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When do Mangroves Create an Economic “Safe Haven” from Tropical Storms?

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Abstract

Evidence suggests that climate change will increase the frequency of intense storms. Mangroves may protect economic activity in coastal areas. We develop a model that illustrates protections from mangroves and coastal elevation and estimate the impacts of cyclones on coastal economic activity. We find that higher elevation *or* expansive mangroves alone shelter economic activity from “indirect” cyclone exposure whereas economic activity is only protected from “direct” cyclone exposure in high elevation communities *with* expansive mangroves. Our global mapping reveals that the majority of these “safe havens” are in upper middle-income countries but are used by populations in lower middle-income countries.

Introduction

Recent evidence suggests that the frequency of intense tropical cyclones has been increasing, and that this trend is likely to continue with climate change (Bacmeister et al. 2018; Walsh et al. 2016). As a consequence, there is growing interest in the protective role of mangroves that shelter coastlines during storm events by mediating the physical impacts of storms, such as decreasing water flow pressure, storm surge height, and wind speeds while also reducing flooding levels, durations and saline water intrusion (Alongi 2008; Marois and Mitsch 2015; Ouyang et al. 2018; Sandilyan and Kathiresan 2015; Spalding et al. 2014; Zhang et al. 2012). However, around one quarter of the world's mangroves have been lost due to human activity, mainly through conversion to aquaculture, agriculture and urban land uses (Duke et al. 2007; Friess and Webb 2014; Hamilton and Casey 2016; Spalding 2010). The global disappearance of mangroves is having a major impact on the vulnerability of coastal populations and property in developing countries, especially with respect to damaging and life-threatening storms and floods (Alongi 2008; Barbier 2014; Cochard et al. 2008; Spalding et al. 2014).

As a consequence, a number of studies have estimated the benefits of mangroves in terms of protecting physical property, local agriculture and industry, and lives in coastal areas (Badola and Hussain 2005; Barbier 2007; Das and Crépin 2013; Das and Vincent 2009; Dasgupta et al. 2011; Huxham et al. 2015; Laso Bayas et al. 2011; Mahmud and Barbier 2016; Hochard et al. 2019; Menéndez et al. 2020; del Valle et al. 2020). To date, most studies of the protective benefit of mangroves focus on loss of economic activity and property, and do not estimate any resulting impacts on either the disutility from risk aversion or the risk of possible injury, illness or death as a result of cyclones. One exception is Das and Vincent (2009), who estimate that, during the 1999 cyclone that struck Orissa, India, there would have been 1.72 additional deaths per village within 10 km of the coast if mangroves had been absent. Similarly, Laso Bayas et al. (2011) calculate that, during the 2004 Indian Ocean tsunami, mangroves, forests and plantations situated between villages and the coastline in Aceh, Indonesia may have decreased loss of life by 3% to 8%.

Nevertheless, these and other studies suggest that there are three important spatial aspects of the protective benefits of mangroves. First, the presence of mangroves, especially in low-lying coastal villages, may mitigate otherwise permanent loss of economic activity due to direct cyclone exposure, and this protection is affected by differences in widths of seaward mangrove found along coastlines (Badola and Hussain 2005; Barbier 2007; Barbier et al. 2008.; Huxham et al. 2015; Hochard et al. 2019; del Valle et al. 2020). Second, even in low-lying coastal zones, difference in elevation may matter, in that households and communities located in higher coastal elevations may be less vulnerable to cyclone damage and may not necessarily require more protection from mangroves (Das and Vincent 2009; Laso Bayas et al. 2011). Finally, the role of both mangroves and coastal elevation may depend on cyclone exposure; that is, households and communities in the direct path of the storm experience more damaging storm impacts, such as rainfall, flooding extent, wind speeds, storm intensity, etc. (Dagupta et al. 2011; Das and Crépin 2013; Mahmud and Barbier 2016).

The purpose of the following paper is to examine the influence of these spatial aspects of the protective benefits of mangroves in protecting against cyclone damage to coastal property and economic activity. We begin by developing a model that incorporates these effects, to illustrate how the protection afforded by high seaward density of mangroves and coastal elevation may interact and how this interaction may be influenced by cyclone exposure (see SI: Theoretical Model). In addition, employing estimations based on an annual panel dataset of nighttime luminosity from 2000 to 2012 of 2,559 coastal mangrove-holding communities within 102 countries, we estimate the impacts of cyclones of varying intensity on damages to the economic activity in villages with varying elevations and mangrove widths (see SI: Empirical Strategy). We use this empirical evidence to investigate whether higher elevation and more expansive mangroves interact to shelter communities from experiencing cyclone damage, and whether this effect is related to indirect cyclone exposure (between 100 and 300 km from the cyclone's eye) or more direct cycle exposure (within 100km of the cyclone's eye). We find that higher elevation *or* more expansive mangroves alone shelter communities experiencing indirect cyclone exposure, whereas economic activity

is only protected from direct cyclone exposure in coastal communities that are high elevation *with* expansive mangroves.

