and these numbers are expected to double by 2100. Our study suggests that restoration and conservation in recently reclaimed areas have the potential to reduce this vulnerability by 45%. Hence, natural habitats have proved to be a great defense against coastal hazards and should be prioritized in coastal planning and development. The findings confirm that natural habitats are critical for coastal resilience and can act as a recovery force of coastal functionality loss. Therefore, we recommend that the Chinese government prioritizes restoration (where possible) and conservation of the remaining habitats for the sake of coastal resilience to prevent natural hazards from escalating into disasters.

Plain Language Summary Coastal populations are especially at risk from sea-level rise (SLR), induced storm surges, and other natural hazards. Therefore, it becomes essential to analyze the current and future vulnerabilities of coastal regions to natural hazards. Furthermore, it is desirable for the policy and the decision making to propose the suitable approaches for the resilience enhancement. This paper analyzes the current and future vulnerability of mainland China’s coast to the SLR-induced natural hazards using a natural hazard index incorporating a coupled approach to vulnerability and resilience. The results show that the restoration of lost mangroves (where possible) and conservation of remaining coastal natural habitats can reduce the future coastal vulnerability by 45%. This study confirms that natural habitats are significant for coastal resilience and the governments should prioritize them for the sake of coastal resilience to mitigate the impacts of natural hazards.

1. Introduction

Rising sea levels are putting coastal populations around the globe at higher risk from inundation and erosion. Exposure to coastal hazards is particularly high in Asia (Dumenu & Obeng, 2016) where 75% of the world’s population resides (Smith, 2011). Sea-level rise (SLR), combined with tsunamis, hurricanes, and other flooding, is responsible for the deaths of thousands of people and destruction of hundreds of coastal communities (Hallegatte et al., 2013; Jones, 2017; Reed et al., 2015; Wood et al., 2015; Woodruff et al., 2013). The
amplified risk of natural hazards leads to life-threatening flooding, destruction of infrastructure, and the decline of economic and ecological systems in coastal urban areas (Claudia et al., 2012; Hallegatte et al., 2013; Woodruff et al., 2013; Xu et al., 2016a, 2016b). This situation is alarming for the low-lying coastal regions, especially in some developing nations as they are ill-equipped to deal with current and future climate change (Cutter & Finch, 2008; Nicholls & Cazenave, 2010).

According to the China’s New-Type Urbanization Plan 2014–2020, over 12 million rural residents will become new urban residents annually across the next few decades. Urban and economic development fueled by the expected population growth contributes to the degradation of China’s coastal ecosystems. Coastal land reclamation is the single largest contributor among all threats to coastal ecosystems, comprising 30.3% of ecosystem degradation (Qiu, 2011). China has lost about 69% of its total mangrove areas and 80% of its total coral reef areas due to rapid urbanization and economic development-related activities (Wang et al., 2014). Without strict conservation efforts, irreplaceable habitat loss and degradation will continue in the coming decades.

Fifty-seven percent of coastal wetlands in China has been lost to land reclamation since the 1950s (Cui et al., 2016; Qiu, 2011). Coastal ecosystems buffer the shoreline from storm damage and erosion (He et al., 2014; Sousa et al., 2016); therefore, its degradation puts coastal populations and critical infrastructure at risk from natural weather occurrences. Monitoring and modeling of urban expansion and its impacts on ecological and social systems are key to sustainable development (Güneralp & Seto, 2013; Srinivasan et al., 2013). These processes require innovative tools and models to assess current and future changes (He et al., 2016; Liu et al., 2015; Peng et al., 2016).

The reclamation of coastal land is arguably one potential solution to the growing demand for land, and its reclamation can be observed on a large geographical scale in coastal nations such as the Netherlands (Butler, 1972), the United States (Kennish, 2001), and Japan (Suzuki, 2003). As a result of reclamation during the past half-century in China, a large number of tidal flats were lost (Larson, 2015b).

In order to prioritize ecosystem services for conservation or restoration, it is necessary to know in which areas natural habitats have more potential to decrease exposure to flooding and erosion from SLR and storm surges. This can provide place-based information of where the natural habitats shield susceptible populations from surges and flooding (Arkema et al., 2017; Guan et al., 2015). Despite the fact that many coastal communities are increasingly willing to integrate ecosystem approaches for coastal hazard reduction (Arkema et al., 2017), the previous literature in this field provides little information on conservation measures and restoration approaches for natural habitats and coastal defense in China. Furthermore, policy development in China did not adequately consider the role of natural habitats in risk reduction, and its implementation was not risk-informed. Moreover, the existing approaches focused on vulnerability assessment and were isolated in nature (Boettlet al., 2016; Claudia et al., 2012; Ekstrom et al., 2015; Lovelock et al., 2015; Mechler et al., 2014; Tessler et al., 2015), rather than integrating these assessments in future planning and management to enhance the resilience of coastal areas (see Text S1, Supporting Information) (Arkema et al., 2013, 2015; Liu et al., 2015). The objectives of this study are (1) to assess the current and future vulnerability of communities to coastal natural hazards through coupling human–natural systems, (2) to highlight the role of coastal natural habitats for their ability to shield coastal populations from natural hazards, and (3) to stress the conservation and restoration of natural habitats for the sake of coastal resilience.

