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Abstract

In recent decades, hurricane frequency and intensity have increased in the Caribbean Basin. From 2000 to 2012, more than 100 hurricanes impacted lives, infrastructure, and economic activity along the region's shorelines. Studies suggest that mangrove forests' dense root systems might mitigate the impact of hurricanes, which would help stabilize the coastline and prevent erosion from waves and storms. Although many tropical mangroves are found on Caribbean coasts, climatic and anthropogenic events have been clearing these wetland ecosystems at an annual rate of 1 percent since the 1990s. This study quantifies the effects of hurricane windstorms on economic activity using nightlight as a proxy at the highest spatial resolution data available (1 square kilometer). Using different widths of the mangrove belt, it measures levels of mangrove natural protection against the impact of hurricanes and studies the broader socioeconomic and environmental effects of this protection. The results suggest that while major hurricanes reduce nightlight by approximately 2 percent and up to 16 percent in storm surge prone areas, the presence of mangroves on the coast mitigates the impact of hurricanes, reducing nightlight by 1–6 percent.

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Mangroves as Coastal Protection for Local Economic Activities from Hurricanes in the Caribbean[1]

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1. Introduction

The Caribbean, a region highly susceptible to losses from natural hazards, is prone to tropical storms and hurricanes formed in the Northern Atlantic Ocean Basin, which includes the North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico.[6] The official Caribbean hurricane season runs from June to November, although infrequent storms have formed outside these dates (Johnson 2015). According to the National Oceanic and Atmospheric Administration (NOAA), an average Atlantic hurricane season produces 12 named storms, including six hurricanes, three of which are Category 3, 4, or 5.[7] Between 2017 and 2019, the region experienced three Category 5 hurricanes.

With populations in the Caribbean often subjected to repeated hurricane strikes without respite, a sense of helplessness and hopelessness can set in (Gin and Lubin 1989). Despite overall improvements in living conditions, poverty rates in the region average 30 percent (Bowen 2007). Since 2010, most countries have shown persistently weak economic growth, with annual gross domestic product (GDP) growth rates for 2010–17 averaging only 0.8 percent, compared with 4.7 percent in other small states (OECD et al. 2019). Most Caribbean islands exhibit high levels of growth volatility, which creates uncertainty, hinders economic growth, and negatively affects public finances (Beuermann et al. 2018).

Meteorological damage has long-term consequences at both national and regional levels. According to the Emergency Events Database EM-DAT, 283 disasters caused by hurricanes either made landfall in the region or passed within 69 miles of the Caribbean islands between 1950 and 2014.[8] The database only recorded damages for 148 of these, which amounted to roughly $52 billion (in 2010 constant U.S. dollars). This is equivalent to an average of 1.6 percent of GDP in damages every year in the islands (Acevedo Mejía 2016).

Of the world's top 25 countries with the most tropical cyclones per square kilometer, 15 are Caribbean islands. Acevedo, LaFrambroise and Wong (2017) find that hurricanes have caused major damage to hotel facilities and disrupted tourist arrivals in the region, where tourism infrastructure tends to concentrate in coastal areas, which are more exposed to hurricanes and floods. For example, when Hurricane Ivan hit Grenada in 2004, it damaged most hotels, while Hurricane Omar in 2008 essentially wiped out tourism in St. Kitts and Nevis by damaging its main hotel. In 2012, Hurricane Sandy caused severe disruptions to hotel operations in The Bahamas.

Recent scientific literature demonstrates that natural disasters have direct and indirect economic effects. The former include short-term damage to infrastructure, crops, extractable natural resources, as well as mortality and morbidity (Noy and Dupon 2018; Ishizawa, Miranda and Strobl 2019). The latter, on the other hand, are associated with emergency costs, business interruption, and longer-term consequences for economic growth, social and community network, as well as impacts on security and stability (Cavallo and Noy 2011; Hallegatte 2014). Direct impacts can also lead to indirect impacts, such as changes in economic activity after a disaster (Botzen, Deschenes and Sanders 2020).

However, both the nature of the storms and local community characteristics—such as weak infrastructure—mean that economic impacts can vary widely across space (Bertinellli and Strobl 2013). Developing nations are more susceptible to the adverse impacts of disasters than industrialized nations

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[6] For more information on Caribbean hurricanes, see https://www.nhc.noaa.gov/climo/

[7] NOAA, "Extremely active hurricane season possible for Atlantic Basin", last modified August 6, 2020, https://www.noaa.gov/media-release/extremely-active-hurricane-season-possible-for-atlantic-basin

[8] It must be noted that not all hurricanes and tropical cyclones that pass close to a Caribbean island will result in a disaster, as the threshold for that classification requires that at least 100 people be affected, or at least 10 people killed, or a state of emergency declared.

in the short and long terms (Rasmussen 2004; Loayza et al. 2012). The most vulnerable countries are Small Island Developing States (SIDS), including Caribbean island states, which often experience growth collapse as a result of climatic events and find it difficult to recover immediately. This is due to the impact of shocks on their macroeconomic indicators, which includes the deterioration of fiscal and trade balances (Heger, Julca and Paddison 2008).

Natural habitats, such as coral reefs, seagrasses, and mangroves, can protect coastal communities against the impacts of waves and storms. In particular, mangroves are a form of natural infrastructure that protects coasts from storm surge and flooding in tropical regions (Blankespoor, Dasgupta and Lange 2016). Multiple studies have shown that mangroves—areas of forest and other wooded land with mangrove vegetation (FAO 2010)—can attenuate wave energy (Brinkman et al. 1997; Mazda et al. 1997; Massel, Furukawa and Brinkman 1999; Quartel et al. 2007; Barbier et al. 2008; Gedan et al. 2010; McIvor et al. 2012; Pinsky, Guannel and Arkema 2013). The width of mangrove greenbelt and cross-shore distance are major factors in wave height decline (Bao 2011); other factors include shore slope, root diameter, spectral characteristics of incident waves, and tidal stage on forest entry (Alongi 2008).

Mangroves are spread along the coasts of 13 sovereign Caribbean states and 17 dependent territories, from The Bahamas in the north to Trinidad and Tobago in the south. Bermuda's low-island mangroves are among the northernmost in the world (32º20'N). But as a result of high population pressure in coastal areas, many mangrove areas have been converted to other uses, including urbanization, industrialization, aquaculture, and tourism. These disturbances are taking place at increasing spatial and temporal scales, and require increasing recovery time (Tuholske et al. 2017; Polidoro et al. 2010; FAO 2007; Duke, Pinzon and Prada 1997; Ellison and Farnsworth 1996). Overall, the region is losing mangrove forest at a rate of 1 percent per year; and this is happening much faster on the mainland (1.7 percent) than on the islands (0.2 percent) (Ellison and Farnsworth 1996). After the Indo-Malay Philippine Archipelago, the Caribbean has the world's second highest mangrove area loss, losing approximately 24 percent of its total mangrove area over the past quarter-century (FAO 2007).

Del Valle et al. (2020) suggest that mangroves also can mitigate the impact of hurricanes on local economic activity. They show that within Central America's coastal lowlands, nightlight intensity, as a proxy of GDP, decreases by up to 24 percent in areas that are unprotected by mangroves and is fully mitigated in areas protected by mangrove belts of 1 kilometer or more. This study follows this line, providing a regional perspective on how mangroves can act as natural barriers to mitigate the negative impact of hurricane windstorm in the Caribbean on a particular set of social and economic outcomes. In a region where more than half the population lives within 1.5 kilometers of the shoreline, hurricanes might pose serious socioeconomic risks (Waite et al. 2014).

This paper finds robust evidence that hurricanes significantly affect the intensity of nightlight. In locations hit by a Category 3 hurricane (wind speed of 203 kilometers per hour or kph), we estimate a 2.9 percent reduction in nightlight intensity, using the average intensity level for 2000. The effect is even greater in storm surge-prone, low-elevation coastal zones, where Category 3 hurricane winds are associated with a 16.1 percent decrease in nightlight. But where mangrove forests are a natural defense, a mangrove width of just 0.25 kilometer reduces nightlight intensity to 4.7–5.1 percent above and below the median. Where the mangrove width is greater than 1.26 kilometers and has an average width of 2.3 kilometers, nightlight reduction falls to 1–6.5 percent.