We construct an annual panel dataset from 2000 to 2012 of 2,559 coastal communities within 102 countries. Population counts from 2000 to 2012 for each community were calculated from the Landsat population database (Oak Ridge 2014) and coastal communities were defined as the lowest level administration units with an oceanside coastline of each country using the Global Administrative Areas Database v2.7. Using the National Oceanic and Atmospheric Administration's (NOAA) global nighttime lights data, we examine trends in economic activity before and after a cyclone event. The growth rate in average annual luminosity from nighttime lights trends with economic growth and has been used as an effective proxy for local economic activity (Henderson et al. 2011; Henderson et al. 2012; Hodler and Raschky 2014; Hochard et al. 2019; del Valle et al. 2020). However, trends in nighttime luminosity should not be interpreted as a measure of economic growth. Instead, we focus on tracking the dynamic impacts of nighttime luminosity (e.g. deviations from trends) that indicates whether an exposed community's economic activity recovers or suffers permanent damage. The average elevation of each coastal community was calculated using a void-filled Shuttle Radar Topography Mission (SRTM) data at 3 arc-seconds, or approximately 90 m² at the equator (Jarvis et al. 2008). The mangrove coverage dataset was adapted from the Continuous Global Mangrove Forest Cover for the 21st Century (CGMFC-21) database for the years 2000 to 2012 (Hamilton and Casey 2013). The coastline length of each community, based on Global Self-Consistent, Hierarchical, High-Resolution Shoreline Database (Wessel and Smith 1996), was used to normalize the area of mangroves offshore of each coastal community creating a measurement for the "width" of mangroves per meter of coastline.

Tropical storm locations for all years were recreated from the International Best Track Archive for Climate Stewardship (IBTrACS) Annual Tropical Cyclone Best Track Database. Precise measurements of exposure, combined with high-resolution luminosity data, allows to distinguish the heterogeneous impacts of cyclones on exposed communities and the capacity for mangroves to shelter coastal economic activity

at different elevations and for different mangrove widths. The intensity of exposure is measured by the distance of the cyclone’s “eye” from the exposed village’s nearest boundary. Characteristic of the

Table 1: 2010 sample summary statistics for full sample of 102 countries and 2,559 coastal communities.

	Total pop.	Total pop. (%)	Mangrove coverage (m²)	Mangrove coverage (%)
Global	386,965,537	100.0%	1,801,499,731	100.0%
Developing Regions				
East Asia and Pacific	176,125,918	45.5%	545,933,765	30.3%
Latin America and Caribbean	57,502,721	14.9%	716,500,099	39.8%
Middle East and North Africa	1,883,012	0.5%	6,144	0.0%
North America	0	0.0%	0	0.0%
South Asia	65,931,108	17.0%	22,434,918	1.2%
Sub-Saharan Africa	27,757,586	7.2%	313,265,667	17.4%
Income Categories				
High Income	57,765,192	14.9%	203,359,139	11.3%
Upper-Middle Income	136,526,522	35.3%	1,008,680,816	56.0%
Lower-Middle Income	180,537,070	46.7%	565,858,041	31.4%
Low Income	12,136,753	3.1%	23,601,736	1.3%
Developed vs. Developing				
Developed	57,765,192	14.9%	203,359,139	11.3%
Developing	329,200,345	85.1%	1,598,140,592	88.7%

Note: Categories are based on World Bank Country and Lending Groups current for the 2019 fiscal year. Low income countries are those with a Gross National Income (GNI) per capita less than \$995, lower-middle income countries have a GNI/pp between \$996 and \$3,895, upper-middle income countries have a GNI/pp between \$3,896 and \$12,056 and upper-middle income countries have a GNI/pp >\$12,056. Developing regions exclude countries with high income in their aggregations.

tropical cyclone wind profile (Holland 1980), villages passing within 100km of the cyclone’s eye were likely to experience maximum wind velocity *and* surface level pressure whereas those villages passing within more distant bands – i.e., 100km-200km and 200km-300km, were likely to experience similar surface level pressure but a non-linear reduction in wind velocity. Binning wind velocities in this way recognizes the highly non-linear relationship between wind velocity and on-the-ground damages from cyclone events (Bakkensen and Mendelsohn 2016). We therefore expect the capacity for mangroves and elevation to shelter economic activity also to depend on this intensity of exposure.

Our full sample encompasses nearly 400 million individuals in 102 countries and 2,559 mangrove-holding communities (Table 1). Based on 2019 fiscal year World Bank categorizations, most of our sample resides in developing countries (85.1%) with 46.7% in lower-middle income (gross national income/per capita between \$996 and \$3,895) and 35.3% in upper-middle income countries (gross national income/ per capita between \$3,896 and \$12,056). We also find that most mangrove coverage in our sample exists within developing countries (88.7%) and overwhelmingly in upper-middle income countries (56.0%) in the Latin America and Caribbean (LAC) and East Asian and Pacific (EAP) developing regions. While only 14.9% of our sample’s global population resides in LAC countries, these

countries account for 39.8% of mangrove holdings in our sample whereas the 45.5% of the population residing in EAP countries only account for 30.3% of mangrove coverage.