2. Methods and Data

2.1. Data

The datasets used in our research include the coastline data, 25-year coastal reclamation data and coastal land use categorization data, coastal population data, and coastal key habitats data in mainland China. We also use seven different types of biogeophysical variables for the integrated valuation of ecosystems and tradeoff (InVEST) model (see Table S1, for a list of these variables) and the National Marine Function Zoning dataset for mainland China. For more information on key data, description, and sources, please refer to Table S2.

2.2. Research Framework

Our research framework involves conducting a coastal assessment using satellite data to facilitate the calculation of coastal vulnerability, resilience implication, and concluding with integration into decision-making
and policy formulation, as shown in Figure 1. The research is based on the coupling of human–natural systems (reclamation and coastal development representing the human systems and biogeophysical variables representing the natural system) as both are interconnected. The change in one system has obvious effects on the other.

There are three major modules. The first one is an evaluation of shoreline changes from 1990 to 2015 and the assessment of coastal reclamation along with the identification of directly lost natural habitats using remote sensing (RS) and geographic information system (GIS). The data collected are then integrated to produce one present and two future scenarios. The second module includes a collection of all the input data and use of the InVEST coastal vulnerability model to assess the exposure of coastal communities to natural hazards, such as coastal flooding and storm surges, under the aforementioned scenarios. The third module discusses the significance of coastal natural habitats for coastal resilience against natural hazards. A detailed research framework is presented in Figure S1.

2.2.1. Land Use Cover Change of Coastal Reclamation Area

To understand the degradation of coastal natural habitats due to coastal development, we assess the coastal reclamation between 1990 and 2015. We obtain data regarding the changes in mainland of China’s coastline during the given period and analyze it using GIS with a linear approach. The evaluation of these changes in the shoreline, together with the visual interpretation of high-resolution satellite images, helps develop land use data in recently reclaimed areas. Further assessment of this dataset unveils the major drivers behind land reclamation as well as information regarding the degradation of coastal natural habitats in China from 1990 to 2015. The reclamation data are acquired through the assessment of the Landsat Thematic Mapper (TM) RS images for the given period with a 5-year interval and were complemented with the Quick-Bird satellite datasets for the same years to enhance the accuracy. The changes in land use are obtained by visual interpretation of the very-high-resolution Google Earth images, Quick-Bird and TM RS images (Figure 2). For more details on coastal reclamation in different areas of China from 1990 to 2015, see Figure S2.

2.2.2. Sea Level and Habitat Scenarios

Due to the unavailability of data related to future SLR along mainland China’s coastline, we hypothesize that the eustatic sea level in China is expected to be similar to worldwide SLR as projected by Intergovernmental Panel on Climate Change (IPCC) in the fifth assessment report (IPCC, 2013). Furthermore, this worldwide mean SLR is trimmed to attain a 0.34–1.18 m eustatic SLR of China by 2100 (Arkema et al., 2013). The National Land Subsidence Prevention Plan (2011–2020) states that China’s eastern coast is unlikely to face ground subsidence because of its mostly granite geology, and due to the absence of any historical record of uplift (Ministry of Land and Resources of the People’s Republic of China, 2012). However, while the coast as a whole is unlikely to experience much subsidence, localized areas of increased subsidence are likely because of the compaction of depositional sediments in the major river estuaries, such as the Perl River Delta region (Brown & Nicholls, 2015; Xu et al., 2016a, 2016b). Considering the spatial scale of our study, we do not consider vertical land movement in our analysis. We preferred eustatic SLR (0.34–1.18 m) for the future SLR scenarios. By considering this range as a baseline, we develop three SLR scenarios: current, B1, and A2 SLR scenario.

Previous studies lack assessment of potential solutions along with adaptive approaches, including the introduction of conservation and restoration of natural habitats along coastal areas. Coastal development through reclamation, in response to urban expansion, has also been neglected in previously produced scenarios, which is a key driving force behind the direct/indirect loss of important habitats. Here, we propose
two different habitat scenarios: (1) with the current status of natural habitats along China’s coastline and (2) after the restoration of lost and conservation of existing natural habitats along China’s coastline under current, B1, and A2 SLR. Hence, there are six scenarios (two habitat conditions $\times$ three SLR conditions) in total to be examined (Table S3).

In this study, the “with habitat scenario” includes four natural habitats (mangrove, seagrass, saltmarsh, and coral reef) present on China’s eastern coast (Figure S3). Here, “with habitat” refers to the current status of natural habitats along China’s coastline. We had planned to include more coastal natural habitats such as shrubs.
in our study as these also have significant implications for coastal vulnerability to natural hazards; however, spatial datasets for these natural habitats at the scale and time period of our study were not available.

The direct loss of habitats to coastal reclamation process is identified as shown in the first module of Figure 1. These areas combined with unused land from Figure 2 are used to create the conservation and restoration scenario. For this study, conversion means the restoration of lost natural habitats to reclamation and conservation means securing the remaining coastal habitats especially those in the vicinity of reclaimed land.