The remainder of the paper proceeds as follows. Section 2 describes the nightlight data used in this study, and the frequency of hurricane damages in the Caribbean. It also presents detailed mangrove forest data in the region, as well as a brief description of hurricane data and our proxy for potential damage from hurricanes. Section 3 explains our empirical estimation approach, and Section 4 presents our results. Section 5 concludes the paper.

2. Data and statistics

To quantify the impact of hurricane strikes on local economic activity in the Caribbean, we used three main data sets: nightlight data as a proxy for local economic activity; hurricane windstorm hazard data from a wind field model; and global mangroves databases.

2.1. Nightlight application

The Defense Meteorological Satellite Program (DSMP) – Operational Linescan System (OLS) nighttime light (NTL) data are primary data on economic activity, available at local, regional and global scales (Bertinellli and Strobl 2013; Henderson, Storeygard and Weil 2012; Chen and Nordhaus 2011). Compared to other remote sensing satellite observations, these data are particularly useful for evaluating policies with highly localized effects, or in countries with poor or non-existent subnational GDP data (Lowe 2014). With their global coverage and long temporal span, DSMP NTL data have also been extensively used in studies on electricity consumption, socioeconomic activities, light pollution, urban ecosystems, and urban extent mapping (Li et al. 2020).

Scientists at the NOAA developed a method to remove cloud-obscured pixels from raw nightlight imageries, as well as sources of transient lights such as the bright half of the local cycle, auroral activity, forest fires, and other events. Since 1992, they have processed raw daily nightlight imageries from around the world, delivering yearly cloud-free nightlight composites that essentially capture nocturnal human activity (Elvidge et al. 2010). NTL data records have digital number (DN) values, ranging from 0 (no light) to 63 (maximum light); the spatial resolution is 30 arc-seconds, and there is near-global coverage of 180ºW to 180ºE longitude and 65ºS to 75º latitude (Li et al. 2020).

For this study, we use imagery recorded by satellite between 2000 and 2012, covering 29 Caribbean countries and territories: Anguilla; Antigua and Barbuda; Aruba; The Bahamas; Barbados; Bermuda; Bonaire, Sint Eustatius and Saba; British Virgin Islands; Cayman Islands; Cuba; Curaçao; Dominica; the Dominican Republic; Grenada; Guadeloupe; Haiti; Jamaica; Martinique; Montserrat; Puerto Rico; St. Kitts and Nevis; St. Lucia; St. Vincent and the Grenadines; St. Barthélemy; St. Martin; Sint Maarten; Trinidad and Tobago; Turks and Caicos Islands; and Virgin Islands (U.S.). Although some studies—such as Bertinellli and Strobl (2013) and Andreano et al. (2020)—use yearly frequency nightlight data to predict local economic activities and map poverty in the Caribbean, this paper is one of the first to use and exploit yearly NOAA frequency data to assess the role of mangroves as natural protection against the damaging effects of hurricane strikes on local economic activities in the Caribbean.

Many of the economists who use nightlights as a proxy for economic activity—such as Doll, Muller and Morley (2006) and Keola, Andersson and Hall (2015)—pay great attention to nightlight saturation in urban centers. Henderson, Storeygard and Weil (2012), however, who use a fixed-effects specification for a panel of 188 countries over 17 years to test whether sensor saturation impairs the capacity of nightlight to predictive GDP, find that the estimated elasticity of nightlight with respect to GDP and R^2 remains unchanged after controlling for the number of top-coded pixels.[9] In the same way, this study examines

[9] The R-squared reflects the contribution of lights to explaining within-country and within-year variation in income.

the extent to which saturation weakens the suitability of nightlight as a proxy for local economic activity in the Caribbean.

Table 1 shows the frequency distribution of DNs across pixels for Caribbean islands, along with the information on land areas, population density, and GDP per capita based on purchasing power parity (PPP). In most small states, a large land area (or number of pixels)[10] has a DN value of 0—that is, it has no artificial lights for the entire 12-year sample period. In Haiti, for example, which is relatively more exposed to hurricane strikes, 70 percent of pixels are unlit, while in Cuba, The Bahamas, and the Dominican Republic, more than a quarter of pixels are unlit. Following Bertinellli and Strobl (2013) and Elliott, Strobl and Sun (2015), who also use nightlight data to study the economic impact of tropical storms on local activity, this study assumes there is no economic activity in pixels with a DN value of 0 for the entire sample period and therefore excludes them from the econometric analysis. They make up about 67 percent of the total sample.

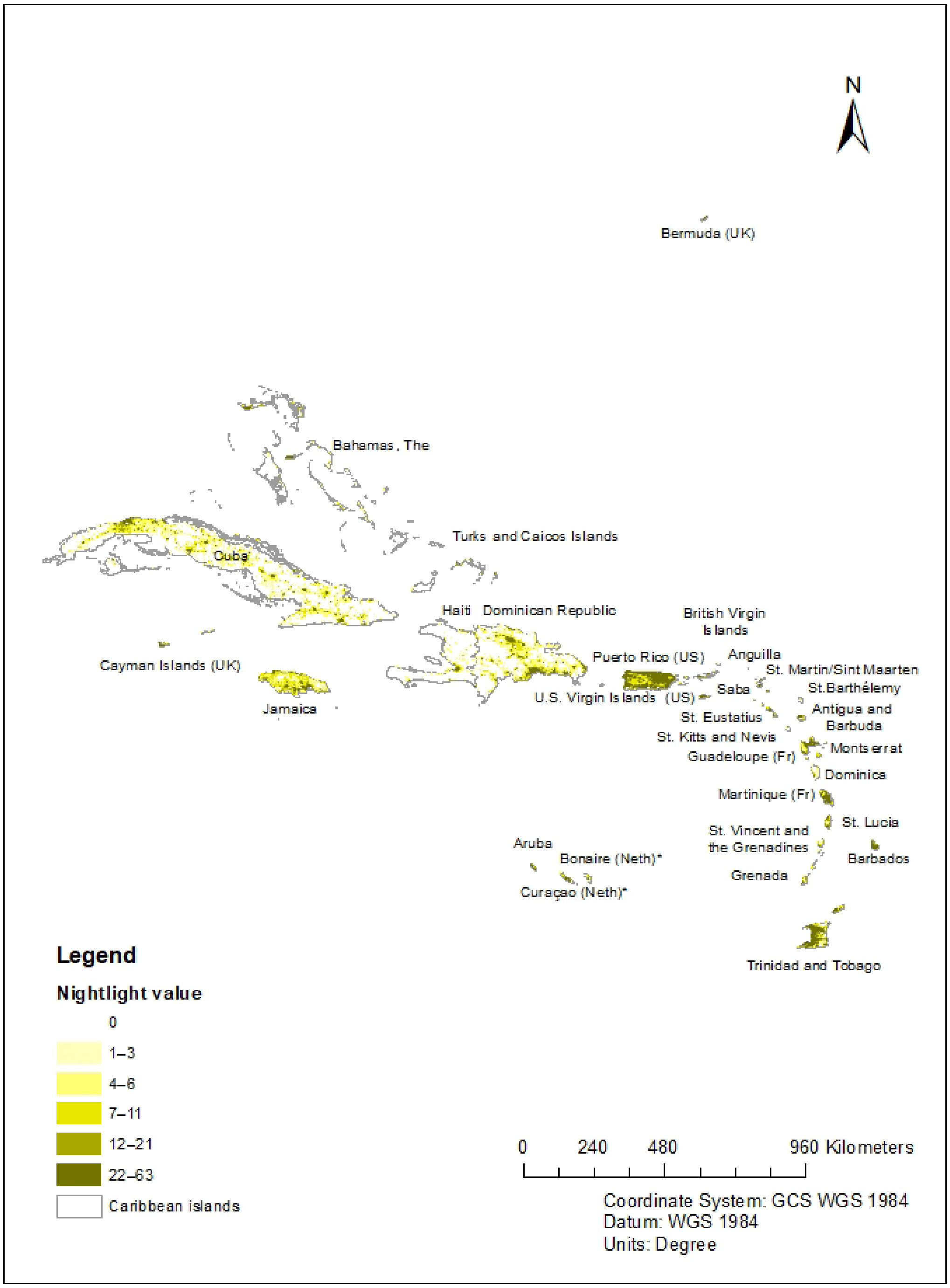
Table 1 also shows the number of top-coded pixels (with a DN value of 63) and the mean DN across the sample. The percentages of censored pixels are zero or close to zero, suggesting that nightlight saturation in urban centers might not be a major issue in the Caribbean. By contrast, the average DN value shows some variance across the 29 countries and territories. The island of Sint Maarten/St. Martin, which is half Dutch and half French territory, has the region's highest average DN (with 53.67 and 46.02, respectively); this is followed by Bermuda (36.24) and Aruba (36.08), countries with the highest income level in the Caribbean. In some way, the correlation between nightlight and income levels could be proved for these countries. However, nightlight might not be a reliable proxy for income levels due to cultural differences in the use of lights and light saturation in large cities (Ghosh et al. 2010). Instead, nightlight data work better as a proxy of economic growth (Henderson, Storeygard and Weil 2012). For this reason, our empirical strategy (see Section 3) centers on variations in nightlight intensity across pixels and over years, after controlling for time-invariant and time-specific effects, to isolate the impact of hurricanes on local economic activity.