Results

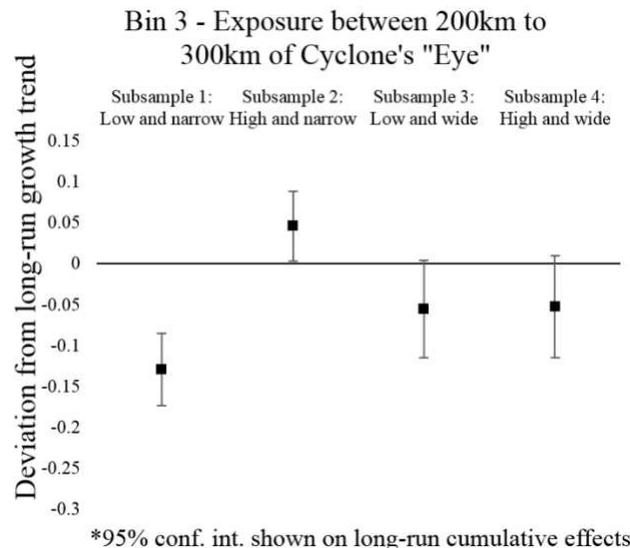
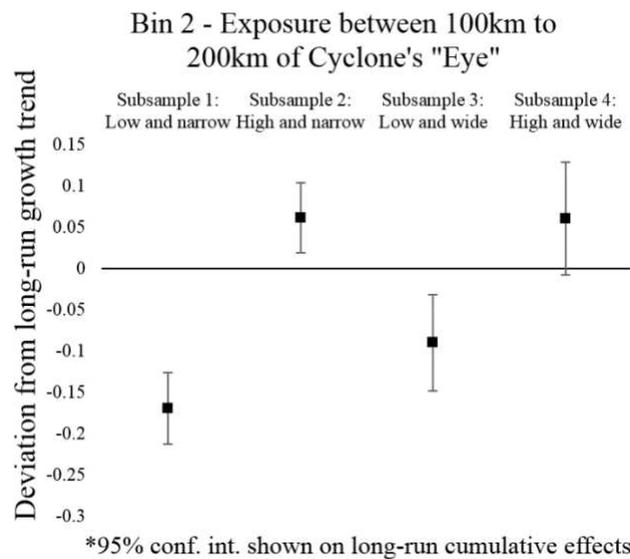
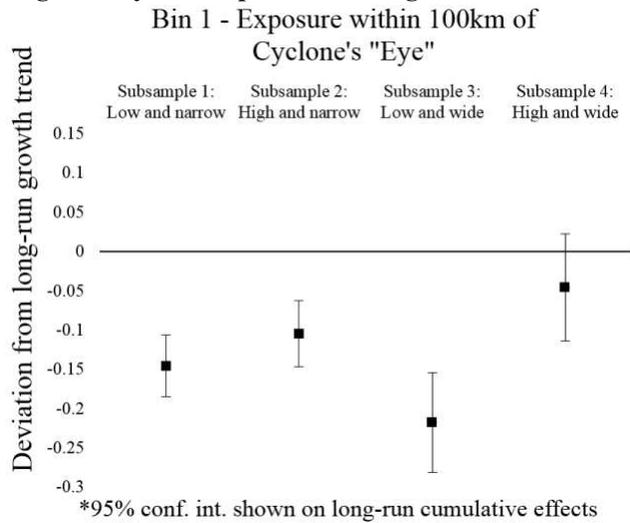
Table 2. Cumulative effects of cyclone exposure on growth rate in economic activity.

β vector	Subsample 1: <i>low and narr.</i>	Subsample 2: <i>high & narr.</i>	Subsample 3: <i>low & wide</i>	Subsample 4: <i>high & wide</i>
Bin 1 (0 to 100km)				
Lag 0 - Impact year	-0.0459***	-0.0164**	-0.0547***	-0.0193
+ Lag 1	-0.0835***	-0.0354***	-0.1165***	-0.0297
+ Lag 2	-0.1151***	-0.0633***	-0.1624***	-0.0354
+ Lag 3	-0.1398***	-0.0877***	-0.1953***	-0.0437
+ Lag 4	-0.1456***	-0.1046***	-0.2172***	-0.0459
Bin 2 (100 to 200km)				
Lag 0 - Impact year	-0.0472***	0.0056	-0.0341***	0.0065
+ Lag 1	-0.0903***	0.0144	-0.0618***	-0.0112
+ Lag 2	-0.1346***	0.0360**	-0.0893***	-0.0043
+ Lag 3	-0.1515***	0.0568***	-0.1092***	0.0278
+ Lag 4	-0.1698***	0.0616***	-0.0900***	0.0599
Bin 3 (200 to 300km)				
Lag 0 - Impact year	-0.0354***	0.0030	-0.0294***	-0.0247**
+ Lag 1	-0.0667***	0.0048	-0.0411***	-0.0584***
+ Lag 2	-0.1021***	0.0235	-0.0585***	-0.0774***
+ Lag 3	-0.1139***	0.0398**	-0.0691***	-0.0727***
+ Lag 4	-0.1290***	0.0460**	-0.0551***	-0.0522
Fixed effects – Year	Y	Y	Y	Y
Fixed effects - Community	Y	Y	Y	Y
N (communities)	12,005	6,294	6,719	2,751
R-squared	0.8271	0.8399	0.8376	0.8710
Root MSE	0.1431	0.1224	0.1444	0.1157

Note: All specifications report cumulative effects with robust standard errors, four autoregressive lags, two forward lags on cyclone exposure and controls for mangrove width and the baseline logged growth rate.