The “conservation and restoration” scenario is used to appraise where and to what extent coastal natural habitats contribute significantly to protecting the coastal populations. It is further used to determine where conservation, restoration, and plantation are required to reduce the risk from coastal hazards. Additionally, we estimate scenarios for natural habitats for recently reclaimed coastal land in China to develop a possible solution for coastal ecosystem depletion/degradation due to natural and anthropogenic influences. In the habitat conservation and restoration scenario, we assess how and which recently reclaimed coastal areas could be used sustainably to protect the manmade environment from natural hazards under current and future (B1, A2) SLR scenarios. The reclaimed area in our study is assumed to be wetlands (mangroves and salt marshes), as this ecosystem has the highest potential to defend the shoreline from erosion, shield it from flooding, and serve as a carbon sink. Wetlands are the most vulnerable areas to coastal reclamation in coastal regions of the world, which also supports our assumption.

### 2.2.3. Coastal Hazards Index Quantification

To assess the comparative exposure of each 1 km² section of the Chinese coastline for current and future scenarios, an index was calculated using the InVEST coastal vulnerability model. This package is open source and can be accessed as well as downloaded from www.naturalcapitalproject.org. An accurate digital elevation model (DEM) is critical for any future assessment of SLR impacts along coastal areas. Therefore, we use the best available DEM with a resolution of 90 m provided by the Resources and Environmental Sciences, Chinese Academy of Sciences (http://www.resdc.cn), for our analysis, as this is an essential input for the InVEST model. The resultant index from this model comprises the influence of coastal natural hazards, such as storm surges, through integrating experimental statistics on the potential of surges, waves, and wind in coastal regions, including records and models for the other four main variables, that is, type of habitat, SLR, relief, and shoreline. Because of the ambiguity among available models regarding the association between climate change and waves, we assume that both the frequency and intensity of the storms would be similar in both current and future scenarios (the future scenario is projected to be the year 2100, the end of the century). Furthermore, the reanalysis results of the 6-year (2005 – 2010) WAVEWATCH III model HINDCAST from the National Oceanic and Atmospheric Administration (NOAA) are utilized to project the present-day wind and wave exposure. By using the observed and modeled data, the absolute measures of each indicator for every 1 km² division of coastline are generated and then variables are ranked for every section, from very low (Rank 1) to very high (Rank 5) susceptibility as presented in Table S1.

The coastal natural hazard index (NHI) is given as

$$ HI = \left( R_{\text{Habitat}} \times R_{\text{Shoreline type}} \times R_{\text{Relief}} \times R_{\text{SLR}} \times R_{\text{Wind}} \times R_{\text{Waves}} \times R_{\text{Surge potential}} \right)^{1/7} $$

where “HI” is the hazard index and “R” is the exposure rank for each variable.

All the variables are weighted equally in our study following numerous former coastal vulnerability concepts. The outcomes are the comparative exposure to the coastal natural hazard of each 1 km² section in relation to all other sections countrywide as well as across all six habitats-by-climate scenarios. For mapping, the hazard, the distribution of outcomes for all sections, and scenarios (with a range of 1 – 5) are further categorized into different quartiles based on the highest (upper 25%), intermediate (central 50%), and the lowest (lower 25%) vulnerability to natural hazards.

### 2.2.4. Risk Quantification

To assess the human population imperiled by hazards, the mapped population data of the entire Chinese shoreline are combined in each 1 km² segment of coastline. The total population is estimated in 1 km² segments classified as upper quartile/highest hazard. This risk quantification is based on all sea-level scenarios, with the current state of natural habitats and the conservation and restoration of natural habitats in recently reclaimed areas across mainland China’s east coast. We project the total number of people living within
1 km² segments of high hazard areas, and estimate elderly people (older than 65 years) and nonadults (between 0 and 14 years old) under one current and two future sea-level scenarios with the current state of natural habitats, conservation, and restoration of natural habitats in China’s coastal areas. We divide the population assessment into three different criteria — total population, elderly population (above 65 years old), and young population group (from 0 to 14 years old) — because these age groups are the most vulnerable to the effects of natural hazards.

We further analyze the vulnerable areas obtained through the InVEST coastal vulnerability model under different SLR and natural habitat scenarios. This step helps us to understand where the restoration and conservation of natural habitats have the least, intermediate, and greatest potential to enhance coastal resilience by safeguarding coastal communities.

3. Results

3.1. Coastal Vulnerability Mapping Under Different Scenarios

From total segments of the entire shoreline, we identify the upper quartile (“Highest Hazard”) measure as larger than 3.74 across all the scenarios. Today, 25% of mainland China’s coastline comprises high hazard areas (in the current sea-level scenario and “with current state of habitats”), which is more than the United States in 2013 (Arkema et al., 2013), presenting a potentially devastating situation on a national scale (Figure 3).

