sustainability

MDPI

Article

Assessing Nature-Based Coastal Protection against Disasters Derived from Extreme Hydrometeorological Events in Mexico

Octavio Pérez-Maqueo [1,*], M. Luisa Martínez [2], Flor C. Sánchez-Barradas [1] and Melanie Kolb [3]

1 Red de Ambiente y Sustentabilidad, Instituto de Ecología, A.C., Xalapa 91070, Veracruz, Mexico; flower_1909@hotmail.com

2 Red de Ecología Funcional, Instituto de Ecología, A.C., Xalapa 91070, Veracruz, Mexico; marisa.martinez@inecol.mx

3 Instituto de Geografía, UNAM, Ciudad de México 04510, Mexico; kolb@igg.unam.mx

* Correspondence: octavio.maqueo@inecol.mx; Tel.: +52-228-842-1800 (ext. 4303)

Received: 23 January 2018; Accepted: 19 April 2018; Published: 24 April 2018

Abstract: Natural ecosystems are expected to reduce the damaging effects of extreme hydrometeorological effects. We tested this prediction for Mexico by performing regression models, with two dependent variables: the occurrence of deaths and economic damages, at a state and municipality levels. For each location, the explanatory variables were the Mexican social vulnerability index (which includes socioeconomic aspects, local capacity to prevent and respond to an emergency, and the perception of risk) and land use cover considering different vegetation types. We used the hydrometeorological events that have affected Mexico from 1970 to 2011. Our findings reveal that: (a) hydrometeorological events affect both coastal and inland states, although damages are greater on the coast; (b) the protective role of natural ecosystems only was clear at a municipality level: the presence of mangroves, tropical dry forest and tropical rainforest was related to a significant reduction in the occurrence of casualties. Social vulnerability was positively correlated with the occurrence of deaths. Natural ecosystems, both typically coastal (mangroves) and terrestrial (tropical forests, which are located on the mountain ranges close to the coast) function for storm protection. Thus, their conservation and restoration are effective and sustainable strategies that will help protect and develop the increasingly urbanized coasts.

Keywords: nature-based coastal protection; extreme hydrometeorological events; tropical cyclones; economic damage; casualties; Mexico; coast; sustainable coasts

1. Introduction

Globally, extreme hydrometeorological event—such as hurricanes, cyclones, and tropical storms—are considered to be amongst the most socioeconomically damaging disasters which, from 1900 to 2017, have cost over 1 million lives, 1200 billion USD in property damage, and affected more than 1 billion people [1]. Moreover, during the last decades, the risk of these events and their impacts having an adverse effect on human populations has grown because of increasing human encroachment on the coasts [2] and a higher frequency of tropical cyclones, especially category 4 and 5 hurricanes [3]. In addition, as coastal ecosystems are lost and as the occurrence of coastal squeeze expands [4], the functionality (natural hydro-sedimentary and ecological dynamics) of the coasts is gradually being diminished. The result is a high-risk situation for both human lives and assets, as well as for ecosystems, that needs to be addressed as effectively as possible. Indeed, for many decades, the construction of groins, levees, dykes, and sea walls was considered as the best protection against flood risks, because this infrastructure helps reduce local erosion and prevents flooding by mitigating the impact of battering waves. The problem is that these hard-defense options have been increasingly challenged because: (a) when they are not built properly (for example, see [5]), the natural hydro-sedimentary dynamics are hindered, and severe erosion problems occur down-drift; (b) as the supply of sand is altered, the long-term buildup of beaches and dunes is compromised; (c) the need for maintenance is continuous and costly [6,7].

The abovementioned problems have promoted the search for new strategies to protect the coasts, such as nature-based management options. The premise of this alternative is that species from these environments are adapted to the abiotic limitations of the coast [8–11], thus, species tolerance to flooding and erosion [9,12] enables the ecosystems to reduce the impact of coastal hazards. In consequence, it is expected that nature-based coastal protection can cost-effectively reduce the damaging effects of extreme meteorological events on coastal populations by absorbing storm energy [13]. In addition, coastal ecosystems also help protect the coast by either producing sediments (sea grass beds and coral reefs) or by holding the sand together (mangroves and coastal dunes) [7,14,15]. It has also been demonstrated that coastal herbaceous wetlands help reduce economic damages generated by hurricanes and their impacts [13,16]. In brief, this option promotes coastal protection through the recovery of the natural functioning of natural ecosystems by means of conservation and restoration actions [6,17]. The trade-offs between socioeconomic development and conservation can be integrated [18–20], which will help with improving coastal development and promoting a sustainable coastal development.

In Mexico in particular, the impact of tropical cyclones (e.g., hurricanes) is highly relevant because they affect both the Atlantic and Pacific coasts on a yearly basis. The exposure to waves and storm surges induced by hurricanes usually covers many kilometers and affects large regions, inducing heavy rains and floods on both the coast and further inland. During the last 50 years, at least 17 high-impact hurricanes have landed on Mexican coasts, resulting in billions of dollars in damages as well as thousands of lost lives (Table 1) (NOAA, National Hurricane Center). However, not only high-impact hurricanes land on Mexican coasts. Many low-category hurricanes with large amounts of water and relatively strong storm surges also arrive (for instance, see hurricane Stan in 2005, Table 1).

The high frequency of hurricanes affecting Mexico is combined with the intense and increasing human encroachment on the coast. Currently, almost 13 million people (10% of the Mexican population) live less than 20 km from the coast, and 7 million live less than 10 m above sea level [21]. Given the growing need for coastal protection, it is necessary to assess if nature-based protection can indeed be a viable alternative in Mexico, considering local socioeconomic and environmental attributes. Specifically, it is of relevance to assess how different natural ecosystems can help protect the coasts because their long-term sustainability needs to guarantee a healthy environment and adequate socioeconomic conditions. To achieve this, the conservation of natural ecosystems and their functionality, with a focus on shoreline dynamics, can be combined with the protection of human lives and infrastructure. In this study, we explored the evidence of how natural ecosystems can contribute to nature-based protection of the coasts, thereby minimizing economic damages and loss of human lives [22].

Table 1. Most damaging hurricanes in recent Mexican history (NOAA, National Hurricane Center). Damages for Manuel and Ingrid are combined because they occurred simultaneously.