Mean nightlight by Caribbean country or territory conveys different shapes of trends (Annex 1). In 2000, Haiti, Dominica, Montserrat, and Cuba presented the lowest DN value in the region (< 5), while St. Martin, Sint Maarten, Bermuda, and Puerto Rico, showed a value of 38–48, with 63 being the maximum value of nightlight. Surprisingly, five years later, in 2005, the islands with the lowest DN value at the beginning of the period had decreased their luminosity by approximately 2 points, while those with the highest DN values had decreased by around 8 points. In other words, the low-income islands reduced their value of nightlights by a lower number than the high-income islands. Overall, mean nightlight in the 29 countries and territories fell from 7.73 in 2000 to 6.12 in 2015. The impact of hurricanes and tropical storms on their local economies during that period could be a reason for this decline.

By 2010, DN values in almost all Caribbean islands had increased by 2–16 points, with the exception of Aruba, where it had reduced by 1 point. Trinidad and Tobago exhibited the highest growth in luminosity, from 13.51 to 29.32 points, followed by St. Martin and Martinique with a rise of 11–12 points. At the end of the studied period, in 2012, average nightlight on all the islands had dropped by 1 point. Five countries or territories— Aruba; Bonaire, Sint Eustatius, and Saba; Cayman Islands; Curaçao; and St. Martin showed a 1–3 point increase, and in Haiti, St. Kitts and Nevis, and St. Lucia, the DN value remained the same. Resilience to natural disasters on these islands may have improved the last decades. Figure 1 presents the map of nightlight intensity in the Caribbean Islands during the 2000–12 period.

[10] A country's number of pixels is proportional to its land area.

Figure 1. Map of nightlight imagery for the Caribbean region



Source: Based on the NOAA's Global DMSP-OLS Nighttime Lights Time Series 2000–12.
*Bonaire and Curaçao are formerly part of the Netherlands Antilles.
Note: Nightlight value corresponds to the pixel converted into a DN representing light intensity, with values ranging from 0 to 63.

Table 1. Average nightlight data for Caribbean countries and territories (2000–12)

Country / Area	DN value							Average DN	Average DN (excluding 0)	Area (sq km)	Population density (per sq km, 2018)	GDP per capita, PPP (2019 $)
	0	0-3	4-6	7-11	12-21	22-63	63					
Anguilla	0%	0%	2%	11%	50%	45%	0%	21.00	21.00	91	169.8	19,890
Antigua and Barbuda	11%	15%	13%	27%	27%	30%	0%	17.99	20.22	440	219	22,817
Aruba	0%	0%	7%	12%	16%	72%	7%	36.08	36.16	180	588	38,442
Bahamas, The	37%	52%	42%	10%	4%	10%	1%	7.21	11.47	13,880	39	37,266
Barbados	0%	0%	0%	9%	36%	61%	4%	30.90	30.90	430	667	16,287
Bermuda	0%	0%	1%	3%	11%	89%	0%	36.24	36.24	4,290	1184	59,474.60
Bonaire, Sint Eustatius, and Saba	18%	23%	40%	29%	14%	11%	0%	8.93	10.84	328	79.9 (year 2020)	24,266 (year 2016)
British Virgin Islands	8%	17%	44%	17%	19%	21%	0%	12.25	13.26	150	199	48,511
Cayman Islands	1%	4%	26%	38%	19%	29%	1%	18.88	19.17	260	267	72,481
Cuba	44%	57%	43%	12%	3%	2%	0%	3.60	6.38	109,880	109	8,821
Curaçao	5%	8%	23%	27%	17%	37%	7%	23.58	24.95	444	361	25,572
Dominica	32%	48%	56%	11%	3%	1%	0%	3.47	5.10	750	96	12,659
Dominican Republic	33%	41%	42%	18%	7%	6%	0%	6.15	9.18	48,670	220	19,182
Grenada	0%	3%	45%	47%	16%	10%	0%	10.07	10.10	340	328	17,956
Guadeloupe	1%	4%	24%	26%	28%	31%	1%	17.69	17.88	1,705	245.8 (year 2020)	26,855 (year 2016)
Haiti	70%	71%	19%	9%	3%	3%	0%	2.72	9.12	27,750	404	1,801
Jamaica	5%	11%	46%	42%	14%	9%	1%	9.59	10.13	10,990	271	10,661
Martinique	0%	2%	11%	17%	26%	54%	1%	25.31	25.42	1,128	354 (year 2020)	30,056 (year 2016)
Montserrat	29%	41%	51%	27%	1%	0%	0%	3.81	5.37	103	52.4 (year 2020)	12,753
Puerto Rico	0%	1%	4%	18%	24%	61%	5%	30.69	30.83	8,870	360	34,948
Sint Maarten	0%	0%	0%	0%	0%	100%	2%	53.67	53.67	34	1,193	23,366
St. Barthélemy	5%	7%	1%	3%	26%	68%	0%	26.79	28.29	25	9,961 (year 2016)	21,514 (year 2014)
St. Kitts and Nevis	1%	5%	30%	46%	0%	15%	0%	12.58	12.70	260	202	27,449
St. Lucia	1%	6%	31%	39%	0%	16%	0%	12.76	12.94	620	298	16,089
St. Martin	1%	1%	0%	0%	3%	96%	2%	46.02	46.39	54	672	16,572 (year 2014)
St. Vincent and the Grenadines	14%	23%	47%	32%	10%	7%	0%	7.28	8.44	453	283	12,983
Trinidad and Tobago	8%	11%	25%	25%	19%	33%	3%	19.58	21.27	5,130	271	27,261
Turks and Caicos Islands	31%	45%	38%	11%	9%	14%	0%	8.02	11.58	950	40	27,055
Virgin Islands, U.S.	1%	2%	11%	15%	17%	63%	1%	32.83	33.11	350	306	35,090 (year 2018)

Source: Based on estimates from the Food and Agriculture Organization (FAO), the World Bank the United Nations, the French National Institute for Statistics and Economic Studies and the Dutch Central Bureau of Statistics. *Note:* DN value corresponds to the pixel converted into a digital number representing light intensity, with values ranging from 0 to 63.