We find that direct cyclone exposure – i.e., within 100km of the cyclone’s “eye” - has a permanent impact on long-run economic outcomes (Bin 1, +lag 4) in the absence of natural protections that buffer winds or reduce stormwater inundation. Five years following exposure, point estimates show a 10% to 22% loss in economic activity when compared to pre-cyclone trends. However, for those coastal communities at high elevation with wide mangroves, we estimate a statistically insignificant point effect of -0.0459. Whereas the cumulative effect of exposure on “unprotected” communities continues to worsen in the fifth year, results suggest that cyclone exposure disrupts economic activity in coastal communities in the year of impact *and* in subsequent years following exposure. Higher elevation and wide mangroves, together,

Figure 1 Cyclone exposure and long-run economic effects. buffer this initial impact of storm exposure and



enable communities to return to pre-exposure growth rates quickly thus avoiding long-term impacts on economic activity. In the case of direct exposure, elevation or mangroves alone appear incapable of sheltering economic activity.

For indirect exposure – i.e., a cyclone passing within 100km-200km or within 200km to 300km of a coastal community, we find that mangroves or elevation alone have the capacity to generate tremendous storm protection benefits (Table 2 and Figure 1). For those exposed between 100km and 200km of the cyclone’s eye, low elevation communities with narrow mangroves experienced a 17.0% reduction in long-run economic growth, which was reduced to 9.0% for similarly low elevation communities with wide mangroves. Likewise, for those communities exposed between 200km and 300km of the cyclone’s eye, low elevation communities with narrow mangroves experienced a 12.9% reduction in long-run economic growth, which was reduced to 5.5% for similarly low elevation communities with wide mangroves. For these indirect exposures,

higher elevation has a substantial benefit for those communities with narrow mangroves, but this benefit from being at higher elevation appears dampened for those coastal communities that already have wide mangroves.

For indirect exposures, it appears storm protection services from mangroves are substitutable for increased elevation, whereas for direct exposures, it appears mangroves and elevation are necessary complements to sheltering long-run economic growth from cyclones (Table 2 and Figure 1). Importantly, for all direct exposure specifications, including the case of combined elevation and mangrove protections (subsample 4), the cumulative effect continues to increase in magnitude five years following exposure. While it appears these disruptive effects to economic activity are “tapering off”, future research should focus on longer run (e.g. 10-year and 20-year) dynamic effects following cyclone exposure to examine whether further damages to economic activity mount after 5 years or whether a delayed recovery phase (5 to 10 years following storm exposure) ensues, with above normal growth in economic activity, which may offset these permanent losses.

With climate predictions of increased frequency of intense storm events, our work presents two key findings. First, low-lying coastal areas require expansive mangrove forests more than 10 m / meter of coastline to buffer long-term losses to economic activity – narrow bands of mangroves provide little protection. Second, even expansive mangroves are only capable of sheltering those communities exposed indirectly to cyclones. Third, for coastal safe havens to be sheltered against increasingly intense storm events requires both high elevation and expansive mangroves.

Although our sample contains nearly 400 million individuals with mangroves along the coastline of their community (Table 1), approximately 60 million have wide enough mangroves to generate protection from an indirect exposure event (Table 3). These communities are located overwhelmingly in lower-middle income countries (38.4%) and within LAC (34.0%) and EAP (32.8%). We estimate only 10.9% of this population is in the developed world. Coastal communities within lower-middle income countries appear to be concentrated behind a relatively small share of the world’s expansive mangroves (34.7%) compared to upper-middle income countries that have 10.9% of the sample population in the areas but 52.4% of the

Table 3: 2010 sample summary statistics for low & wide subsample 3 including 44 countries and 605 coastal communities.

	Total pop.	Total pop. (%)	Mangrove coverage (m²)	Mangrove coverage (%)
Global	60,319,584	100.0%	1,801,499,731	100.0%
<i>Developing Regions</i>				
East Asia and Pacific	19,774,557	32.78%	315,065,268	26.35%
Latin America and Caribbean	20,508,593	34.00%	478,746,329	40.04%
Middle East and North Africa	0	0.00%	0	0.00%
North America	0	0.00%	0	0.00%
South Asia	3,226,796	5.35%	7,029,840	0.59%
Sub-Saharan Africa	10,240,435	16.98%	249,932,650	20.90%
<i>Income Categories</i>				
High Income	6,376,547	10.57%	144,877,151	12.12%
Upper-Middle Income	6,569,203	10.89%	626679056.1	52.41%
Lower-Middle Income	23,131,744	38.35%	414,258,137	34.65%
Low Income	2,159,859	3.58%	9,836,894	0.82%
<i>Developed vs. Developing</i>				
Developed	6,569,203	10.89%	144,877,151	12.12%
Developing	53,750,381	89.11%	1,050,774,087	87.88%

Note: Categories are based on World Bank Country and Lending Groups current for the 2019 fiscal year. Low income countries are those with a Gross National Income (GNI) per capita less than \$995, lower-middle income countries have a GNI/pp between \$996 and \$3,895, upper-middle income countries have a GNI/pp between \$3,896 and \$12,056 and upper-middle income countries have a GNI/pp >\$12,056. Developing regions exclude countries with high income in their aggregations.