Year	Hurricane	Category	Landing	Economic Damages (Million USD)	Death Toll
1955	Hilda	3	Yucatan, Tamaulipas	120	300
1955	Janet	5	Yucatan, Veracruz, Tamaulipas	45	800
1959	Mexico	5	Colima, Jalisco	280	hundreds
1967	Beulah	3	Tamaulipas	100	38
1988	Gilbert	5	Yucatan, Campeche, Veracruz, Tamaulipas	2000	202
1995	Opal	5	Yucatan, Campeche, Tabasco, Quintana Roo	5.1	63
1995	Roxane	3	Campeche, Quintana Roo, Tabasco, Veracruz, Yucatan	1500	14
1997	Pauline	4	Oaxaca, Guerrero	7500	400
2005	Emily	4	Quintana Roo, Campeche, Tamaulipas	632	9
2005	Wilma	5	Quintana Roo, Campeche	10,000	19
2005	Stan	1	Campeche	3000	1668
2007	Dean	5	Yucatan, Campeche, Veracruz	200	12
2012	Charlotte	2	Oaxaca	113	7
2013	Manuel	1	Guerrero	5700	168
2013	Ingrid	1	Gulf of Mexico		
2014	Odile	4	Baja California	1200	18
2015	Patricia	5	Jalisco	460	13

2. Materials and Methods

2.1. Impact of Extreme Hydrometeorological Events in Mexico

To assess the long-term impact of natural disasters that have occurred in Mexico, we used the EM-DAT database [1], which is the longest-running disaster database for the country. This database enabled us to determine the most damaging events that have hit Mexico from 1900 to 2018. In addition, we used a more detailed database from a Mexican Government Agency, CENAPRED (*Centro Nacional de Prevención de Desastres*—National Center for Disaster Prevention), which contains economic damages and number of casualties. This database was reorganized to determine the state-level socioeconomic impacts of different hydrometeorological events, from 2000 to 2015. For each state, the data set from CENAPRED includes the date when each extreme hydrometeorological event occurred, the type of event (tropical cyclones, floods, intense precipitation), states and municipalities affected, number of casualties, population that was affected, the number of houses, schools, and hospitals that were damaged, and the impact on crops. It also includes total damages in Mexican pesos and US Dollars. From this, we added the total number of casualties and economic damages per state for the period covered by the database (2000–2015). In this descriptive analysis, we focused on states rather than on coastal municipalities because: (a) the impact of these events oftentimes goes beyond the coastal area, therefore, we compared coastal vs. inland states, in terms of economic damages and casualties; and (b) the databases that we used do not clearly separate the events. We first analyzed tropical cyclones, flooding, and heavy rains as a single type of event, because the last two are generally associated with tropical cyclones. Later, we focused on tropical cyclones alone, to be more specific.

2.2. Assessing the Protective Role of Natural Ecosystems

For each state and municipality in which a hydrometeorological disaster was recorded, we obtained data on: (a) casualties and economic damage caused by extreme hydrometeorological events that occurred between 2000 and 2015 [23]; (b) the probability of occurrence of tropical cyclones in Mexico (hazard index) [24,25]; (c) socioeconomic vulnerability [26,27]; and (d) land use cover [28–32].

2.2.1. Casualties and Economic Damages

Because of their high intensities and potential damage, the following hydrometeorological events were analyzed: floods (flash floods, riverine floods), heavy rains, storm surges, tropical storms, and strong winds. For each of these events, we gathered information on the reported economic damages and casualties for each of the affected states from 2000 to 2015, which is the time period covered by the official database of CENAPRED [33]. We performed our analyses at two levels: state and municipalities.

State level models: Economic damages were adjusted to 2010 Mexican pesos using the consumer price index (CPI) from the Banco de Mexico [34]. These values were then adjusted to USD using purchasing power parity (PPP) in 2010 [35]. Calculations were made following the methods used by Mendoza-González et al. [36]. In order to avoid the spurious correlation of a higher economic damage taking place in areas with higher economic development (and consequently, a reduced area covered by natural ecosystems) and *vice versa*, economic values were standardized according to the GDP of each state that was affected. Afterwards, these values (economic damage/GDP) were transformed to their natural logarithm +1 (LN (x + 1)) because the distribution was highly skewed (with very large and very small numbers, including zero damages and casualties). Similarly, the number of casualties per state per event was assessed while considering total state population from the year closest to each event.

Municipality level models: Because of the lack of detailed information at a municipality level in the Mexican official sources, we used the database "Desinventar" (Disinvent), which was created by LA RED (Red de Estudios Sociales en Prevención de Desastres en América Latina—Network of Social Studies to Prevent Disasters in Latin America). LA RED is an NGO that gathered information on the disasters that occurred in Latin America from 1994 to 2016. This database is financed by the United Nations Disaster Risk Reduction (UNISDR). We were not able to work with numbers of casualties because of the high variability within the database, thus, we worked with the occurrence of casualties, which was a dichotomic variable indicating the absence = 0 and the presence = 1 of deaths during a tropical cyclone. In this case, we added population size per municipality as an explanatory variable to search for differences in number of inhabitants in each state. We did not use the economic damages reported in this database because of the high variability in the estimates.

2.2.2. Probability of Occurrence of Tropical Cyclones: Hazard Index

After running the general models with all the natural ecosystems considered in this study and all the extreme hydrometeorological events, we created specific models. These were performed at a municipality level and focused on tropical cyclones alone, because they are reported as the most damaging events, especially on the coasts, although they can also affect inland states. In this case, we used the hazard index for tropical cyclones, which CENAPRED has calculated for each municipality in the country [25]. This index estimates the probability of a tropical cyclone occurring with certain intensity in each municipality [37,38], and it is calculated as follows. For each pixel sized $1^\circ \times 1^\circ$, all the categories of a given event were counted, from 1949 to 2015. That is, if, for example, Hurricane Wilma (2005) passed through a pixel, and during its course in that pixel it changed from category 1 to 2, the two events were counted for this pixel. Then, the probability of surpassing the highest hydrometeorological intensity was calculated for each pixel, which was named the probability of exceedance. Thus, the equation to calculate the hazard index was:

$$HI = \sum_{i=1}^{7} v(i) * i \tag{1}$$

where HI = hazard index; $v(i)$ probability of exceedance, and i intensity. Finally, the hazard index of tropical cyclones was classified as: very low (0–0.04); low (0.05–0.14); medium (0.15–0.31); high (0.32–0.57); and very high (0.58–1).

2.2.3. Socioeconomic Vulnerability

In addition, data on social vulnerability for each of the municipalities that were hit by the abovementioned hydrometeorological events from 2000 to 2015 were obtained from CENAPRED [27]. Social vulnerability is calculated based on a combination of economic, social, and cultural factors that determine (1) the degree to which a social group is trained to face an emergency and (2) the following rehabilitation and recovery from a disaster [26]. This social vulnerability index consists of three sections that include: (a) socioeconomic aspects (health, education, housing, employment, income, and population); (b) local capacity of the municipality to prevent and respond to an emergency (for example, local emergency plans; a council for emergency situations; a civil protection unit; disaster prevention; and early alert systems, among many other attributes of the municipality); and (c) the local perception of risk (for example, hazard and risk awareness; previous losses owing to natural disasters; previous events; knowledge of the different hazards and risks; knowledge of what to do in an emergency). The first part of the methodology (socioeconomic aspects) was considered to represent 50% of the index, since the living conditions of the population determine, to a large extent, the degree of vulnerability. The other two components of the vulnerability index are equally weighted, thus they each represent 25% of the total value. The value of the index varies between 0 and 1, and it is categorized into five levels: very low (0–0.20); low (0.21–0.40); medium (0.41–0.60); high (0.61–0.80); and very high (>0.80). For a description of each indicator, the rationale of the questions, and the full methodology to calculate the index, please check CENAPRED [26]. We used the social vulnerability index per municipality because it reveals the socioeconomic situation of all the localities that have been affected by the hydrometeorological events. Indeed, it is considered that the socioeconomic conditions of a town or city will determine the potential impact of any event: the more vulnerable, the more affected. Thus, we wanted to test if the vulnerability index was useful to predict the potential impact of hydrometeorological events.

2.2.4. Land Use Cover

Based on previous studies [13], land use cover was used as a proxy for ecosystem quality and potential protection from storm damage. We worked with this premise because earlier findings have already shown that, for example, mangroves help mitigate storm surge and coastal dunes reduce flooding and erosion [6–8]. In turn, forests were expected to act as buffers to wind disturbance. Thus, our working hypothesis was that storm damage would be inversely related with the area covered by natural ecosystems.