The spatial analysis of China’s coastline under current SLR reveals that on the basis of the NHI, the entire coastline can be divided into two regions — northern and southern. The northern region includes the areas from Shanghai to Liaoning northward and the southern region from Shanghai to Guanxi southward. The northern division of China’s coastline consists of upper hazard index areas (> 3.74), whereas the southern division contains intermediate hazard index areas (2.67–3.74) along with the lowest hazard index areas (<2.67) except the Fujian province.

3.2. Distribution of NHI Under Different SLR Scenarios Along China’s Coast

According to our results, 50% of the coastline of mainland China will be in the highest category of the hazard index (upper quartile) under the “A2” sea-level scenario as portrayed in Figure 4. The general distribution of coastal areas of China falls into the intermediate category of the hazard index (between 2.67 and 3.74); however, this trend will likely change under the A2 SLR from intermediate to the highest category as shown in Figure S4. Similarly, the overall trend of coastal segments follows the intermediate to highest hazard index value (2–4.5), which indicates the high vulnerability of most of the areas along China’s eastern coast as shown in Figure S5.

We evaluate 218 coastal counties of 11 coastal provinces at a national scale in high hazard areas (areas higher than the third quartile of the NHI) under 1 current and 2 future sea-level scenarios. Seven out of 11 coastal provinces are expected to be at high risk under current SLR scenarios with the current state of natural habitats (Figure S6), and 159 out of 218 coastal counties (about 69%) are at high vulnerability (Figure 5). A clear reduction in vulnerability can be seen under conservation and restoration scenario by comparing Figures 4 and 5. The most significant reduction in exposure can be observed in the Pearl River Delta region, which could be a result of mangrove forest presence in this area.

3.3. Risk to Coastal Communities

Today, 25% of mainland China’s coastline, where 5.2 million people reside (approximately 31% of China’s coastal population), has the highest hazard area under current SLR. The area’s population (within 1 km from the coast) is expected to reach 5.5 million (33–35% of the total coastal population of China) under the B2 sea-level scenario and approximately 10 million under the A2 sea-level scenario (approximately 64% of China’s total coastal population). According to our conservation and restoration scenario, natural habitat restoration and conservation can reduce this exposure up to 45% along mainland China’s coastline, as shown in Figure S7. Similarly, the exposure of the nonadult population residing on mainland China’s east coast can be reduced from 0.7 to 0.3 million, from 0.8 to approximately 0.4 million, and 1.5 to 0.5 million under current, B1, and A2 SLR scenarios, respectively, by conservation and restoration of natural habitats along China’s east coast. These conservation and restoration measures can also reduce the exposure of the
Figure 3. Coastal NHL under current sea-level scenario; 25% of mainland China’s coastline is at high risk from natural hazards (upper quartile of hazard index, >3.74) today. The northern region of coastline is more exposed to natural hazards as compared to the southern region. The warmer colors illustrate the regions under higher exposure to coastal hazards.

elderly population from 0.4 to 0.2 million under both the current and B1 SLR scenarios, and 0.8 to approximately 0.23 million under the A2 SLR scenario, as shown in Figure S8.

4. Discussion

4.1. Scenario Analysis (Current State Versus Conservation and Restoration) and Role of Natural Habitats for Resilience

Although China has made remarkable progress in conserving and restoring coastal wetlands since 2002 (Bi et al., 2012), there are increasing threats and pressures from population displacement toward coastal areas
Figure 4. Coastal NHI under A2 sea-level scenario; 50% of mainland of China’s coastline is expected to be at high risk from natural hazards (upper quartile of hazard index) in the future with current state of habitats. This could be more if the degradation of natural habitats is not taken into account seriously during the reclamation process.

and rapid coastal development. To establish more resilient coasts and reduce the impact of future hazards and rapid recovery of the system’s functionality, it is necessary to evaluate the vulnerability of coastal communities and take structural and nonstructural measures coupled with natural features like coastal wetlands and other potential natural habitats (Silliman et al., 2015). This could lead to improved resilience of coastal communities (Linkov et al., 2014). This study provides a technical assessment and spatial analysis of coastal vulnerability in terms of valuing coastal habitats as a defense against hazards induced by rising sea levels along coastal regions of China.
Figure 5. Spatial distribution of the NHI (conservation and restoration scenario) in different marine functional zones: A2 SLR and NHI coupled with National Marine Functional Zones and coastal population. Fourteen percent of this population are 0–14 years old and 7% are older than 65 years. We include these two population groups as these are the most affected by natural hazards or in any crisis type of situation. We also include the 28 National Marine Functional Zones to assess current and future conditions in different functional zones along mainland China's coastline. Of these 28 National Marine Functional Zones, 7 contain areas with high hazard exposure (>3.74), including the Liaohi Delta Sea, Yellow River Estuary and North Western Sea, North East Sea in Shandong Peninsula, Jiangsu Coast Sea, Yangtze River Delta and Zhoushan Archipelago, Central Sea of Fujian, and the North East Sea of Ha.
The loss of coastal wetlands, for example, mangroves, is one of the key reasons for coastal flooding and accelerates the frequency of natural hazards (Haigh et al., 2015; Nadzire et al., 2014). China has lost approximately 57% of its coastal wetlands including mangroves and coral reefs since the 1950s (Qiu, 2011; Sun et al., 2015; Wang et al., 2014) and poor policy of coastal reclamation is a major reason behind this degradation of ecosystems in China (Qiu, 2011). Our study reveals that the regions along China's east coast lacking coastal habitats are in the highest category (upper quartile) of the NHI.