Table 3 (cont.): 2010 sample summary statistics for high & wide subsample 4 including 39 countries and 255 coastal communities.

	Total pop.	Total pop. (%)	Mangrove coverage (m²)	Mangrove coverage (%)
Global	29,676,181	100.0%	504,187,400	100.0%
<i>Developing Regions</i>				
East Asia and Pacific	16,017,540	53.97%	204,777,453	40.62%
Latin America and Caribbean	10,400,889	35.05%	194,159,593	38.51%
Middle East and North Africa	0	0.00%	0	0.00%
North America	0	0.00%	0	0.00%
South Asia	250,628	0.84%	11,195,302	2.22%
Sub-Saharan Africa	1,193,721	4.02%	59,754,429	11.85%
<i>Income Categories</i>				
High Income	1,813,403	6.11%	34,300,624	6.80%
Upper-Middle Income	13,481,963	45.43%	330,975,701	65.65%
Lower-Middle Income	14,014,219	47.22%	127,008,011	25.19%
Low Income	366,596	1.24%	11,903,065	2.36%
<i>Developed vs. Developing</i>				
Developed	1,813,403	6.11%	34,300,624	6.80%
Developing	27,862,778	93.89%	469,886,776	93.20%

Note: Categories are based on World Bank Country and Lending Groups current for the 2019 fiscal year. Low income countries are those with a Gross National Income (GNI) per capita less than \$995, lower-middle income countries have a GNI/pp between \$996 and \$3,895, upper-middle income countries have a GNI/pp between \$3,896 and \$12,056 and upper-middle income countries have a GNI/pp >\$12,056. Developing regions exclude countries with high income in their aggregations.

mangrove coverage. This result suggests lower-middle income countries are currently leveraging their mangrove stocks for protection against indirect storm exposure while upper-middle income countries may have adopted alternative forms of protection, such as shoreline hardening (e.g. built infrastructure substitution for natural infrastructure) or reserve an option for out-migration to safe harbor if storm intensity or frequency increases.

We find that 28% of global mangrove coverage (approximately 504 million m²) has a seaward width more than 10m along communities with mean elevation >50m (Table 3). These areas represent safe havens from direct and indirect exposure from cyclones and are located overwhelmingly in upper-middle income countries (65.7%). Yet, 47.2% of populations in these areas reside in lower-middle income countries whereas only 45.4% of populations in these areas reside in upper-middle income countries (Table 3). This finding appears consistent with our subsample 3 result that lower-middle income coastal communities are already utilizing their relatively sparse (25.2% of total sample coverage) safe havens for protection against storm events while upper-middle income countries retain an option for out-migration to these protected areas.

Discussion

Our findings suggest that mangroves shelter coastal economic activity for over 60 million individuals, prone to indirect cyclone exposure in low-lying areas, located predominately in developing countries. Direct cyclone exposure, which is measured by storm impact within 100km of the cyclone's "eye", leaves a permanent and detrimental impact on economic activity in these communities. Further, this vulnerability to direct storm exposure is likely to persist and potentially amplify as future storms intensify. Whereas mangrove conservation efforts today may shelter coastal communities from future less intensive storms and indirect exposure events, out-migration to elevated areas with expansive mangroves may be needed to protect coastal communities against future exposures.

These "safe havens" characteristic of high elevation ($\geq 50m$ elevation) and wider mangroves ($\geq 10m$ mangroves/m of coastline) are located overwhelmingly in upper-middle income countries (65.7%). Populations in lower middle-income countries control only 25.2% of global mangrove coverage but represent 47.2% of the global population in these areas. The disproportionate use of these safe havens by lower middle-income populations may represent a stronger dependence of poorer, therefore more vulnerable, populations on natural infrastructure for storm protection.

In such a case, we might expect migration to such safe havens following a large storm exposure event in lower middle-income countries. However, for upper middle-income countries, communities may

substitute built infrastructure for natural infrastructure in low-lying areas using shoreline armoring initiatives (e.g. sea walls, groins, jetties, etc.) that provide alternative storm protection services as elevation and expansive mangroves. The substitutability, in terms of protecting coastal communities from storm events, between shoreline armoring and mangrove conservation is not the focus of this work. However, future work should focus on whether the sparsely populated safe havens in middle income-countries serve as an “option” for future adaptation or a redundancy with other built infrastructure investments.

Methods

Theoretical Model

To incorporate key spatial aspects of interest, we modify a model by Barbier (2007) that illustrates the protective benefits of coastal wetlands, such as mangroves, in reducing expected storm damages. Assume that in a coastal region the local community owns all economic activity and property, which may be threatened by damage from periodic cyclone events. Assume also that the preferences of all households in the community are sufficiently identical so that it can be represented by a single household. Following Barbier (2007) and Barbier (2014), let $m(p^x, z, u^0)$ be the representative household’s expenditure function that can be interpreted as the minimum household expenditure required to reach utility level, u^0 , given the vector of prices, p^x , for all of the household’s consumed market-purchased commodities. The expected number or incidence of potentially damaging cyclone events is z^0 . That is, potential damages D from cyclones are an increasing function of the incidence of events z and conditional on the degree of exposure to damaging storm characteristics (e.g. flooding extent, wind speeds, storm intensity, etc.). Such exposure is likely to be related to the distance x of the household from the center, or “eye”, of the cyclone. It follows that

$$D = D(z; x), \quad D' > 0, \quad 0 \leq x \leq \bar{x}, \quad D(z; \bar{x}) = 0, \quad (1)$$

where the household experiences no damages if it is located beyond distance \bar{x} from the eye of the cyclone.