Information of land cover and land use from 1993, 2002, 2008, and 2011 was compiled from official databases [28–31,39] and included mangroves, agriculture, cloud forest, oak forest, shrubland, grassland, tropical rainforest, without vegetation, and other land use types. Detailed data on mangroves for 1981, 2005, and 2010 were obtained from CONABIO [40]. Tropical rainforests included different types of tropical forests (with perennial leaves, deciduous leaves, and dry tropical forest), according to the classification by Rzedowski [41]. Because land use cover changed over time, we analyzed extreme hydrometeorological events and land cover as indicated in Table 2. Data on mangroves were associated with tropical cyclones as follows: hurricanes from 1970 to 1981 with mangroves present in 1981; those that happened from 1982 to 2005 with mangroves present in 2005; and those that occurred from 2003 to 2010 with mangroves reported for 2010.

Table 2. Land cover and hurricane periods that were used in the statistical analyses.

Land Cover Period	Period of Hydrometeorological Events Analyzed
1993	1970–1993
2002	1994–2002
2008	2003–2008
2011	2009 to present

2.2.5. Data Analyses

We performed logistic and regression models, considering two dependent variables: the occurrence of deaths and economic damages. The explanatory variables were social vulnerability and land use cover, considering the different vegetation types, explained earlier. The models were run according to different criteria. First, we performed a general model and analyzed all hydrometeorological events against natural ecosystems. This initial generalized exploration was necessary because of how the databases are organized: the hydrometeorological events distinguish between tropical cyclones, floods, and heavy rains, but all of them can take place when a tropical cyclone hits land. Also, they can occur both on the coast and inland. These models used the data from CENAPRED, which are organized at a state level. Then, we performed a more specific analysis and focused only on tropical cyclones, because they are the most damaging events (specific models). In this case, because we wanted to reduce the scale, we used the dataset from the DESINVENTAR database, which is organized at a municipality level. When analyzing tropical cyclones, we added another explanatory variable: the hazard index (probability of landing of tropical cyclones), which was calculated as explained above. The different configurations and combinations of variables used in the models are shown in Table 3. The time frames covered in the databases we used largely coincided and, in all cases, we used the closest date for the best possible match. The models were simplified by using the Akaike information criterion (AIC) and eliminating those variables that were not significant (“reduced models”). Our working hypothesis was that the occurrence of deaths would increase with reduced cover of natural ecosystems, a higher hazard index, and a higher social vulnerability. In turn, we expected that economic damage would increase with reduced cover of natural ecosystems and a higher hazard index, but it could increase with a reduced social vulnerability because the economic assets are expected to be higher in this case. The analyses were carried out with “R” [42].

Table 3. Summary of the variables used in the multiple regression analyses performed for state and municipality levels (n = number of entries used in each model).

	Regression Type			
	General: States (n = 1984)		**Specific: Municipalities (n = 2288)**	
		Database Used		**Database Used**
Hydrometeorological events used	All (floods, heavy rains, tropical cyclones)	CENAPRED (2000–2015) [33]	Tropical cyclones	DESINVENTAR (1970–2011) [23]
Explanatory variables	Social Vulnerability Index	CENAPRED (calculated with data from 2000–2015) [27]	Social Vulnerability Index	CENAPRED (calculated with data from 2000–2015) [27]
	Population per state (5-year mean)	INEGI [21] (2000–2010)	Population per municipality (5-year mean)	INEGI [21]
	Land use cover (mangroves, agriculture, cloud forest, oak forest, shrubland, grassland, tropical rainforest, without vegetation, and other land use types)	INEGI [28,29,31] (2002, 2007, 2011)	Land use cover (mangroves, agriculture, cloud forest, oak forest, shrubland, grassland, tropical rainforest, without vegetation, and other land use types)	INEGI [28,29,31,39]
	Hazard Index	CENAPRED (calculated with data from 1970–2011) [25]	Hazard Index	CENAPRED (calculated with data from 1970–2011) [25]
Response variables	Economic damages (pondered with state GDP 5-year mean)	CENAPRED (2000–2015) [43]		
	Total number of casualties (pondered with state population—5-year mean)	CENAPRED (2000–2015) [43]	Occurrence of casualties	DESINVENTAR [23]

3. Results

The results are organized according to different approaches. First, we describe the state-level impact of extreme hydrometeorological events in Mexico for 2000–2015. Then, we assess the protective role of natural ecosystems against hydrometeorological events, using regression models performed at a state and a municipality level. These approaches are described in the next sections.

3.1. Impact of Extreme Hydrometeorological Events in Mexico

The EM-DAT [1] database contains the longest official disaster database for Mexico that we found. It shows that from 1900 to the present, tropical cyclones are by far the most damaging natural events that have hit the country, with more than 5000 deaths and an economic damage of nearly 31 billion USD. In turn, even though the CENAPRED database only covers from 2000 to 2015, it also shows that tropical cyclones have been the most damaging events in terms of both casualties and economic losses (Figure 1). Other hydrometeorological events of relevance are floods and heavy rains (probably, these occurred due to tropical depressions). Two interesting patterns can be observed in Figure 1. First, most of the damages are concentrated in a small number of states, most of them located on the coast. That is, the largest damages occur on coastal states, whether the events are typically coastal (tropical cyclones) or not (floods, heavy rains), except for the number of casualties during floods, which is higher inland. Second, meteorological events typical of the coast, such as hurricanes, not only have caused damages and losses on coastal states, but also inland. In all three hydrometeorological events analyzed in Figure 1, the state of Veracruz, regretfully, stands out as one of the top five states with the highest economic damages and casualties. Guerrero, Quintana Roo and Baja California Sur are also amongst the most affected. In turn, inland states are more affected by heavy rains and floods than by tropical cyclones, especially those located in the arid regions of Mexico (for example, Chihuahua and Coahuila).

Like the states, the municipalities are not equally affected by hydrometeorological events, and the ecosystems in their territories are also very contrasting. For example, mangroves abound in the Yucatan Peninsula (southeastern Mexico) and the central-southern Pacific coasts. Other ecosystems that are typically inland are also found very close to the coasts (less than 1 km): tropical dry forests mostly occur along the Pacific coast and the Yucatan Peninsula, and tropical rainforests occur on the coasts of the Gulf of Mexico. Furthermore, oak and cloud forests are found on the mountains along the coasts (Figure 2). All land use covers have been affected by hydrometeorological events.

3.2. Assessing the Protective Role of Natural Ecosystems

The state-level regression models—performed with all the extreme hydrometeorological events and considering the number of casualties as the response variable—revealed a significantly negative regression with pine forests, tropical dry forest, thorn forest, and tropical rain forest, and a positive regression with hazard index, mangrove, shrubland, agriculture, and cloud forest (Table 4). In turn, the regression models with economic damage as the response variable showed that oak and thorn forests reduced the economic damages of hydrometeorological events, but a positive trend was observed for wetlands and "other", which were correlated with an increased economic damage (Table 5). Social vulnerability was only significantly and negatively correlated with economic damages. The remaining explanatory variables that we tested were not significant (Tables 4 and 5).