Moreover, climate change-driven SLR is anticipated to affect both the intensity as well as the frequency of coastal natural hazards (Chen et al., 2017; Ranasinghe et al., 2013). In our study, we estimated that under the A2 SLR, approximately 51% of mainland China's coastal region is expected to be in the upper quartile of the NHI. Coastal cities are growing in areas that are vulnerable to marine-related natural hazards (Güneralp et al., 2015; Muis et al., 2015). Our assessment results show that conservation and restoration of natural habitats such as mangroves and other coastal wetlands in recently reclaimed areas have the potential to reduce the future exposure of coastal populations to natural hazards by 45% in China under the A2 SLR scenario. This study presents the first national scale map of its kind for China's coastal vulnerability under SLR along with an estimation of the size of the population at maximum exposure to natural hazards.

Another effective practice being adopted by coastal communities is the integration of natural and built infrastructure (hybrid approach) into coastal planning. A hybrid approach can shield coastal communities along with providing other benefits to humans as well as nature (Sutton-Grier et al., 2015). Natural habitats reduce the impacts of coastal hazards on coastal communities (Guannel et al., 2015), but if the current and planned reclamation processes in China continue without consideration of conservation and restoration (Sun et al., 2015), the government's red line for coastal wetlands will be broken (Larson, 2015a). This could lead to irreversible degradation of coastal ecosystems along with higher risks for communities from coastal hazards.

4.2. Coastal Reclamation, Habitat Degradation, and mainland China's Policy Effectiveness

Estimating future vulnerability from SLR and valuing the added security features of natural habitats are necessary for design adaptation strategies and plans to reduce flood risk in coastal areas (Hinkel et al., 2014; Kuklikie & Demeritt, 2016). Governments and citizens around the world have already recognized the importance of coastal wetlands. Initiatives are underway in Europe in the form of the Integrated Coastal Zone Management and the “no net loss policy” in the United States, resulting in a net gain of habitat through conservation and restoration practices. Inversely, in China, there has been an increase in the reclamation of coastal wetlands especially from the late 1970s, when the gross domestic product was a dominating criterion for the assessment of local governments. The huge benefits from reclamation have led local governments to evade policy regulations set by the central government. The best example can be seen in the area bondage of 50 ha announced by the central government; however, local governments have divided the larger projects into smaller ones to reap economic benefits. If China continues with land reclamation as highlighted by Wang et al. (2014), this will lead to further degradation of coastal habitats and increased human exposure to natural hazards.

Even though the central government of China has included the environmental impact assessment to performance evaluation criteria, there has been no positive feedback or results reported to date (Ma et al., 2014). Therefore, an effective policy and implementation of that policy is crucial in China. Although the National Marine Functional Zoning (2011–2020) was announced in 2012 by China's State Council to manage the scale of reclamation projects, 0.25 million ha of coastal wetlands are expected to be claimed for infrastructure development and more for agricultural and other activities by 2020, according to the Marine Functional Zoning Plan (2011–2020) (www.gov.cn/zwgk/). This proposed project can have a huge negative impact on coastal habitats, making these areas less resilient to natural hazards in coastal zones. There is a dire need for legislation of a “no net loss” of coastal habitats. The findings of this study improve our understanding of the prominence, sensitivity, and susceptibility of these areas and advise where, why, and to what extent these habitats are crucial for conservation and restoration.

The coastal reclamation in China is a major factor in the destruction of coastal wetlands in the northern part of China's eastern coast especially the area of Bohai Bay and the delta of the Yangtze River, including Shanghai. These areas are highly affected by human pressures resulting in the removal of natural habitats.
from the areas and rendering them prone to natural hazards (Tian et al., 2016). Our study shows that millions of people in mainland China, including youth and the elderly, are at risk from SLR by the end of the century, a finding also supported by Hauer et al. (2016). They estimated that 4.2 million people living in coastal regions of the United States are at risk from SLR (Hauer et al., 2016), half the number projected in China (10.7 million people).

The study also highlights the significance of putting science into practice for human as well as natural systems as it combines the coastal habitats conservation and restoration scenario together with SLR. Nature-based solutions are roadmaps to sustainable coastal societies due to the limitations of conventional engineering approaches, such as the disturbance to natural delta processes, accelerated SLR, and long-term flood risk (Temmerman et al., 2013). Thus, our study emphasizes conservation and restoration of natural habitats along mainland China’s coastal areas. However, better and more focused datasets are required to obtain measures that are more precise and consequently make optimal decisions. Our research is spatially expandable and allows planners, managers, and policy producers to prioritize different areas for both immediate and gradual actions for climate change adaptation as well as sustainable coastal development.