Suppose the expected incidence of cyclones rises from z^0 to z^1 , but without any marked difference in the household's location with respect to these storms. The resulting expected damages to the property and economic livelihood of the household $E[D(z)]$ translates into an exact measure of welfare loss through changes in the minimum expenditure function

$$E[D(z;x)] = m(p^x, z^1, x, u^0) - m(p^x, z^0, x, u^0) = c(z), \quad (2)$$

where $c(z)$ is the compensating surplus. It is the minimum income compensation that the household requires to maintain it at the utility level u^0 , despite the expected increase in damaging cyclone events.

Alternatively, $c(z)$ can be viewed as the minimum income that the household needs to avoid the increase in expected cyclone damages.

However, a greater width or extent of seaward mangrove found along coastlines of coastal wetlands could mitigate the expected incidence of damaging cyclone events. Because of this storm protection service, the width of mangroves, S , along the coast may have a direct effect on reducing the “production” of natural disasters, in terms of the ability of cyclones to inflict damages locally. Equally, one would expect that households located at higher rather than low-lying coastal elevations would also experience less cyclone damages. Thus, the incidence of damaging cyclone events inflicted on the household is likely to be inversely influenced by the coastal elevation h of its location. It follows that the “production function” for the incidence of potentially damaging cyclones experienced by the household can be represented as

$$z = z(S, h), \quad z_S < 0, \quad z_h < 0. \quad (3)$$

It follows from (2) and (3) that $\partial c(z)/\partial S = \partial E[D(z; x)]/\partial S < 0$. An increase in mangrove area, as reflected in greater width of mangroves along the coastline, reduces expected cyclone damages and therefore the minimum income compensation needed to maintain the household at its original utility level. Alternatively, a loss in mangrove area would increase expected cyclone damages and raises the minimum compensation required by the household to maintain its welfare. Thus, we can define the marginal willingness to pay $W(S)$ for the protection services of the mangrove in terms of the marginal impact of a change in mangrove area on expected cyclone damages

$$W(S) = -\frac{\partial E[D(z(S, h); x)]}{\partial S} = -E\left[\frac{\partial D}{\partial z} z_s\right], W' < 0. \quad (4)$$

Borrowing from the intuition derived in Barbier (2014), the function $W(S)$ is parallel to the Hicksian compensated demand function that characterizes marketed goods. Further, the minus sign on the right-hand sign of (4) allows this “demand” function to be represented in the usual quadrant, and it has the normal downward-sloping property (see Figure SI-1) (Barbier 2014; Barbier 2015). Here, an increase in S reduces z and providing the households with an ability to avoid expected damages from cyclones. However, while each household in the coastal area receives additional value from this storm protection service, the marginal value diminishes as mangrove areas increase. Accordingly, as displayed in Figure SI-1, the community’s marginal willingness to pay for more storm protection declines with mangrove area, S .

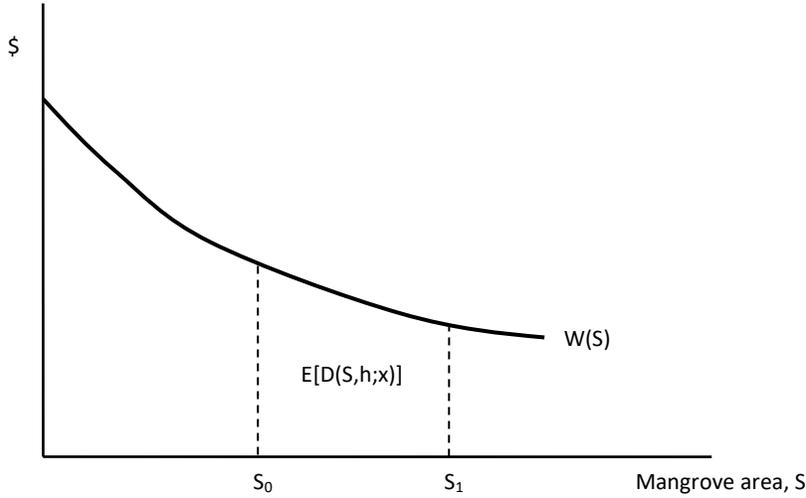


Figure SI-1. Expected damages arising from a change in mangrove area

The value of a non-marginal change in mangrove area, from S_0 to S_1 , can be measured as

$$-\int_{S_0}^{S_1} W(S) dS = E\left[D(z(S, h); x)\right] = c(S). \quad (5)$$

If there is an increase in wetland area, then the value of this change is the total amount of expected damage costs avoided. As shown in Figure SI-1, then this welfare gain is the reduction in total expected damages resulting from the increased incidence of storm events $E\left[D(S, h; x)\right]$, which is the area under the $W(S)$ curve bounded by S_0 and S_1 . As indicated in (5), the valuation of this gain is a compensation surplus measure of a change in the area of mangroves and the increased storm protection service that they provide.