The results were quite different for the municipality-level logistic regression models that were focused on tropical cyclones and considered the occurrence of deaths as the response variable. Here, we found that mangroves, tropical dry forests, and tropical rainforests significantly reduced the occurrence of deaths (Table 6). In turn, grasslands were positively related with the occurrence of deaths (Table 6). Social vulnerability was significantly and positively correlated with the occurrence of deaths. The remaining explanatory variables that we tested were not significant (Table 6).

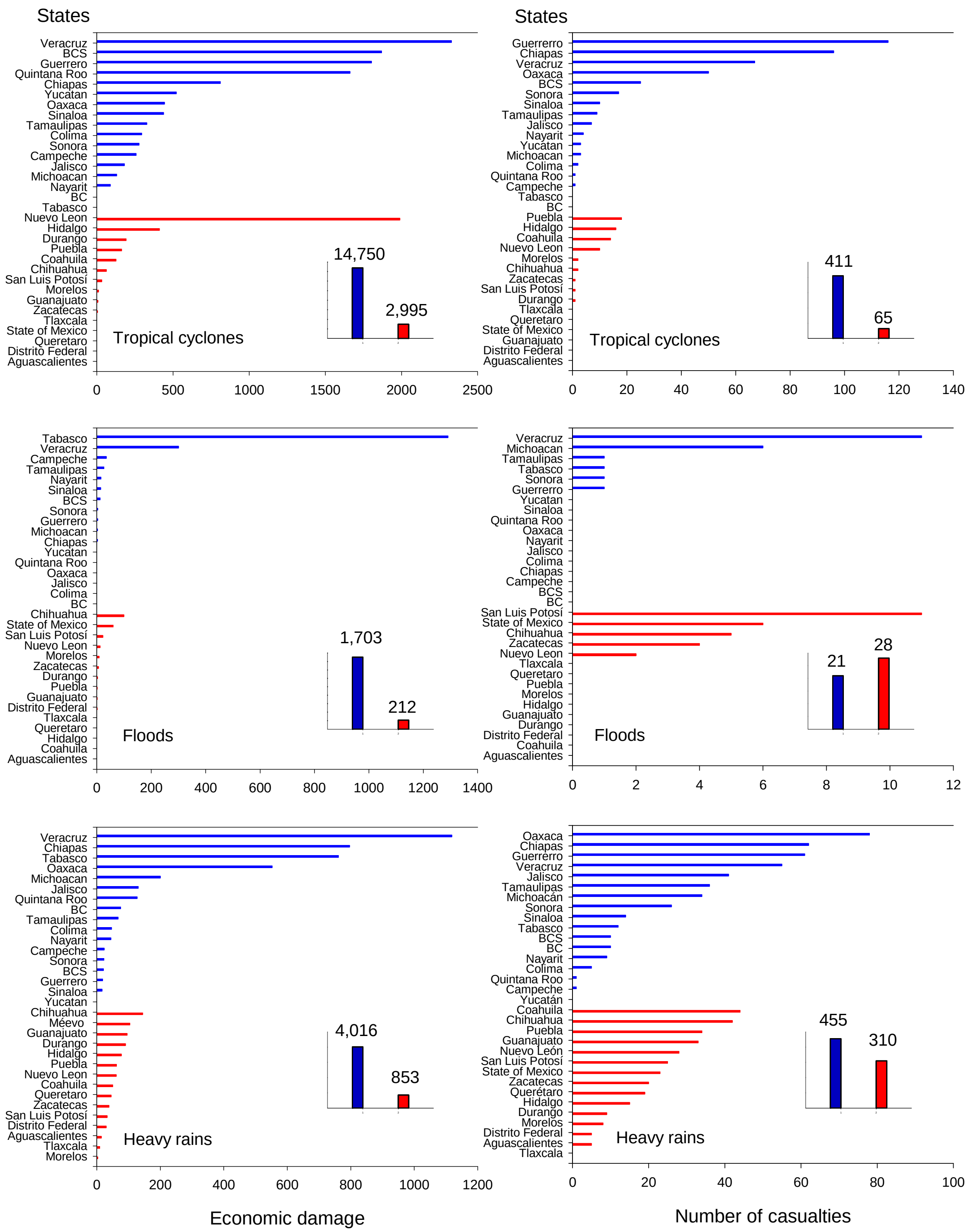

Figure 1. Economic damages and number of casualties owing to different extreme hydrometeorological events, in different states of Mexico (data from CENAPRED [43]), from 2000 to 2015. Blue bars represent coastal states; red bars, inland states. Note the differences in scale of the *X* axis. Inserted graphs show total net coastal and inland economic damages and number of casualties, respectively. Economic damages in USD 2010.

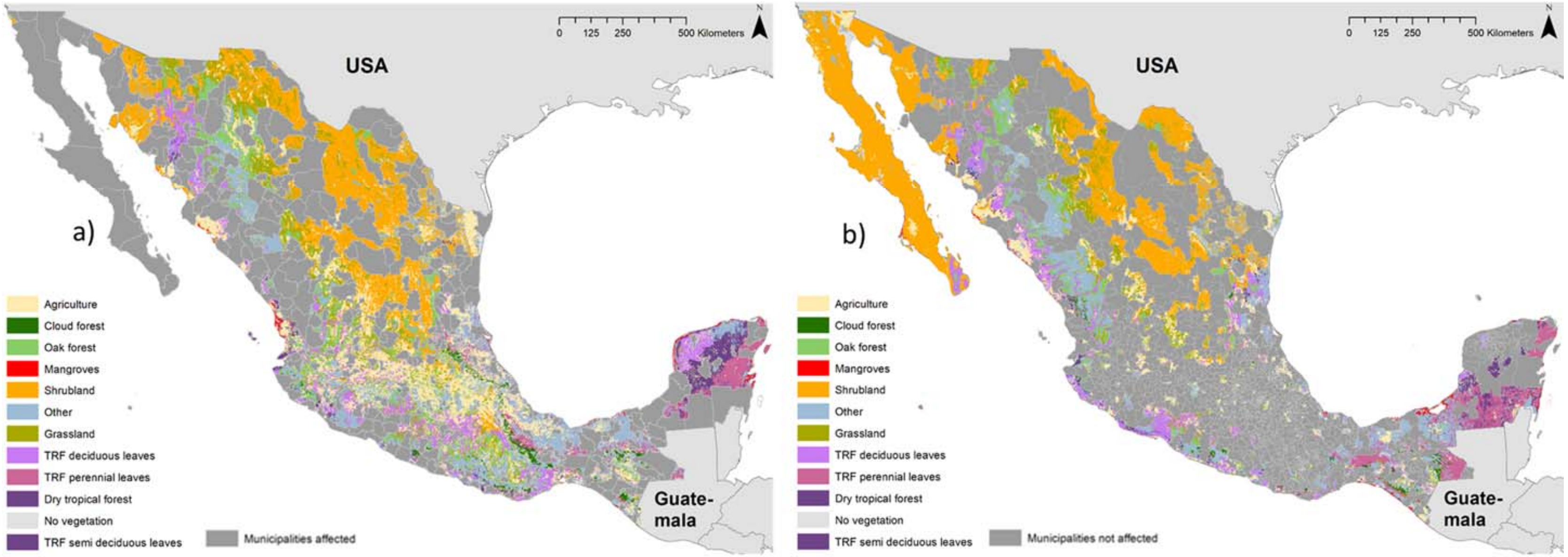

Figure 2. Land use cover in municipalities that have been affected (**a**) and unaffected (**b**) by extreme hydrometeorological events in Mexico (data from INEGI [43]). Grey covers municipalities that have been affected and not-affected, respectively.