2.2. Hurricane damage frequency

Hurricanes cause the most devasting disasters in the Caribbean and they have shaped the region's history and will continue to shape its future. The movement of every tropical cyclic storm is characterized by extreme winds, storm surges, and exceptional levels of rainfall, which may cause flooding (Henderson-Sellers et al. 1998). Although the official hurricane season in the Greater Caribbean region begins on June 1 and lasts through the end of November, atmospheric conditions in the Atlantic Basin mean that approximately 80 percent of tropical storms and hurricanes form in a 45-day window from mid-August to late September.[11]

The number and strength of Caribbean storms vary greatly from year to year, which makes detecting trends in the frequency or intensity of hurricanes over time a challenge. In the last 20 years, the islands in the region have faced storms from low to high intensity, classified in four types by wind speed, as determined by the Saffir-Simpson Hurricane Wind Scale:

- Tropical depression: cyclone with maximum sustained winds of 61 kph or less (Category 0) [12]
- Tropical storm: winds of 62–118 kph (Category 0)
- Hurricane: winds between 119 kph (Category 1) and 177 kph (Category 2)
- Major hurricane: winds of 178–208 kph (Category 3), 209–251 kph (Category 4), and 252 kph or higher (Category 5).

During our sample period of 2000–12, 146 hurricanes (Categories 1–5) and 196 tropical cyclones were reported in the Caribbean region. Figure 2 shows that Cuba, The Bahamas, Haiti, and the Dominican Republic were most affected by hurricanes, with more than 40 episodes in that period. Cuba and The Bahamas were affected by major (Category 3) hurricanes.[13] By contrast, southern areas like the islands of Aruba, Martinique, and Dominica are rarely affected by major hurricanes because they tend to travel away from the equator.

The Dow Jones Island Index ranked Curaçao as the Caribbean island least likely to be hit by hurricanes, followed by Bonaire, Cayman Islands, Barbados, and Aruba. Other Western Caribbean islands are also less likely to be affected by hurricanes than Eastern Caribbean spots like the British Virgin Islands and Puerto Rico. Dominica, Montserrat, and Trinidad and Tobago are among the least affected islands, with fewer than 10 episodes of hurricanes in the 12-year study period. Tropical depressions and storms—which are not hurricanes and therefore classed as Category 0—occur frequently and at any time during the Atlantic Ocean hurricane season. Curiously, the countries most impacted by these are Dominica and Trinidad and Tobago, which presented fewer impacts by hurricanes, and Guadeloupe, with around 13 episodes during 2000–12, followed by Barbados and Bonaire, Sint Eustatius, and Saba, with 12 episodes.[14]

Some Caribbean islands are subjected to higher levels of wind speed more frequently than others. Over time, this has resulted in variations in building vulnerability across the region, as each country adopts or develops its own building codes and construction practices, reflecting its historical storm experience and

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[11] For more information about the peak of the hurricane season, see https://www.noaa.gov/stories/peak-of-hurricane-season-why-now

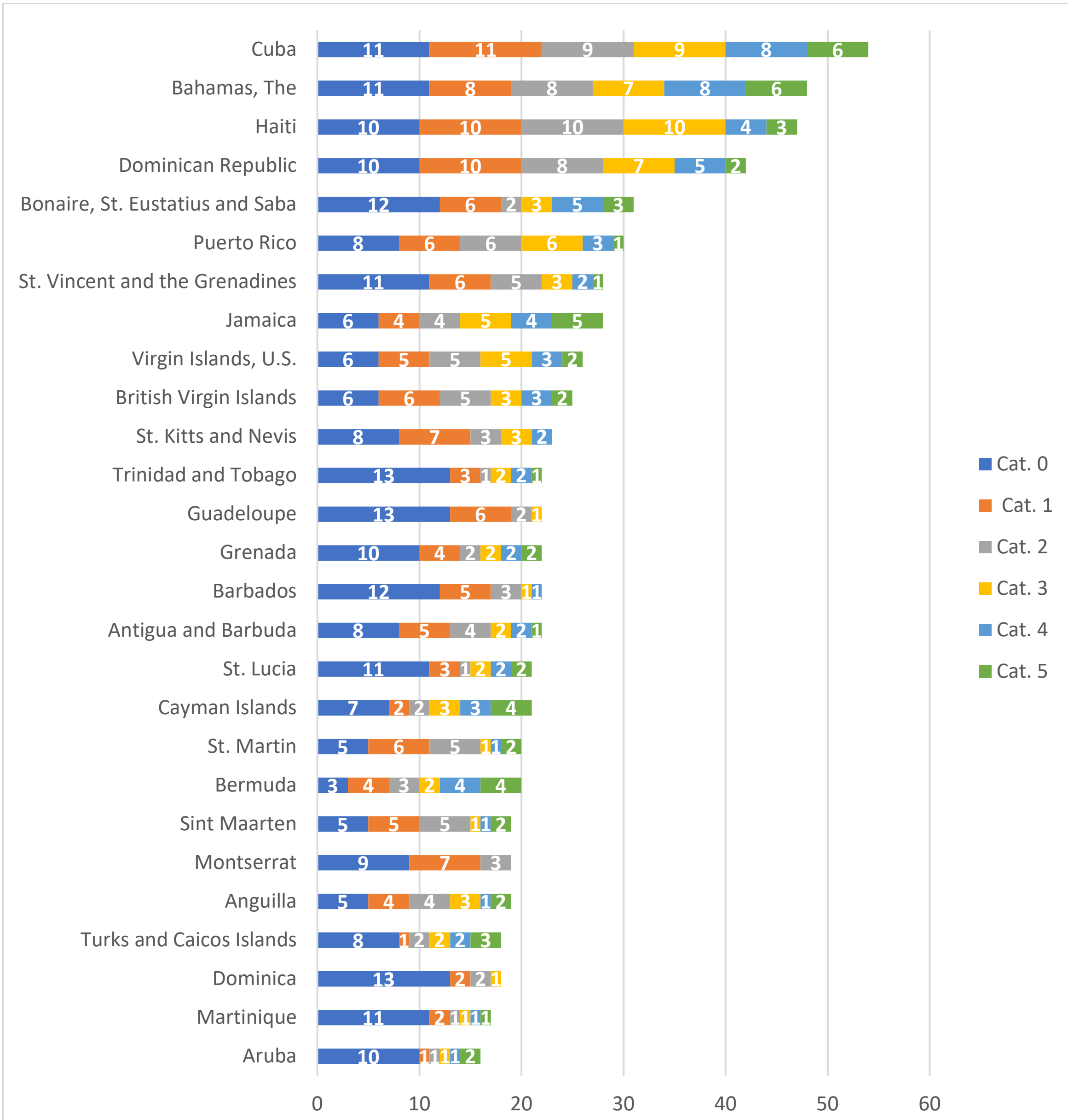
[12] According to NOAA, a tropical cyclone is a rotating, organized system of clouds and thunderstorms that originates over tropical or subtropical waters and has a closed low-level circulation. Tropical cyclones rotate counterclockwise in the Northern Hemisphere.

[13] Annex 2 shows the tendency of the damage index by Category 3 hurricanes by Caribbean country and territory.

[14] For further detail, see Annex 3.

regional building inventories such as the AIR Tropical Cyclone Model for the Caribbean.[15] The resulting construction, occupancy mix, and height distribution of the building stock is a fundamental determinant of the region's vulnerability and the reason why many Caribbean islands have suffered deep impacts from tropical storms and hurricanes in the last 20 years.

Figure 2. Tropical storms and hurricanes in the Caribbean, by country and category (2000–12)



Source: Authors' calculations based on data from The National Hurricane Center's North Atlantic hurricane database reanalysis project (HURDAT2) created by the Hurricane Research Division, and NOAA's Atlantic Oceanographic and Meteorological Laboratory.

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[15] For more information, see https://www.verisk.com/press-releases/2020/july/air-worldwide-releases-updated-tropical-cyclone-and-earthquake-models-for-the-caribbean/

A windstorm hazard model is used to simulate maximum sustained wind speeds,[16] which is a proxy for potential damage from hurricanes, experienced by the affected areas at a resolution of 1 square kilometer. It is capable of producing a fully exogenous measure of hurricane intensity and its potential destructive power at a fine-grained geographical level. The resulting wind speed data are then merged with nightlight data.