However, it also follows from (2) and (3) that, if the coastal household were located at a higher location, then $\partial c(z)/\partial h = \partial E\left[D(z; x)\right]/\partial h < 0$. An increase in coastal elevation reduces expected damages and thus the minimum income compensation needed to maintain the household at its original utility level.

The corresponding marginal willingness to pay $W(h)$ for the change in coastal elevation on expected cyclone damages is

$$W(h) = -\frac{\partial E[D(z(S, h); x)]}{\partial h} = -E\left[\frac{\partial D}{\partial z} z_h\right], W' < 0. \quad (6)$$

A key issue is whether having more expansive (greater width and thus area) of mangrove boosts the effects of higher coastal elevation in reducing expected cyclone damages, or whether the two effects are substitutes. If having more mangroves complements the effects of higher coastal elevation, then one would expect that a greater mangrove expanse would boost the willingness to pay $W(h)$ for a change in coastal elevation, regardless of the level of h . On other hand, if the two effects are substitutes, then more mangroves would reduce $W(h)$.

These two outcome may depend, in turn, on the distance of the household from the center of the cyclone x . For example, suppose that there is some threshold distance $0 < x^* < \bar{x}$ from the eye of the cyclone, which determines whether higher coastal elevation and the presence of more coastal mangroves are complements or complements. That is, if the household is relatively near to the direct path of the cyclone $0 \leq x < x^*$, then an increase in mangrove area will still boost significantly its protection, even if the household is located in a relatively high coastal elevation. However, if the household is relatively far from the cyclone's eye $x^* < x \leq \bar{x}$, then more expansive mangrove will simply reduce the willingness to pay for the change in coastal elevation.

These outcomes are depicted in Figure SI-2. Suppose that the household is located in a low-lying coastal area, but h is still significantly higher than sea-level (which is at $h = 0$). If mangrove area and coastal elevation are complements, which may occur if the household is close to the center of cyclones $x < x^*$, then greater mangrove area will assist the household located at coastal elevation h in avoiding expected damages from the storm, and thus $W(h)$ will increase. This effect may be especially large for households in low-lying coastal zones, but will still occur even if h is relatively high. In contrast, if the household is further away from cyclone exposure $x > x^*$, then damages can be avoided by either a

household located at higher elevation or by greater protection by mangroves. The greater protection afforded by the increase in mangroves is a substitute for avoiding damages from being at a higher coastal elevation h .

We now turn to empirical evidence to investigate whether higher elevation and more expansive mangroves interact to shelter communities from experiencing cyclone damage, and whether this effect is related to indirect cyclone exposure (between 100 and 300 km from the cyclone’s eye) or more direct cycle exposure (within 100km of the cyclone’s eye).

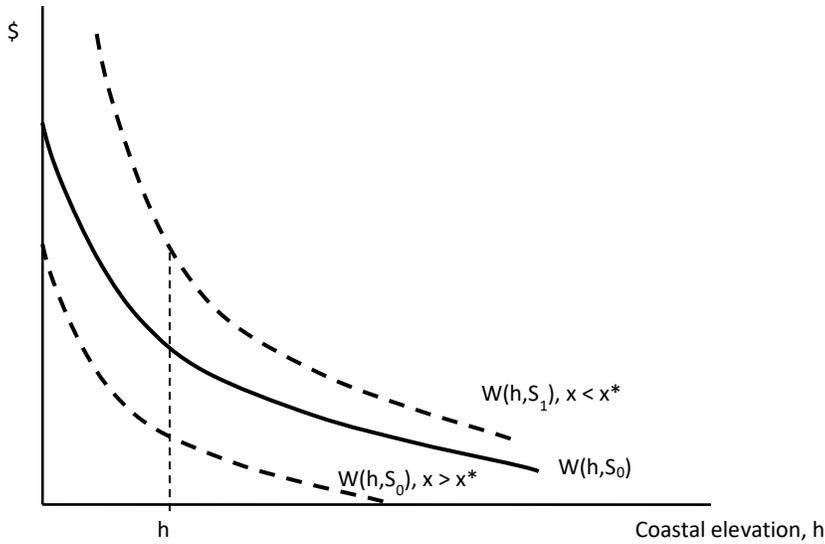


Figure SI-2. Effects of a change in mangrove area on $W(h)$

Empirical Strategy

We use a distributed-lag autoregressive model to measure the initial and permanent effect of cyclone exposure on economic activity in coastal communities. The growth in economic activity for each coastal community is proxied by the difference in logs between years, $growth = \ln(luminosity_t) - \ln(luminosity_{t-1})$. Our estimating equation is

$$growth_{i,j,t} = \sum_{L=0}^n [\beta_L \times C_{i,j,t-L}] + \gamma_j + \delta_t + \eta X_{i,j,t} + \epsilon_{i,j,t} \quad (7)$$

where the β coefficients capture the marginal effects, across three bins of cyclone exposure, on the growth rate of luminosity for the j' th administrative unit, within country i , and in time $t - L$ where t is the observed

year and L is the number of lags ranging from 0 to n . Here, $C_{i,j,t}$ is a vector of cyclone exposures binned by the distance from the cyclone’s “eye” to the nearest boundary of the exposed community (<100km, 100km-200km and 200km-300km). We adopt community-specific and year-specific fixed effects to control for any unobservable impacts, captured by γ and δ , on economic activity for a given community or within a given year. Mangrove width and the logged baseline level of luminosity (digital number units – i.e., DN) are added as control variables in the vector, $x_{i,j,t}$, as well as a linear trend to absorb background growth trends that are shared by communities in our sample. Four autoregressive lags are also included in all specifications and robust standard errors are reported.