Table 4. State-level regression model for the impact of extreme hydrometeorological events that have occurred in Mexico from 2000 to 2015, considering the number of casualties (reflecting state population) as the dependent variable. Significance codes: *** p = 0.001; ** p = 0.01; * p = 0.05; and p = 0.1.

Reduced Model	Estimate	Std. Error	t Value	Pr (>|t|)	Significance
(Intercept)	1.21×10^{-7}	2.47×10^{-7}	0.489	0.62484	
Social vulnerability	-1.04×10^{-7}	7.08×10^{-8}	−1.469	1.42×10^{-1}	
Hazard index	1.97×10^{-7}	4.26×10^{-8}	4.635	3.80×10^{-6}	***
Mangrove	3.58×10^{-12}	1.71×10^{-12}	2.097	3.61×10^{-2}	*
Pine forest	-1.96×10^{-13}	5.66×10^{-14}	−3.469	5.33×10^{-4}	***
Shrubland	6.94×10^{-14}	1.28×10^{-14}	5.417	6.81×10^{-8}	***
Tropical dry forest	-2.03×10^{-13}	8.34×10^{-14}	−2.434	0.015004	*
Agriculture	7.48×10^{-13}	2.99×10^{-13}	2.497	0.012589	*
Thorn forest	-7.59×10^{-13}	4.07×10^{-13}	−1.864	0.062485	
Tropical rain forest	-3.20×10^{-13}	1.31×10^{-13}	−2.452	0.014304	*
Cloud forest	8.38×10^{-13}	3.11×10^{-13}	2.696	0.007079	**
Deviance Residuals:					
Min	1Q	Median	3Q	Max	
-1.527×10^{-6}	-2.622×10^{-7}	-1.581×10^{-7}	-4.300×10^{-9}	3.075×10^{-5}	
n = 1985					
Null deviance: 2.8156×10^{-9} on 1984 degrees of freedom					
Residual deviance: 2.6987×10^{-9} on 1974 degrees of freedom					
AIC: −48,581					
Number of Fisher Scoring iterations: 2					

Table 5. State-level regression model for the impact of extreme hydrometeorological events that have occurred in Mexico from 2000–2015, considering the reported economic damages as the dependent variable, pondered by state GDP. Significance codes: *** p = 0.001; ** p = 0.01; * p = 0.05. and p = 0.1.

Reduced Model	Estimate	Std. Error	t Value	Pr (>|t|)	Significance
(Intercept)	1.43×10^{-3}	1.16×10^{-3}	1.226	0.220266	
Social vulnerability	-9.18×10^{-4}	3.47×10^{-4}	−2.643	0.008279	**
Hazard index	6.99×10^{-4}	2.09×10^{-4}	3.344	0.000843	***
Oak forest	-2.04×10^{-9}	7.80×10^{-10}	−2.614	0.009006	**
Grassland	6.22×10^{-10}	4.13×10^{-10}	1.508	0.131797	
Agriculture	3.54×10^{-9}	1.35×10^{-9}	2.629	0.008633	**
Wetlands	4.91×10^{-9}	1.99×10^{-9}	2.469	0.013641	*
Other	2.05×10^{-8}	9.26×10^{-9}	2.212	0.027056	*
Thorn forest	-5.18×10^{-9}	1.84×10^{-9}	−2.817	0.004893	**
Deviance Residuals:					
Min	1Q	Median	3Q	Max	
−0.005711	−0.001136	−0.000383	0.000313	0.205669	
N = 1984					
Null deviance: 0.085601 on 1983 degrees of freedom					
Residual deviance: 0.083359 on 1975 degrees of freedom					
AIC: −14,343					
Number of Fisher Scoring iterations: 2					

Table 6. Municipality-level logistic regression model for the impact of tropical cyclones that have hit Mexico from 2000 to 2015 considering the occurrence of casualties (yes or no) as the dependent variable. Significance codes: *** $p = 0.001$; ** $p = 0.01$; * $p = 0.05$; and $p = 0.1$.

	Estimate	Std. Error	z Value	Pr (>|z|)	Significance
(Intercept)	-1.52	2.49×10^{-1}	-6.125	9.09×10^{-10}	***
Social vulnerability	1.57×10^{-1}	8.39×10^{-2}	1.873	0.06106	
Mangrove	-3.09×10^{-5}	1.05×10^{-5}	-2.936	0.00333	**
Grassland	1.43×10^{-6}	6.46×10^{-7}	2.218	0.02658	*
Tropical dry forest	-3.95×10^{-6}	1.17×10^{-6}	-3.389	0.0007	***
Tropical rain forest	-1.81×10^{-6}	1.08×10^{-6}	-1.683	0.09238	
Thorn forest	4.96×10^{-6}	3.42×10^{-6}	1.451	0.14688	
Deviance Residuals:					
Min	1Q	Median	3Q	Max	
-1.2734	-0.7554	-0.6745	-0.2163	2.9312	
$N = 1134$					
Null deviance: 1170.6 on 1133 degrees of freedom					
Residual deviance: 1116.5 on 1127 degrees of freedom					
AIC: 1130.5					
Number of Fisher Scoring iterations: 6					

4. Discussion

4.1. The Protective Role of Natural Ecosystems

There have been previous studies that show how natural ecosystems help protect the coasts from the impact of extreme hydrometeorological events. Most of them are either experimental or focus on anecdotal evidence, and only a few have made estimates on the potential protection in terms of economic damages and losses of human lives [7,13,15–17,44]. For example, Barbier [45] studied the value of mangroves for protection against different natural coastal disasters such as floods, windstorms, and tsunamis, and on the Eastern coast of the USA, Costanza et al. [13] calculated the value of herbaceous wetlands for coastal protections against the impact of hurricanes by using spatially explicit data. In addition, Reguero et al. [11] tested the cost effectiveness of nature-based, vs. grey and policy measures and found that nature-based adaptation is among the most cost-effective option. However, each strategy for shoreline protection has its specific costs and benefits.

Other more local studies are those performed by Farber [46] and Costanza et al. [47], who focused on coastal protection in Louisiana (USA). To our knowledge, in spite the relevance of extreme hydrometeorological events hitting Mexico on a yearly basis, there are but a handful of local studies that address this issue. Mendoza-Gonzalez et al. [36] calculated the economic value of storm protection through a "replacement costs approach", in which the estimated values of ecosystem services were based on the costs of replacing ecosystem services. Other local studies on coastal protection by natural ecosystems in Mexico are those by Silva et al. [14,48], in which it was shown that artificial coral reefs and coastal dunes helped mitigate coastal erosion both under natural and laboratory conditions, respectively. The current study is the first one performed in Mexico, in which the potential protection from the impact of extreme hydrometeorological events provided by natural ecosystems is analyzed at a national level.