Recent studies have focused on improving natural hazard modeling to more explicitly address the impact of adverse natural events on socioeconomic indicators. For example, Hsiang and Jina (2014) and Strobl (2012) evaluate hurricane windstorm hazard data using global hurricane models to generate a gridded data set with different levels of resolution. One of the main innovations in this paper is its use of the fully probabilistic hurricane windstorm model developed by Strobl (2012), which we have validated and calibrated for the Caribbean region to generate hazard information with the temporal and spatial resolution needed for this study. We use windstorm hazard data to calculate the damage indexes, which we then use as inputs in both the macro and micro models. As a result, the paper substantially improves the understanding of how hurricane windstorm hazards could affect socioeconomic outcomes.

2.3. Mangrove forest data

Mangroves are commonly found along sheltered coastlines in the tropics and subtropics, where they fulfill important socioeconomic and environmental functions, from providing a large variety of wood and non-wood forest products to protecting the coast against the effect of wind, waves, and water currents, and conserving coral reefs, sea-grass beds, and endangered animals for biological diversity (FAO 2007). Together, coastal mangroves, coral reefs, and seagrass beds act as a natural barrier from the high wave energy and strong coastal currents that are typical of the Caribbean environment (Menéndez et al. 2020).

Although Caribbean mangroves have sustained human activity since pre-Columbian times (Sanoja 1992), climate-forcing factors, such as extreme winds caused by tropical storms, and anthropogenic factors like deforestation and urbanization have severely impacted mangroves in the region. In fact, anthropogenically-driven increases in atmospheric carbon dioxide concentration and regional sea level are expected to have a huge impact on mangroves (Ellison and Farnsworth 1996). Unfortunately, the demands on mangrove forests are more intensive and pervasive and include converting them to other uses such as agricultural production and urbanizing their uplands. This lack of concern for these ecosystems has led to the loss of mangroves, changed the conditions that regulate their functioning, and caused the overexploitation of dependent fisheries and other forest products (Lugo 2002).

The literature on mangrove forests is extensive and many case studies describe their extent and losses over time; yet, comprehensive global information on the status and trends in mangrove extent is lacking. The first attempt to estimate total mangrove area worldwide was undertaken as a part of the FAO and United Nations Environment Programme's *Tropical Forest Resources Assessment* in 1980, which estimated the world mangrove total area at 15.6 million hectares. More recent estimates range from 12 to 20 million hectares (FAO 2007).

For this study, we used two mangrove distribution sources:

- Mangrove data from the *World Atlas of Mangroves* (Spalding, Blasco and Field 1997): the first collection of harmonized maps from 1960 to 1996, which estimates a total mangrove extent of 18.1 million hectares in 112 countries and territories (including small island nations).

[16] We thank Eric Strobl for sharing the model results.

- The first global map of mangrove forests using remotely sensed data (Giri et al. 2011): this map uses over 1,000 Landsat scenes acquired between 1997 and 2000, with supervised and unsupervised digital image classification, to construct a 30 m^2 resolution map of global mangrove distribution, and estimates a total mangrove extent of 13.7 million hectares in 118 countries and territories in the world's tropical and subtropical regions.

Spalding, Blasco and Field (1997) estimate that there are 880,173 hectares of mangrove forest in the 29 countries and territories selected for this study. Of these, Cuba and The Bahamas have the most extensive mangrove areas, with approximately 556,900 and 211,400 hectares, respectively. Giri et al. (2011), on the other hand, find that mangroves extend over 616,440 hectares in the 26 Caribbean countries and territories studied (excluding Dominica, Montserrat, and Sint Maarten). They also estimate that Cuba (440,641 hectares) and The Bahamas (82,408 hectares) have a larger mangrove areas, although these differ from Spalding, Blasco and Field (table 2).

Table 2. Mangrove areas in Caribbean countries and territories (hectares)

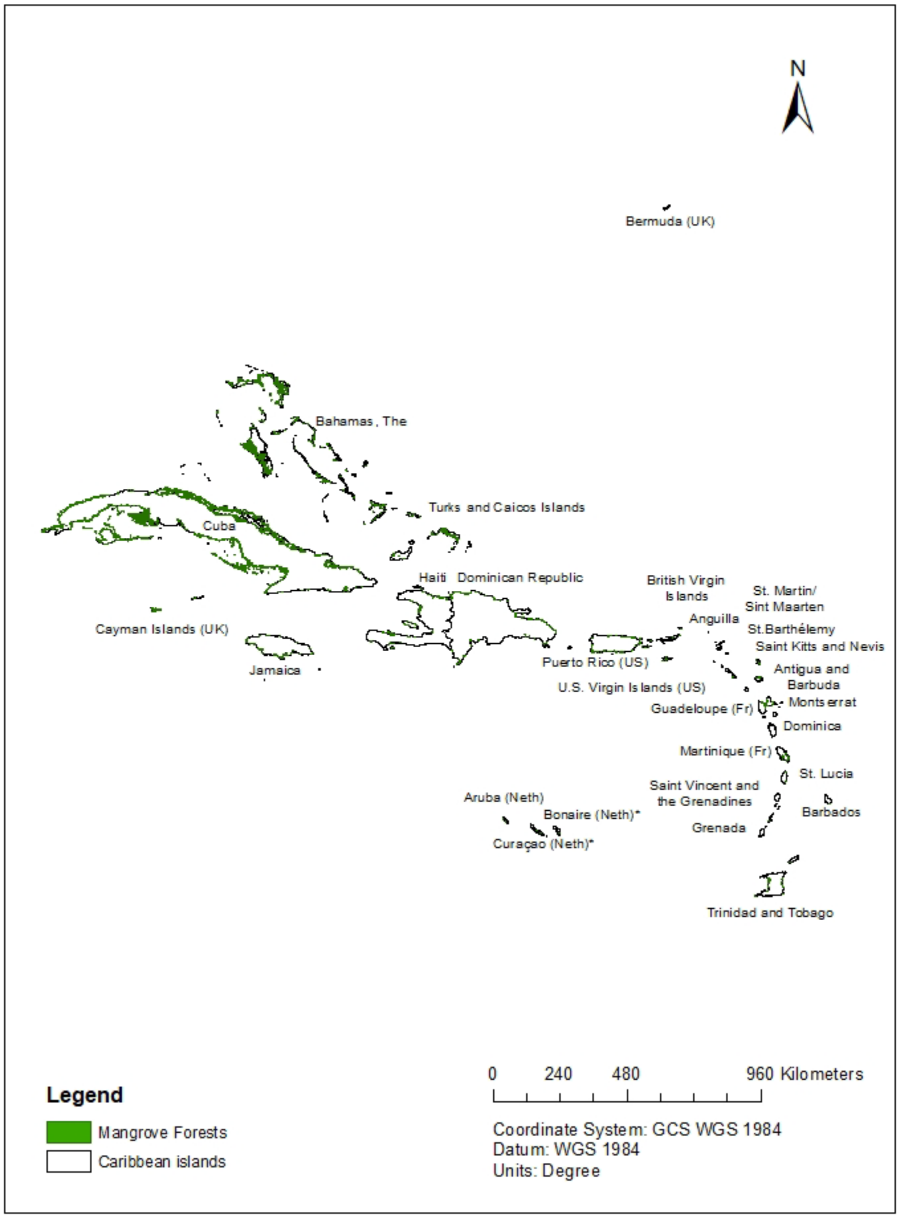
Country/Territory	Spalding, Blasco and Field (1997)	Giri et al. (2011)	Country/Territory	Spalding, Blasco and Field (1997)	Giri et al. (2011)
Anguilla	90	5	Haiti	13,400	15,496
Antigua and Barbuda	1,316	973	Jamaica	10,600	9,817
Aruba	420	79	Martinique	1,587	1,197
Bahamas, The	211,400	82,408	Montserrat	31	–
Barbados	30	40	Puerto Rico	9,200	8,831
Bermuda	10	9	St. Kitts and Nevis	43	57
Bonaire, Sint Eustatius, and Saba	n.a.	252	St. Lucia	125	158
British Virgin Islands	435	82	St. Vincent and the Grenadines	154	46
Cayman Islands	7,100	8,063	St. Barthélemy	–	3
Cuba	556,900	440,641	St. Martin	–	17
Curaçao	n.a.	81	Sint Maarten	–	–
Dominica	156		Trinidad and Tobago	5,400	7,419
Dominican Republic	32,500	19,180	Turks and Caicos Islands	23,600	17,921
Grenada	536	229	Virgin Islands, U.S.	106	199
Guadeloupe	3,983	3,229	The Netherlands Antilles (leeward group)	1,051	n.a.