Resilient coasts are far less vulnerable to natural disasters due to their functionality as compared to less resilient. Linkov et al. (2014) present the idea of system’s functionality, function loss due to stressors, and recovery of that functionality based on the risk management. The current study focuses on the risk analysis, which is a central component of Linkov’s resilience management framework. We identify that coastal natural habitats can play a significant role within both components of system’s functionality. Taken as a broader notion, resilience is the capacity to absorb, recover from, and more effectively adapt to internal as well as external extremes. Based on Linkov’s resilience theory (Linkov et al., 2014), we present the idea of vulnerability modeling with resilience theory to comprehend the linkage between human—natural systems, the vulnerability–resilience paradigm, and the role/benefits of conservation and restoration of coastal natural habitats. Exposure to natural hazards in this study is presented as a possible threat under which the coastal functionality can reach its lower tipping point. The consequences of this threat are evaluated on three different population groups, and the vulnerability of coastal communities is analyzed to assess the risk for an in-depth evaluation at a national scale. Based on our results, we argue that the conservation and restoration of coastal natural habitats play a significant role into helping the overall system absorb and recover from the shocks of natural hazards. Notably, this information is convincing for governments to form better policies regarding protection of coastal habitats, and for stakeholders to plan coastal regions under resilience framework. Coastal reclamation processes contribute to the decline of a coastal system’s functionality in any region of the world. Therefore, it is advisable to initiate appropriate actions and value, as well as prioritize coastal ecosystems, to cope with climate change and its byproducts through multiple services provided by these systems. The limitations, challenges, and future work are discussed in Text S2 (Bilskie et al., 2016; Larson, 2015a, 2015b; Liu et al., 2015; Qiu, 2011; Seto et al., 2012).

5. Conclusions

Our research signifies the potential of natural habitats to shield coastal communities from natural hazards. The findings show that 25% coastline of mainland China is under upper quartile (high vulnerability) harboring 5 million residents. These numbers are expected to double by the year 2100 under A2 SLR scenario. This exposure of the population to coastal hazards can be reduced as much as 45% by the end of 21st century through conservation and restoration of coastal natural habitats in recently reclaimed areas. This study focuses on coupled human—natural systems to highlight the necessity of conservation and restoration of coastal natural habitats and sustainable use of reclamation process in coastal areas. Our approach puts forward first national-level risk reduction map under different SLR and natural habitat scenarios for China. The proposed research is spatially extendable to a regional or global level.

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Earth’s Future

Supporting Information for

Assessing Hazard Vulnerability, Habitat Conservation, and Restoration for the Enhancement of mainland China’s Coastal Resilience

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Introduction

This file contains the supporting information regarding the manuscript entitled above. The file contains additional images, tables and texts to explain the research work. The data sets and resources for data are mentioned for replicating the research.
Text S1. Introduction

The rapid urbanization puts coastal areas under high pressure leading to not only environmental degradation and related risks, but natural environment of coastal regions as well (Li et al., 2016). Urbanization consequently drives these coastal regions to become more prone to natural hazards under climate change, Sea Level Rise (SLR) and flooding (Arkema et al., 2015).

Previous studies emphasize the physical side of coastal vulnerability mapping using datasets and forecasts of climate scenarios to identify areas at greatest risk, and social matrices of vulnerability to map the consequences of these natural hazards (Arkema et al., 2013). What is missing is an integration of climate change scenarios, natural habitats and demographic datasets to model the significance and capacity of these habitats to defend human and natural systems. Quantifying ecosystem services provided by coastal habitat and embedding them in coastal planning leads to better outcomes for both humans and nature (Arkema et al., 2015).
Resilience Implication
How coastal habitats are effecting the resilience curve against Natural hazards?
Enhancing----Reducing----Neutral

Coupling Physical and Ecological Modelling Systems

Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) Coastal Vulnerability Model

Variables Rankings
Exposure Index
Vulnerability Assessment

Risk Quantification

Coupling Vulnerability and Risk Assessment Model with Resilience

Resilience Implication
How coastal habitats are effecting the resilience curve against Natural hazards?
Enhancing----Reducing----Neutral

Integration into Decision Making and Policy formulation
Prioritize action on the bases of Exposure, Vulnerability and Risk
Integration into Emergency & Risk Management
Educate and engage stakeholders, governments and decision makers