The regression models performed to test for the impact of hydrometeorological events and tropical cyclones that have occurred in Mexico from 2000 to 2011, considering the reported economic damages and the occurrence of casualties, showed that natural ecosystems had a varying effect. In the state-level models, considering all hydrometeorological events, the results showed that some ecosystems were negatively correlated but others were positively so. At this scale, typical coastal ecosystems such as mangroves were not statistically significant, possibly because of the scale. Mangroves cover a very reduced surface of each state, thus state-level damages were measured at a much larger scale, which made them practically invisible. In turn, the municipality-level model for tropical cyclones revealed that mangroves significantly reduced the occurrence of casualties, as well as tropical dry forest and tropical rainforest. This means that the occurrence of casualties was significantly reduced when these ecosystems were present. The approach we followed by means of logistic and linear regressions can be used to support adaptation strategies.

The protective role of mangroves has long been recognized in the literature [49–52], because they are located on the coast and their impact is immediate and direct. However, the findings for the different types of forests are new, considering that these are typically noncoastal ecosystems. This unexpected result can be explained by analyzing the geographical distribution of natural ecosystems in the country. In the South Pacific shores of Mexico, the mountain ranges are very close to the coast, and are mostly covered by tropical dry forests [53]. Here, the states of Guerrero, Oaxaca, and Chiapas are also frequently affected by hurricanes, thus their forests on the coastal mountain ranges are probably playing an important role in protection. Similar findings are reported for the state of Quintana Roo in the Yucatan Peninsula. In this case, previous studies demonstrated that common coastal tree species from tropical dry forests were more resistant to wind damage than inland species [54], and that older forests (with high stand size and large basal area) were more affected by Hurricane Dean than younger stands [55]. Furthermore, it is important to bear in mind that the role of vegetation in the watershed has long been recognized as relevant for the processes that take place on the coast and can also affect the response to the impact of hydrometeorological events [56,57]. In brief, the protective role of natural ecosystems depends on the type of ecosystem, regional interactions (i.e., watershed scale), as well as ecosystem attributes (species composition, structure, and age). Furthermore, the mechanisms through which ecosystems help mitigate damages may not be linear [17] and also may be different for each ecosystem. For instance, mangroves and wetlands may attenuate coastal flooding [16], coastal dunes reduce erosion [5], and shrublands and tropical dry forests may reduce runoff from rain and wind damage [55].

The mitigating effects predicted by the models were very low, but we think they are still relevant. The reduction of casualties is relevant, given the binary nature of the data we used: if natural ecosystems help reduce the occurrence of casualties, it may represent from one to many thousand lives, so it is worthy of consideration. In terms of avoided economic damages, previous estimated coastal protection values have ranged from USD 1700 to 5850 ha^{-1} year^{-1} [46,47], and higher estimates include those by Costanza et al. [13] (more than USD 100,000 per km^2 per year), and Mendoza-González et al. [36] (USD 67,874 ha^{-1} year^{-1}). Our reduced estimates are probably the result of the lower economic value of coastal development in Mexico, and can also be an underestimation that is derived from the databases that we used, because they were not spatially explicit and only cover 15 years. That is, unlike the work by Costanza et al. [13] and Mendoza-González et al. [36], in this study, the economic damages and occurrence of deaths were not as spatially detailed as land use cover was. The protective role of natural ecosystems can take place in a geographically distant location, such as updrift along the coast, or in the upper areas of the watersheds. Because of this, we think that more detailed, spatially explicit data—which should also include the regional functioning of natural ecosystems—will probably confirm our results with higher mitigating effects.

Another apparently unexpected result was the positive effect of shrublands on economic damages for all the hydrometeorological events. In this case, shrublands mostly occur in the Baja California Peninsula [53] and co-occur with hotels and urban infrastructure, hence the positive relation with the impact of hydrometeorological events and hurricanes. Also, it is important to note that shrublands can promote runoff and thus the economic damage could be increased.

In turn, the occurrence and intensity of casualties depends on many factors, which are summarized in the social vulnerability index. The vulnerability index includes socioeconomic aspects, local capacity of the municipality to prevent and respond to an emergency, and the local perception of risk. These are discussed below in terms of the sustainability of the Mexican coast when facing hydrometeorological disasters.

4.2. Sustainability of Mexican Coasts

In countries such as Mexico, where the growing human encroachment on the coast is combined with a frequent exposure to extreme hydrometeorological events, the vulnerability of the human settlements needs to be dealt with [26]. To achieve this, the Mexican government created the social vulnerability index, which addresses the vulnerability to many kinds of events. Hypothetically, we expected that those municipalities with the highest vulnerability index would be the most affected by the extreme events we tested. This hypothesis was not confirmed, because the vulnerability index was significantly positive for casualties at the state and municipality levels and negative for economic damages. This means that the social vulnerability index does not predict the possible outcome of the impact of hydrometeorological events, given the data that were available to us. It thus seems like a good idea to review the index and make it spatially explicit. Consequently, upon reviewing the index, the insertion of natural ecosystems should be considered in the calculations and the elaboration of the risks map.

Finally, although mostly effective, there are limitations of a nature-based protection and it is likely that different strategies can be combined to promote the conservation of natural ecosystems and protect the coasts [11]. We conclude that, besides improving coastal protection strategies, it is fundamental to reduce human pressure by mobilizing populations inland (or at least promoting new developments further inland) and minimizing the negative impact of human activities.

4.3. Caveats of the Study

As with any modeling exercise, our study had several caveats that need to be considered. First, the description of hydrometeorological events in the CENAPRED database is confusing. These events are described as tropical cyclones, floods, and heavy rains. Nevertheless, floods and heavy rains can occur when a tropical cyclone hits the country, as well as during other events such as cold fronts during the winter months. In this case, we only used the dates that were tagged as "tropical cyclones", although we may have missed additional events that were tagged as floods or heavy rains.

Second, the official databases that we used for land cover [26,28–31,37–40] are a good source of information, but some very relevant ecosystems are not described in detail. For instance, what is described as "other" probably includes coastal dunes, which are also a good alternative for coastal protection [7,8,45]. The specific inclusion of coastal dunes in these analyses will probably yield interesting results on how they help protect the coast from the impact of tropical cyclones.

Finally, it is relevant to acknowledge that the lack of information on the detailed features of the coast (that is, to consider the nearly 12,000 km of Mexican coastline as homogeneous) is another confounding effect. Indeed, the impact of each tropical storm will depend on the geomorphological features of the coast, as well as the other variables that we explored here. Certainly, as more spatially explicit and local information becomes available, the regression models to test for the protective role of natural ecosystems will largely improve. Also, the inclusion of spatial and temporal variability of the impact of hydrometeorological events would probably strengthen the predictive power of the models.

5. Conclusions

The effectiveness of the mitigation and protection against the impact of environmental hazards depends on several factors, such as the type of hydrometeorological event, the type of ecosystem, the heterogeneity of the coast, and socioeconomic and political attributes of the populations exposed. Thus, the preservation, restoration, and adequate management of natural ecosystems, as well as the reduction in social vulnerability, can be considered for coastal protection.

Author Contributions: Octavio Pérez-Maqueo and Flor C. Sánchez-Barradas conceived and designed the experiments; Flor C. Sánchez-Barradas gathered the databases; Octavio Pérez-Maqueo. and Flor C. Sánchez-Barradas

analyzed the data; Melanie Kolb generated spatially-explicit databases for land-use information and helped with data analyses; M. Luisa Martínez and Octavio Pérez-Maqueo interpreted the models and wrote the paper.