Source: Authors' calculations, based on estimates by Spalding, Blasco and Field 1997 and Giri et al. 2011.
Notes: Grenada includes St. Martin and St. Barthélemy. *The Netherlands Antilles (leeward group)* is formed of Bonaire and Curaçao. The Netherlands Antilles dissolved on October 10, 2010. Curaçao and Sint Maarten became autonomous territories of the Kingdom of the Netherlands. Bonaire, Saba, and Sint Eustatius now fall under the direct administration of the Netherlands.

The services provided by mangroves are threatened by anthropogenic processes, including deforestation and sea level rise (Schuerch et al. 2018), and Caribbean mangroves have historically been reclaimed for urbanization, industrialization, and increasingly, tourism. Although global mangrove deforestation rates have slowed since the turn of the millennium, with annual loss rates of 0.2–0.7 percent (Hamilton and Casey 2016; Friess et al. 2019), the Caribbean region is losing mangrove forest at an overall rate of 1 percent per year. This is higher on the mainland, where the rate is approximately 1.7 percent than on the islands, where it is approximately 0.2 percent (Ellison and Farnsworth 1996).

Despite the lack of a robust database of post-2000 mangrove change, numerous studies of this change at the global, national, and local scales express concern over mangrove deforestation (for example, Satapathy et al. 2007; Hamilton 2013). Mangrove forests have been shown to contain more economic value to ecosystem services and carbon sequestration per hectare of any forest type globally (Barbier and Cox 2004; Barbier 2006; Bouillon et al. 2008; Donato et al. 2011). This includes substantial carbon stored below the ground in mangrove soil (Donato et al. 2011; Murdiyarso et al. 2015), which means mangrove deforestation probably releases more carbon dioxide per hectare than any other forest type. Work is under way to place economic value on the carbon stored in mangrove forests (Siikamäki, Sanchirico, and Jardine 2012), which will adding substantially to the potential economic value of mangrove preservation. Figure 3 presents the map of mangroves in the Caribbean region, using the distribution of Giri et al. (2011).

Figure 3. Mangrove distribution in the Caribbean



Source: Based on geographic system information from Giri et al. 2011.

*Bonaire and Curaçao are formerly part of the Netherlands Antilles.

3. Empirical strategy

To estimate whether mangroves can reduce hurricane damage, we divide the Caribbean region into 1 square kilometer grid cells and construct a cell-year panel for the 2000–12 period. The panel combines measures of economic activity, potential hurricane damage, and mangrove protection.

First, to assess the impact of hurricanes on economic activity, we estimate the impact of a damage function on our nightlight data set, which is our proxy for economic activity. Specifically, we follow Del Valle et al. (2020) and consider the following two-way fixed effect equation:

$$NL_{it} = \alpha + \beta f_{it} + \pi_t + \mu_i + \varepsilon_{it}$$

Where NL_{it} is nightlight intensity (in logarithms) of cell i in year t, f_{it} is the damage index,[17] π_t are year fixed effects, μ_i are cell fixed effects, and ε_{it} is the error term. The inclusion of cell fixed effects aims to capture the fact that certain areas in the Caribbean may have been exposed to more frequent and greater incidence of hurricanes, leading to the reallocation of segments of the population—and thus economic activity—or to the implementation of disaster prevention actions. Issues related to time-varying common shocks and nightlight time comparability are addressed by including year fixed effects. The estimation method is based on Correia (2016), which accounts for linear models with many levels of fixed effects (as in our case).

Second, to measure the level of protection, we use two data sets with different calculations of mangrove width and test for a potential nonlinear relationship. Our interest is to study the effectiveness of this potential mitigation property as the level of mangrove protection—that is, mangrove width—increases.

3.1. Modeling the windstorm model

We use the wind speed data to obtain a damage index using the transformation and parameters proposed by Emanuel (2011) in the following expression:

$$f_{it} = \frac{\left[\frac{\max\,(V_{it} - V_T, 0)}{V_H - V_T}\right]^3}{1 + \left[\frac{\max\,(V_{it} - V_T, 0)}{V_H - V_T}\right]^3}$$

Where V_{it} represents the wind speed in cell i at year t, V_T is the threshold below which damage is unlikely to occur, which is set at 50 knots or roughly equal to 92.6 kph, and V_H is the wind speed at which half of all structures are expected to be destroyed set as 150 knots or roughly equivalent to 277.8 kph.

Storm surge-prone area: As we mentioned at the beginning of this section, the f_{it} represents the damage index that provides an informative measure of wind damages from excess rainfall and storm surge. But, as storm surge is often considered one of the most harmful aspects of hurricanes, we further investigate whether coastal lowlands are disproportionately affected by hurricanes. Specifically, we create a coastal lowland indicator variable identifying continuous areas along the coast that are less than 10 meters above

[17] For this exercise, we used the f damage index with $V_H = 203\ kph$. However, the impact was also estimated with $V_H = 278\ kph$, with similar results.

sea level.[18] This storm surge-prone area is composed of 432,068 cells (approximately 18.70 percent of all cells). For each of these cells, we also calculate the shortest path—that is, Euclidean distance—from the centroid of the cell to the coast. The average distance to the coast is 23.44 kilometers.

3.2. Mangroves for coastal protection

As described in Section 2.3, our mangrove distribution data come from two sources: we used Spalding, Blasco and Field (1997) to identify areas that have historically supported mangrove habitats, and Giri et al. (2011) to precisely measure the presence of mangrove at the beginning of our sample period (2000–12).

Mangrove protection benefits can be derived from their location in areas that are naturally more protected, such as on a continental shelf, on a rugged coastal topography with elevations rising up to 200 meters, or between the shoreline and the continental slope (Jackson 1997). Hence, we began by excluding from our analysis any areas that have not historically supported mangrove habitats. Specifically, for every cell in the storm surge-prone area, we excluded cells that Spalding, Blasco and Field (1997) define as having no mangrove on their shortest path to the coast. We found that 20,504 cells (4.74 percent of all cells in storm surge-prone areas) have mangrove on their path to the coast.

For each of the remaining cells, we then calculated the mangrove width in two steps. First, we identified the line segments along the shortest path to the coast that overlap mangrove forests as defined by Giri et al. (2011). Second, we summed the line segments to measure cumulative mangrove width on the shortest path to the coast. Figure 4 provides a visual representation of the mangrove width calculations on the coast. We found that in our sample, the average mangrove width is 0.25 kilometers, with a minimum of 0 and a maximum of 20.67 kilometers.

[18] Nordhaus (2006) considers areas with elevation of less than 8 meters as vulnerable to storm surge. We use a less stringent definition because Shuttle Radar Topography Mission elevation estimates under 10 meters are not considered reliable (McGranahan, Balk and Anderson 2007).

Figure 4. Mangrove distribution in The Bahamas' North Caribbean Coast Autonomous Region

Source: Based on the geographic system information in Giri et al. 2011 and data from Spalding, Blasco and Field 1997 and the NOAA.