Figure S1. Comprehensive Framework of Research
<table>
<thead>
<tr>
<th>Variable</th>
<th>1 (Very Low)</th>
<th>2 (Low)</th>
<th>3 (Moderate)</th>
<th>4 (High)</th>
<th>5 (Very high)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NATURAL HABITATS</td>
<td>Coral Reef;</td>
<td>Emergent marsh;</td>
<td>Low dune</td>
<td>Seagrass Bed</td>
<td>No habitat</td>
</tr>
<tr>
<td></td>
<td>Coastal Forest (Mangroves)</td>
<td>oyster reef</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SHORELINE TYPE</td>
<td>Rocky; high cliffs seawalls</td>
<td>Medium cliff; indented coast</td>
<td>Low cliff alluvial plain</td>
<td>Cobble beach; estuary; lagoon; bluff</td>
<td>Barrier beach; sand beach; mud flat; delta</td>
</tr>
<tr>
<td>RELIEF</td>
<td>1st quantile</td>
<td>2nd quantile</td>
<td>3rd quantile</td>
<td>4th quantile</td>
<td>5th quantile</td>
</tr>
<tr>
<td>SEA-LEVEL CHANGE</td>
<td>1st quantile</td>
<td>2nd quantile</td>
<td>3rd quantile</td>
<td>4th quantile</td>
<td>5th quantile</td>
</tr>
<tr>
<td>WIND EXPOSURE</td>
<td>1st quantile</td>
<td>2nd quantile</td>
<td>3rd quantile</td>
<td>4th quantile</td>
<td>5th quantile</td>
</tr>
<tr>
<td>WAVE EXPOSURE</td>
<td>1st quantile</td>
<td>2nd quantile</td>
<td>3rd quantile</td>
<td>4th quantile</td>
<td>5th quantile</td>
</tr>
<tr>
<td>SURGE POTENTIAL</td>
<td>1st quantile</td>
<td>2nd quantile</td>
<td>3rd quantile</td>
<td>4th quantile</td>
<td>5th quantile</td>
</tr>
</tbody>
</table>

*Modified from Arkema et al. 2013*

Table S1. Ranking system of seven bio-geophysical variables used to measure the Hazard Exposure to Natural Hazards
<table>
<thead>
<tr>
<th>Data</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coastline Data</td>
<td>The coastline of this research is divided into three types: natural coastline, artificial coastline surrounding and artificial coastline filling, which includes six types of coastline vector data (1990, 1995, 2000, 2005, 2005 and 2015) for eleven provinces and 218 coastal counties along mainland China's East coast. We obtained the coastline data of mainland China in 1990, 1995, 2000, 2005, 2010 and 2015 by using the method of visual interpretation, based on the latest Google Earth images for 2015 and historical images (1990-2010). Moreover, the data for the years 2005, 2010 and 2015 was obtained from Quick-Bird remote sensing image, and the data for the years 1990, 1995 and 2000 was complimented with TM and Quick-Bird data to enhance the accuracy.</td>
<td>We processed the coastline data by using ArcGIS10.2 platform, acquired the changed part of the coastline in 2010 by comparing with the coastline in 2015, of 2005 by comparing with coastline in 2010, and so on. With the help of this data, we got the changes of the reclamation domain. The change in land use was obtained by visual interpretation of Google Earth images, Quick-Bird and TM remote sensing images. Our GIS experts have worked for one year to get this job done.</td>
</tr>
<tr>
<td>Coastal Reclamation</td>
<td>We obtained five time periods reclamation data (1996-1995, 1995-2000, 2000-2005, 2005-2010 and 2010-2015) and the land use types (primary classification includes cultivated land, forest, grassland, construction land, natural wetland, artificial wetland and unused) according to the coastline data. Hence coastal reclamation area and its proportion of all provinces are available with distribution, area, and ratio of different land use types.</td>
<td></td>
</tr>
<tr>
<td>Coastal Population</td>
<td>The coastal population data of 11 coastal provinces and 218 coastal counties was included in our analysis. We used the data into three different groups: Total population, Non-Adult Population (0-14 years old) and Elderly population (Above 65 Years) to assess the population in areas under highest natural hazard index. We obtained the data by using the method of visual interpretation, based on the latest Google Earth images for 2015 and historical images (1990-2010). Moreover, the data for the years 2005, 2010 and 2015 was obtained from Quick-Bird remote sensing image, and the data for the years 1990, 1995 and 2000 was complimented with TM and Quick-Bird data to enhance the accuracy.</td>
<td>Mao Q, Long Y, &amp; Wu K. (2015). Spatio-Temporal Changes of Population Density and Exploration on Urbanization Pattern in China: 2000-2010. City Planning Review, 39(2): 38-43. Wu, K., Long, Y., Mao, Q., &amp; Liu, X. (2015). Mushrooming Jiedaos, Growing Cities: An Alternative Perspective on Urbanizing China. Environment and Planning A, 47, 1-2.</td>
</tr>
</tbody>
</table>
The data for natural habitat distribution along mainland China's coastline was obtained from different national and global sources and then was combined for Invest Coastal Vulnerability Model. We assessed 4 different key habitats along the mainland China's East coast under different sea level scenarios including Mangroves, Sea Grass, Salt Marshes and Coral Reefs.


Key Natural Habitat


National Marine Functional Zoning

We used the National Marine Function Zone data to inform the management authorities, planners and policy makers that where and to what extent the conservation and restoration of natural habitats play a significant role to shield the coastal communities.


The Functional Zones map was digitized on the basis of above mentioned using ArcGIS Desktop 10.1

Table S2. Different data sets used in this study along with description and sources
Figure S2. Coastal Reclamation in mainland China from 1990 to 2015 and different Land Use type in Reclaimed area in Tianjin, Shanghai, Xiamen and Guangzhou as determined by satellite and remote sensing imagery.
Figure S3. Coastal distribution of Natural Habitat along mainland China's east coast. The north-south division between tropical/sub-tropical and temperate coastal habitats is primarily driven by temperature.