Acknowledgments: Octavio Pérez-Maqueo received partial funding from CONABIO to gather and perform data analyses of this study. We largely appreciate the assistance of A. Hernández-Huerta for helping us find the databases on economic damage of hurricanes in Mexico. We are very thankful to three anonymous reviewers who largely improved earlier versions of this article. No doubt, their insightful and detailed comments helped us improve the document a great deal.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. EM-DAT. The Emergency Events Database-Université Catholique de Louvain (UCL)—CRED, D. Guha-Sapir. Available online: www.emdat.be (accessed on 31 December 2017).
2. McGranahan, G.; Balk, D.; Anderson, B. The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environ. Urban.* **2007**, *19*, 17–37. [CrossRef]
3. Webster, P.J.; Holland, G.J.; Curry, J.A.; Chang, H.R. Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* **2005**, *309*, 1844–1846. [CrossRef] [PubMed]
4. Doody, J.P. "Coastal squeeze"—An historical perspective. *J. Coast. Conserv.* **2004**, *10*, 129–138. [CrossRef]
5. Silva, R.; Martínez, M.L.; Hesp, P.A.; Catalan, P.; Osorio, A.F.; Martell, R.; Fossati, M.; Miot da Silva, G.; Mariño-Tapia, I.; Pereira, P.; et al. Present and Future Challenges of Coastal Erosion in Latin America. *J. Coast. Res.* **2014**, *71*, 1–16. [CrossRef]
6. Temmerman, S.; Meire, P.; Bouma, T.J.; Herman, P.M.J.; Ysebaert, T.; De Vriend, H.J. Ecosystem-based coastal defence in the face of global change. *Nature* **2013**, *504*, 79–83. [CrossRef] [PubMed]
7. Salgado, K.; Martinez, M.L. Is ecosystem-based coastal defense a realistic alternative? Exploring the evidence. *J. Coast. Conserv.* **2017**, *21*, 837–848. [CrossRef]
8. Feagin, R.A.; Figlus, J.; Zinnert, J.C.; Sigren, J.; Martínez, M.L.; Silva, R.; Smith, W.K.; Cox, D.; Young, D.R.; Carter, G. Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion. *Front. Ecol. Environ.* **2015**, *13*, 203–210. [CrossRef]
9. Maun, M.A. *The Biology of Coastal Sand Dunes*; Oxford University Press: Oxford, UK, 2009; ISBN 978-0-19-857036-3.
10. Spalding, M.D.; Ruffo, S.; Lacambra, C.; Meliane, I.; Hale, L.Z.; Shepard, C.C.; Beck, M.W. The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean Coast. Manag.* **2014**, *90*, 50–57. [CrossRef]
11. Reguero, B.G.; Beck, M.W.; Bresch, D.N.; Calil, J.; Meliane, I. Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLoS ONE* **2018**, *13*, e0192132. [CrossRef] [PubMed]
12. Martínez, M.L.; Vázquez, G.; White, D.A.; Thivet, G.; Brengues, M. Effects of burial by sand and inundation by fresh- and seawater on seed germination of five tropical beach species. *Can. J. Bot.* **2002**, *80*, 416–424. [CrossRef]
13. Costanza, R.; Pérez-Maqueo, O.; Martinez, M.L.; Sutton, P.; Anderson, S.J.; Mulder, K. The Value of Coastal Wetlands for Hurricane Protection. *Ecol. Econ.* **2008**, *37*, 241–248. [CrossRef]
14. Silva, R.; Mendoza, E.; Mariño-Tapia, I.; Martínez, M.L.; Escalante, E. An artificial reef improves coastal protection and provides a base for coral recovery. *J. Coast. Res.* **2016**, *75*, 467–471. [CrossRef]
15. Reguero, B.G.; Beck, M.W.; Agostini, V.N.; Kramer, P.; Hancock, B. Coral reefs for coastal protection: A new methodological approach and engineering case study in Grenada. *J. Environ. Manag.* **2018**, *210*, 146–161. [CrossRef] [PubMed]
16. Narayan, S.; Beck, M.W.; Wilson, P.; Thomas, C.J.; Guerrero, A.; Shepard, C.C.; Reguero, B.G.; Franco, G.; Ingram, J.C.; Trespalacios, D. The Value of Coastal Wetlands for Flood Damage Reduction in the Northeastern USA. *Sci. Rep.* **2017**, *7*, 1–12. [CrossRef] [PubMed]
17. Barbier, E.B.; Koch, E.W.; Silliman, B.R.; Hacker, S.D.; Wolanski, E.; Primavera, J.; Granek, E.F.; Polasky, S.; Aswani, S.; Cramer, L.A.; et al. Coastal ecosystem-based management with nonlinear ecological functions and values. *Science* **2008**, *319*, 321–323. [CrossRef] [PubMed]