The impact of a cyclone on long-run trends in economic activity z years later is

$$\Lambda_{i,j} = \sum_{L=0}^z [\beta_L],$$

which is cumulative effect (summation of marginal effects) of cyclone exposure on luminosity growth. To examine the scope for mangroves of varying width and topography of varying elevation to shelter coastal economic activity, we stratify our sample into four subsamples: “low and narrow”,

		Mean elevation (m)	
		<50	>=50
Mean mangrove width (m)	<10	Subsample 1 <i>Low and narrow</i>	Subsample 2 <i>High and narrow</i>
	>=10	Subsample 3 <i>Low and wide</i>	Subsample 4 <i>High and wide</i>

Figure SI-3 Subsamples for elevation and mangrove width stratifications.

“low and wide”, “high and narrow” and “high and wide”. “Low” sub-samples contain coastal communities with a mean elevation < 50 meters and “narrow” sub-samples contain coastal communities with a mangrove width of <10 meters per meter of coastline (Figure SI-3). We hypothesize that communities in subsample 1, lacking natural protections against storm exposure, are the most vulnerable and would experience the strongest effect on long-run economic outcomes. We further hypothesize that communities in subsample 4, receiving protection from mangroves and topography, would be the most insulated against storm exposures. Likewise, we would expect communities benefiting from either expansive mangroves or high elevation, would be partially protected from exposure and adverse long-run economic impacts. In terms of “intensity of exposure”, we hypothesize that those communities

passing within the nearest proximity to the cyclone's "eye" will experience the largest adverse impact on economic growth – i.e., bin 1 > bin 2 > bin 3.

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Figures

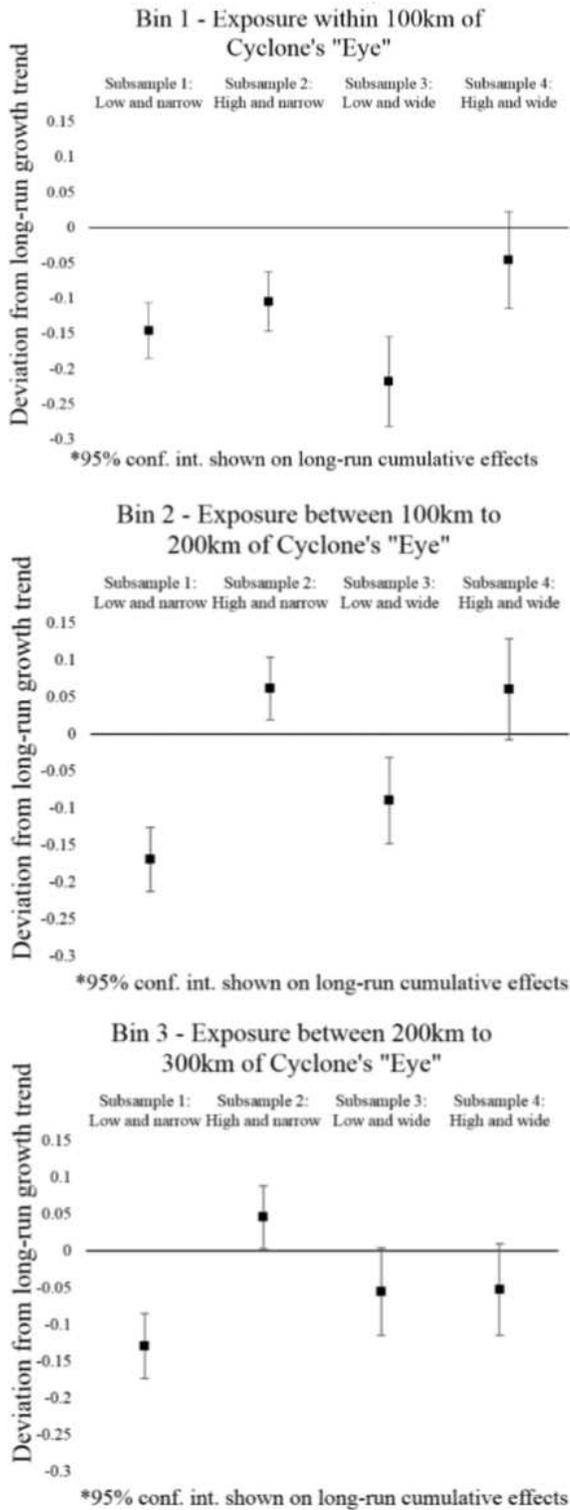


Figure 1

Cyclone exposure and long-run economic effects.

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