<table>
<thead>
<tr>
<th>Sea Level Rise Scenario</th>
<th>Habitat Scenario</th>
<th>Coastal Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
<td>Current Habitat * Conservation and Restoration**</td>
<td>• Total Population</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Non-Adult Population (Age 0-14 years)</td>
</tr>
<tr>
<td>B1</td>
<td>Current Habitat Conservation and Restoration</td>
<td>• Elderly Population (Above 65 Years)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In highest exposure coastal segments</td>
</tr>
<tr>
<td>Current</td>
<td>Current Habitat Conservation and Restoration</td>
<td>(&gt; 3.74) by 1 Km² for National Scale and with National Marine Function Zone</td>
</tr>
</tbody>
</table>

Note: we followed the IPCC 2007 SLR projections to develop the SLR Scenarios

* Current Habitat scenario is based on the existing natural habitat along mainland of China's East Coast

** Conservation and Restoration scenario is developed in the reclaimed land along coastal areas where coastal habitats are degraded due to coastal reclamation

Table S3. Climate by Habitat Scenarios for Coastal Vulnerability assessment
Figure S4. Percentage of Coastal Segments. Under Current, B1 and A2 Sea Level Rise scenarios with current state of Natural Habitat along mainland China’s East Coast. The Maximum No. of segments (Out of total 19188 segments) are in highest quartile under A2 Sea Level Rise Scenario and the overall trend of these segments is increasing as we move from Current to A2 sea Level Rise Scenario.

Figure S5. Distribution of mainland China’s Coastal segments (Each coastal segment= 1Km2) on Natural Hazard Index under Current Sea Level Rise, with habitat Scenario (1-5, where 1 is the minimum Exposure to natural hazards and gradually increase as we move towards 5): The highest no. of segments fall in category 3.5-4 (23%) followed by 3-3.5 (22%), 2.5-3 (21%) and 2-2. (17%) respectively. The 12% of mainland China’s eastern coastal segments fall in
the category 4-4.5 with indicate the seriousness of the situation regarding exposure to coastal hazards. The overall situation of mainland China’s eastern coastline is from intermediate to Highest.

Figure S6. Coastal Provinces under natural hazard exposure under current sea level rise scenario. To provide a general idea for provincial management, we also analyzed the population distribution of 11 coastal provinces combined with National Marine Function zones which also indicated the northern areas especially Shandong province, Jiangsu province, Shanghai and northern part of Zhejiang province as more vulnerable as compared to southern.
Figure S7. Assessment of Total coastal population under current and two future scenarios with current state of natural habitat and conservation and restoration scenario. The conservation and restoration of natural habitat along mainland China’s coastline has potential to shield 40% more population under A2 Sea Level Scenario. The population is estimated only in the areas of Highest Natural Hazard Index.

Figure S8. Assessment of Elderly (Above 65 Years) and Non-Adult age group of population under upper quartile of Current, B1 and A2 Sea Level Rise with current state of natural habitat and Conservation and restoration Scenarios

Text S2. Challenges, Limitations and Future work

Coastal areas are always under pressure from natural as well as anthropogenic pressures, i.e., rising pollution, land reclamation, drainage and development. China is facing a challenging ecosystem state as the country has lost about 57 percent of its coastal wetlands, 75 percent of mangrove forests, and 85 percent of coral reefs. Land reclamation was an important factor for coastal ecosystem degradation (Qiu, 2011). Coastal wetlands are well known for their multiple advantages for both humans and natural systems. China is experiencing rapid urbanization, coastal reclamation, wetland loss (Larson, 2015) and new seawall establishment that threatens the biodiversity of coastal systems (Seto et al., 2012) which should be addressed properly for not only the sustainability of China’s coast but also the adjacent regions through tele-coupling (Liu et al., 2015).
One of the limitations of this study is the large spatial scale, while the local processes and dynamics mainly drive the impacts and physics of coastal hazards. However, the main focus of this study was to explain the restoration and conservation of coastal habitats, which can be achieved more effectively on a larger scale. Furthermore, regardless of this limitation, this research can provide initiation for finer-scale assessments such as the further evaluation of areas within the upper quartile of NHI. Additionally, as far as the applied model is concerned, the InVEST model uses a static or “bathtub” approach regarding SLR-based assessments, which sometimes under- or over-predicts water levels driven by surges in near shore zones (Bilskie et al., 2016). Considering the scale of our assessment, the static approach was only viable option, despite its limitations, due to the lack of available data. Lastly, we had to use the same dataset of population for future vulnerability assessment due to unavailability of future population projections at the scale of our assessment. No doubts that this can have substantial implications as the coastal regions are expected to harbor more populations in near future. This means more and more people will be living in high hazard areas due to increasing population densities in coastal zones.

Our future work will present the significance of conservation and restoration measures and quantification of services provided by natural habitats (ecosystem-based solutions) to recover the functionality of coastal system.