18. Chua, T.-E.; Bonga, D.; Bermas-Atrigenio, N. Dynamics of Integrated Coastal Management: PEMSEA's Experience. *Coast. Manag.* **2006**, *34*, 303–322. [CrossRef]
19. Duarte, C.M.; Losada, I.J.; Hendriks, I.E.; Mazarrasa, I.; Marbà, N. The role of coastal plant communities for climate change mitigation and adaptation. *Nat. Clim. Chang.* **2013**, *3*, 961–968. [CrossRef]
20. McLeod, K.L.; Lubchenco, J.; Palumbi, S.; Rosenberg, A.A. *Scientific Consensus Statement on Marine Ecosystem-Based Management*; Communication Partnership for Science and the Sea; Duke University: Durham, NC, USA, 2005.
21. INEGI Censo de Población y Vivienda 2010. Available online: http://www.beta.inegi.org.mx/proyectos/ccpv/2010/ (accessed on 1 August 2017).
22. Tapsell, S.; McCarthy, S.; Faulkner, H.; Alexander, M. *Social Vulnerability and Natural Hazards*; CapHaz-Net WP4 Report; Flood Hazard Research Centre, Middlesex University: London, UK, 2010.
23. DesInventar DesInventar. Sistema de Inventario de Desastres, Guía Metodológica. Available online: https://www.desinventar.org/ (accessed on 3 September 2017).
24. CENAPRED. *Diagnóstico de Peligros e Identificación de Riesgos de Desastres en México. Atlas Nacional de Riesgos de la República Mexicana*; Zepeda Ramos, O., Susana, G.M., Eds.; Electronic; Centro Nacional de Prevención de Desastres, Secretaría de Gobernación: Mexico City, Mexico, 2001; ISBN 970-628-593-8.
25. CENAPRED. Grado de Riesgo por Ciclones Tropicales. Available online: https://datos.gob.mx/busca/dataset/centro-nacional-de-prevencion-de-desastres (accessed on 20 December 2017).
26. CENAPRED. Guía Básica para la Elaboración de Atlas Estatales y Municipales de Peligros y Riesgos: Evaluación de la Vulnerabilidad Física y Social. In *Serie Atlas Nacional de Riesgos*; Centro Nacional de Prevención de Desastres, Secretaría de Gobernación: Mexico City, Mexico, 2006; p. 166, ISBN 9706289062.
27. CENAPRED. Grado de Vuilnerabilidad Social. 2010. Available online: https://datos.gob.mx/busca/dataset/centro-nacional-de-prevencion-de-desastres (accessed on 20 December 2017).
28. INEGI. Uso del Suelo y Vegetación, Escala 1:250,000, Serie IV (Continuo Nacional). Available online: http://www.conabio.gob.mx/informacion/gis/?vns=gis_root/usv/inegi/usv250s5ugw (accessed on 1 January 2014).
29. INEGI. Uso del Suelo y Vegetación, Escala 1:250,000, Serie III (Continuo Nacional). Available online: http://www.conabio.gob.mx/informacion/gis/?vns=gis_root/usv/inegi/usv250s5ugw (accessed on 1 January 2014).
30. INEGI. Uso del Suelo y Vegetación, Escala 1:250,000, Serie II (Continuo Nacional). Available online: http://www.conabio.gob.mx/informacion/gis/?vns=gis_root/usv/inegi/usv250s5ugw (accessed on 1 January 2014).
31. INEGI. Conjunto de Datos Vectoriales de uso de Suelo y Vegetación Escala 1:250,000, Serie V (Capa Unión). Available online: http://www.conabio.gob.mx/informacion/gis/?vns=gis_root/usv/inegi/usv250s5ugw (accessed on 1 January 2014).
32. INEGI. *Guia Para la Interpretación de Cartografía Uso del Suelo y Vegetación Escala 1:250,000 Serie V*; INEGI: Aguascalientes, Mexico, 2014.
33. CENAPRED. Base de Datos Sobre el Impacto Socioeconómico de los Daños y Pérdidas Ocasionados por los Desastres en México. Available online: http://www.atlasnacionalderiesgos.gob.mx/archivo/descargas.html (accessed on 26 March 2018).
34. Banco de México. Consumer Price Index. Available online: http://www.banxico.org.mx/portal-inflacion/inflation.html (accessed on 10 January 2018).
35. OECD. Purchasing Power Parities (PPP). Available online: https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm (accessed on 25 March 2018).
36. Mendoza-González, G.; Martínez, M.L.; Lithgow, D.; Pérez-Maqueo, O.; Simonin, P. Land use change and its effects on the value of ecosystem services along the coast of the Gulf of Mexico. *Ecol. Econ.* **2012**, *82*, 23–32. [CrossRef]
37. Fuentes Mariles, Ó.A.; Matías Ramirez, L.G.; Jiménez Espinosa, M.; Mendoza Estrada, D.R.; Baeza Ramírez, C. Elaboración de mapas de riesgo por inundaciones costeras por marea de tormenta. In *Guía Básica Para la Elaboración de Atlas Estatales y Municipales de Peligros y Riesgos*; Fenómenos Hidrometeorológicos; Centro Nacional de Prevención de Desastres, Secretaría de Gobernación: Mexico City, Mexico, 2006; pp. 221–293, ISBN 970-628-905-4.
38. Jiménez Espinoza, M.; Baeza Ramírez, C.; Matías Ramírez, L.G.; Eslava Morales, H. Mapas de Índices de Riesgo a Escala Municipal por Fenómenos Hidrometeorológicos. 2012. Available online: http://www.anr.gob.mx/Descargas/Metodologias/Hidrometeorologico.pdf (accessed on 18 October 2017).

39. INE-INEGI. Uso del Suelo y Vegetación, Escala 1:250,000, Serie I (Continuo Nacional). Available online: http://www.conabio.gob.mx/informacion/gis/?vns=gis_root/usv/inegi/usv250s5ugw (accessed on 1 January 2014).
40. CONABIO. Biodiversidad Mexicana. Available online: http://www.biodiversidad.gob.mx/ecosistemas/manglares2013/manglares.html (accessed on 14 January 2018).
41. Rzedowski, J. *Vegetación de México*, 1a ed.; Limusa, Ed.; Comisión Nacional para el Conocimiento y Uso de la Biodiversidad: Mexico City, Mexico, 2006.
42. R Development Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2008.
43. CENAPRED. Impacto Socioeconómico de Desastres de 2000 a 2015. Available online: https://datos.gob.mx/busca/dataset/impacto-socioeconomico-de-desastres-de-2000-a-2015/resource/868fe928-b3e7-4940-9e33-3abbb7cd41aa (accessed on 11 April 2017).
44. Sutton-Grier, A.E.; Gittman, R.K.; Arkema, K.K.; Bennett, R.O.; Benoit, J.; Blitch, S.; Burks-copes, K.A.; Colden, A.; Dausman, A.; Deangelis, B.M.; Hughes, A.R.; et al. Investing in Natural and Nature-Based Infrastructure: Building Better Along Our Coasts. *Sustainability* **2018**, *10*, 523. [CrossRef]
45. Barbier, E.B. Valuing ecosystem services as productive inputs. *Econ. Policy* **2007**, *22*, 178–229. [CrossRef]
46. Farber, S. The value of coastal wetlands for protection of property against hurricane wind damage. *J. Environ. Econ. Manag.* **1987**, *14*, 143–151. [CrossRef]
47. Costanza, R.; Farber, S.C.; Maxwell, J. Valuation and management of wetland ecosystems. *Ecol. Econ.* **1989**, *1*, 335–361. [CrossRef]
48. Silva, R.; Martínez, M.L.; Odériz, I.; Mendoza, E.; Feagin, R.A. Response of vegetated dune-beach systems to storm conditions. *Coast. Eng.* **2016**, *109*, 53–62. [CrossRef]
49. Fosberg, F.R.; Chapman, V.J. Mangroves v. tidal waves. *Biol. Conserv.* **1971**, *4*, 38–39. [CrossRef]
50. Alongi, D.M. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. *Estuar. Coast. Shelf Sci.* **2008**, *76*, 1–13. [CrossRef]
51. Bruun, P.; Gerritsen, F.; Morgan, W.H. Florida Coastal Problems. *Coast. Eng. Proc.* **1957**, *1*, 463–509. [CrossRef]
52. Barbier, E.B. Natural barriers to natural disasters: Replanting mangroves after the tsunami. *Front. Ecol. Environ.* **2006**, *4*, 124–131. [CrossRef]
53. Challenger, A.; Soberón, J. Los ecosistemas terrestres. In *Capital Natural de México, Vol. I. Conocimiento Actual de la Biodiversidad*; CONABIO: Mexico City, Mexico, 2008; pp. 87–108.
54. Vandecar, K.L.; Lawrence, D.; Richards, D.; Schneider, L.; Rogan, J.; Schmook, B.; Wilbur, H. High Mortality for Rare Species Following Hurricane Disturbance in the Southern Yucatán. *Biotropica* **2011**, *43*, 676–684. [CrossRef]
55. McGroddy, M.; Lawrence, D.; Schneider, L.; Rogan, J.; Zager, I.; Schmook, B. Damage patterns after Hurricane Dean in the southern Yucatán: Has human activity resulted in more resilient forests? *For. Ecol. Manag.* **2013**, *310*, 812–820. [CrossRef]
56. Samaras, A.G.; Koutitas, C.G. Modeling the impact of climate change on sediment transport and morphology in coupled watershed-coast systems: A case study using an integrated approach. *Int. J. Sediment Res.* **2014**, *29*, 304–315. [CrossRef]
57. Corbetts, C.W.; Wahlb, M.; Porter, D.; Edwards, D.; Moise, C. Nonpoint source runoff modeling A comparison of a forested watershed and an urban watershed on the South Carolina coast. *J. Exp. Mar. Biol. Ecol.* **1997**, *213*, 133–149. [CrossRef]