Notes: Dots represent centroids of cells; lines show the shortest path to the coast. The green line segments represent mangrove on the path to the coast.

4. Results and discussion

In this section, we first evaluate the impact of hurricanes on economic activity and assess the mitigating role of mangroves against hurricanes in the Caribbean region. Using the hurricane windstorm model—and the nightlight data set to quantify the causal effects of the hurricane windstorm model on local economic activities—we categorize three hurricane damage indexes, which provides a higher level of detail. In a second step, we include mangrove data and characteristics to evaluate its potential mitigation effect of the impact of hurricanes on economic activity. The main descriptive statistics for the variables in the sample used in this section can be found in Annex 4.

4.1. Impact of hurricanes on nightlight

We initially explore the impact of hurricanes on nightlight using data for 29 Caribbean countries and territories. This comprises more than 2 million observations due to the grid-cell measurement for the 2000–12 period.[19]

The econometric results show a negative, statistically significant, association between nightlight and the hurricane damage index. Table 3 provides estimates for the two-way fixed effect equation described in Section 3 and using three specifications (columns 1 to 3) to include a potential lagged effect of hurricanes on nightlight and to discriminate the effect in low-elevation coastal zones. Particularly, the size for the estimate for β, which measures the impact of hurricanes on nightlight, shows that nightlight in cells that experience Category 3 hurricane winds ($f = 0.2$, wind speed of 203 kilometers per hour) decrease by 0.35 units ($\approx -1.75 * 0.2$).[20] Given that the average level of nightlight intensity in 2000 was 12.1,[21] the effect is equivalent to a 2.9 percent decrease in local economic activity.

Table 3 shows that the negative association between nightlights and the hurricane damage index seems to be short-lived. In column 2, it is possible to evidence that, consistent with previous literature (Elliott, Strobl and Sun 2015; Del Valle et al. 2018), hurricanes have a short-lived effect on local economic activity. To evaluate this, we included a lagged term for the hurricane damage index and found that, while the contemporaneous coefficient remains negative and statistically significant, the lagged coefficient is positive and statistically significant. This may be related to implementing rehabilitation and reconstruction stages following a disaster shock.

The effect of windstorms is more negative in storm surge-prone areas, measured as low-elevation coastal zones. Column 3 provides estimates to assess whether hurricane impact is dissimilar in coastal lowland zones. For this purpose, we included dummy variables to identify these areas and create interaction terms with the f damage index. The estimated coefficient for non-storm-prone areas is positive and statistically significant, while the coefficient for storm-prone areas is negative and statistically significant as well. This suggests that the effect of hurricanes is considerably greater in low-elevation coastal zones. Specifically, using average nightlight levels for 2000 (as in column 1), we found that the negative effect of Category 3 hurricane winds is associated with a 16.1 percent decrease in local economic activity.[22]

[19] For the regression analysis, we excluded data from Cuba, as they seem to be driven by a positive association between nightlight and the damage index, perhaps due to limited data density but large coverage (see Annex 5).

[20] Recall that our specification is a log-linear regression model. Therefore, to find the coefficient that is multiplied by the damage index (f), the following calculation is performed: *[exp (-0.0177)-1] *100.*

[21] Records in nightlight image data are the DN values, ranging from 0 (no light) to 63 (maximum light).

[22] The calculation was as follows: *[[[exp (-0.0103)-1] *100] *(0.2)]*[1/12.1]*.

Table 3. Impact of hurricanes on nightlight

	(1) Ln (nightlight)	(2) Ln (nightlight)	(3) Ln (nightlight)
f	-0.0177** (0.00715)	-0.0244*** (0.00733)	
$f(t-1)$		0.0991*** (0.00731)	
f in non-storm surge-prone areas			0.0211** (0.00831)
f in storm surge-prone areas			-0.103*** (0.0117)

Source: Authors' calculations.
Notes: Dependent variable: nightlights. Estimates from OLS regression, cell and year fixed effects included but not reported. ***p<0.01, **p<0.05, *p<0.1. Robust standard errors in parentheses. The number of observations is 1,159,340 for column 1 and 3; and 1,070,160 for column 2). Average nightlight in 2000 is 12.1.

4.2. Mangroves reduce hurricane impact

Mangrove forest, an essential component of many Caribbean coastlands, can act as a natural defense against hurricanes. For example, Zhang et al. (2012) find that along South Florida's Gulf Coast, each kilometer of mangrove width reduces storm surge by 50 centimeters, while Del Valle et al. (2020) find a similar result in their study of how mangrove forest mitigates the impact of hurricanes on economic activity in Central America. Based on these initial findings, it is possible to interpret as hurricanes having an adverse effect on local economic activity, we explore whether mangrove forests can mitigate this effect in the Caribbean region.

To measure the level of protection that mangroves offer, we use two data sets with different calculations of mangrove width and test for potential nonlinear relationships. Our interest is in studying the effectiveness of this potential mitigation property as the mangrove width increases (see Section 2.3 for a description of how the two databases used for the econometric results calculate mangrove width).

Our results indicate that mangrove forests act as natural defense and mitigate the impact of hurricanes in local economic activity. We estimate three models, as in Del Valle et al. (2020), and discretize mangrove width data into various bins or compartments that correspond to its q-quantiles[23] in low-elevation coastal zones (LECZ).

The first model uses *q=2*, and we create a dummy variable for each bin and interact these variables with the f damage index. We then take the resulting variables and include them in our two-way fixed effect econometric equation in place of the f damage index. We repeat this approach for the second model using *q=3*; and the third model, *q=4*.

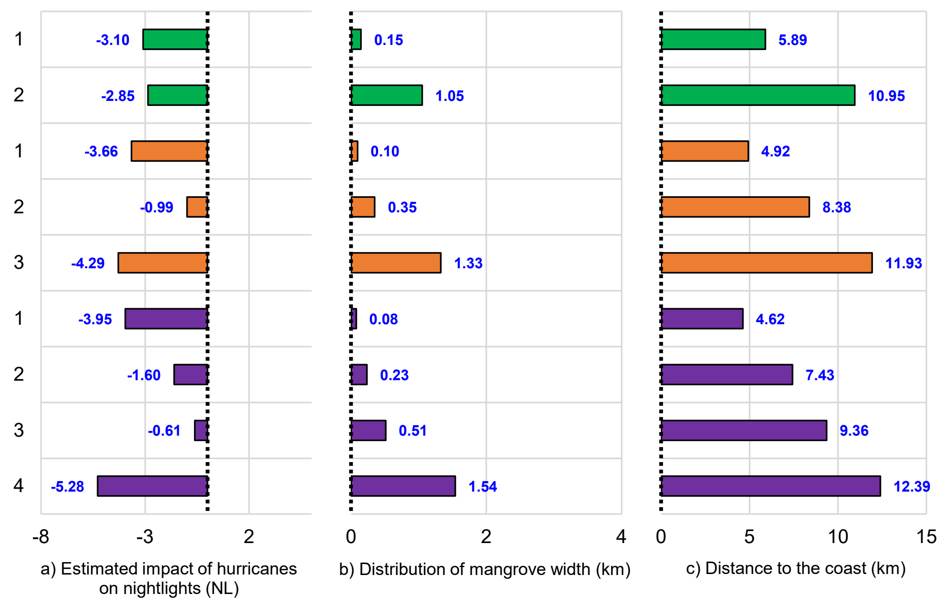
Excluding Cuba from the sample, figure 5 plots the results for 29 countries and territories, in three panels (a, b and c) for three models. Panel a shows point estimates for each of the models regarding the impact

[23] A quantile is a set of values which divide a frequency distribution into equal groups, each one containing the same fraction of the total sample data.

of hurricanes on nightlight for each bin. Panel b plots the distribution of mangrove width for each bin, and panel c plots distance to the coast for each model and bin.

For example, the top two rows, colored with green bars, plot the impact of hurricanes on nightlight for each model 1 (*q=2*) bin, where the bins correspond to cells with above and below median width (approximately 0.25 kilometers) on their path to the coast. It is possible to see that in below-median areas, hurricanes can significantly reduce nightlight. The estimated coefficient of -3.10 indicates that Category 3 hurricane winds ($f = 0.2$, wind speed of 203 kph) would reduce nightlight by 0.62 units ($\approx -3.10 * 0.2$) equivalent to a 5.1 percent reduction, using the inverse of the average nightlight level in 2000.[24] In contrast, the above-median effect is smaller and would imply a 4.7 percent reduction in nightlight.[25] Rows 3–5 (orange) correspond to model 2 (*q=3* or the third tercile) where mangrove width is greater than 1 kilometer and an average width of 2 kilometers. Rows 6–9 (purple) correspond to model 3 (q=4 or the fourth quartile) where mangrove width is greater than 1.26 kilometers and an average width of 2.3 kilometers), respectively. Figure 5 shows that most—though not all—models show a decreasing pattern of hurricane damage as we move through the corresponding bins. For example, using model 3, the impact is reduced until the third bin, where the reduction in nightlights is equivalent to 1 percent,[26] instead of 6.5 percent in the first bin.[27] A similar result can be found in panel c, where, on average, a wider stretch of mangrove also implies a longer distance to the coast.

Figure 5. Impact of hurricanes on nightlight by mangrove width, excluding Cuba



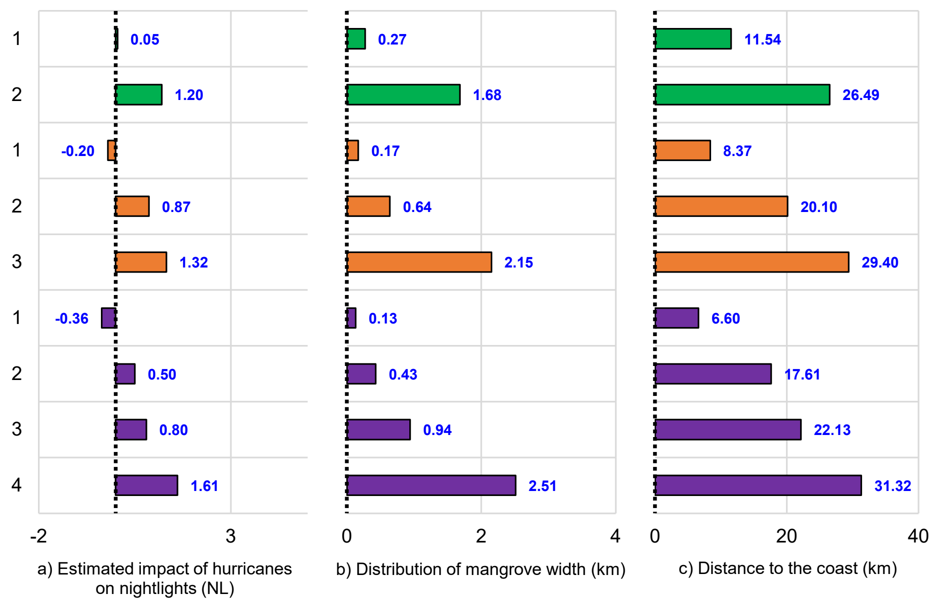
Source: Authors' calculations based on data from LECZ database.
Notes: In models 1-3, from panel (a) we discretize the mangrove width variable into bins that correspond to its q-quantiles and estimate the impact of hurricanes on economic activity for each bin. Model 1 uses q=2 and is colored in green. Model 2 uses q=3 and is colored in orange. Model 3 uses q=4 and is colored in purple. Panel (b) plots the distribution of mangrove width for each bin, and panel (c) plots the distribution of distance to the coast for each bin. Regression coefficients are shown in panel (a) and the average value for panels (b) and (c).

Including Cuba in the sample (figure 6), mangrove width appears to mitigate the impact of hurricanes on nightlight in the first quantile of the models 2 and 3. In model 2 (orange), the estimated coefficient

[24] The calculation was as follows: [$\approx -3.10 * 0.2$] *[1/12.1]
[25] Following the same procedure to find the percentage, using the coefficient -2.85.
[26] Following the same procedure to find the percentage, using the coefficient -0.61.
[27] Following the same procedure to find the percentage, using the coefficient -3.95.

of -0.20 indicates that a Category 3 hurricane wind ($f = 0.2$, wind speed of 203 kph) would reduce nightlight by 0.04 units ($\approx -0.20 * 0.2$)—equivalent to a 0.33 percent reduction—using the inverse of the average level of nightlight in 2000.[28] In model 3 (purple), the effect of the presence of mangroves on hurricanes is greater and implies a 0.60 percent reduction in nightlights.[29] As in Figure 5, panels (b) and (c) show that hurricane damage is lower in cells with more than 1 and 2.3 kilometers of mangrove width during the sample period.

Figure 6. Impact of hurricanes on nightlight by mangrove width, including Cuba



Source: Authors' calculations based on data from LECZ database.
Notes: In models 1–3, from panel (a) we discretize the mangrove width variable into various bins that correspond to its q-quantiles and estimate the impact of hurricanes on economic activity for each bin. Model 1 uses q=2 and is colored green. Model 2 uses q=3 and is colored orange. Model 3 uses q=4 and is colored purple. Panel (b) plots the distribution of mangrove width for each bin, and panel (c) plots the distribution of distance to the coast for each bin. Regression coefficients are shown in panel (a) and the average value for panels (b) and (c).

In general, the results show the potential value of mangroves as natural defenses against hurricanes in the Caribbean region, reflecting the importance of their conservation and restoration. These findings are consistent with other estimates of mangrove protection, which indicate that 2–7 kilometers of mangrove width would be needed to fully attenuate storm surge for the hurricanes that make up the bulk of our sample, particularly for Category 3. We find similar results when using a wide range of alternative assumptions for constructing the hurricane damage function, calculating mangrove width, and specifying models.

[28] The calculation was as follows: [$\approx -0.20 * 0.2$] *[1/12.1]
[29] Following the same procedure to find the percentage, using the coefficient -0.36.

5. Conclusion

In this study, we show that wide mangrove belts in the Caribbean have the potential to mitigate the disruption of economic activity caused by hurricanes. We use remote sensing nightlight data to measure local economic activity, a damage index derived from a wind field model calibrated for the Caribbean to measure potential hurricane destruction, and the calculated cumulated width of mangrove along the closest path to the coast to measure mangrove protection. Using these data, we estimate the impact of hurricanes on economic activity under the assumption that hurricane strikes are exogenous conditional on cell and year fixed effects. We then use a binning estimator to explore whether there is a negative and plausibly nonlinear relationship between mangroves and hurricane damages.

Hurricanes have negative short-term effects on economic activity, with losses likely to be concentrated in coastal lowlands at risk of both wind and storm surge. We further show that within the coastal lowlands, the impact of hurricanes declines with mangrove width and specifically, that the effect of hurricanes in our sample is mitigated by 0.25 kilometer or more of mangrove width. We also conduct various robustness checks and rule out that these findings are driven by the physical characteristics of the location of the mangrove habitat or by the distance to the coast.

Our results contribute to highlight the importance of mangrove conservation and restoration in the Caribbean region, especially in the coastal lowlands, for protecting local economic activity against tropical cyclones and hurricanes. The evidence suggests it is the width of the mangrove belts that give the protection, reducing the flooding impacts of storm surges during major storms, which implies that large-scale efforts will be required to achieve the benefits of the mangrove protection.

Finally, there are two important points to comment. First, we are likely to have underestimated the protective value of mangroves in the long run because mangrove protection may include additional benefits—such as lives saved, health outcomes, and human capital accumulation—that are not well captured by nightlight data. Second, while climate change and the resulting intensification of storms may increase the value of conservation for protection purposes, it is vital that that decisions around areas designated for conservation or restoration consider the threat of sea level rise. Consequently, identifying areas that should be prioritized for conservation and restoration and that have the potential to be mangrove habitats is an important avenue for future research.

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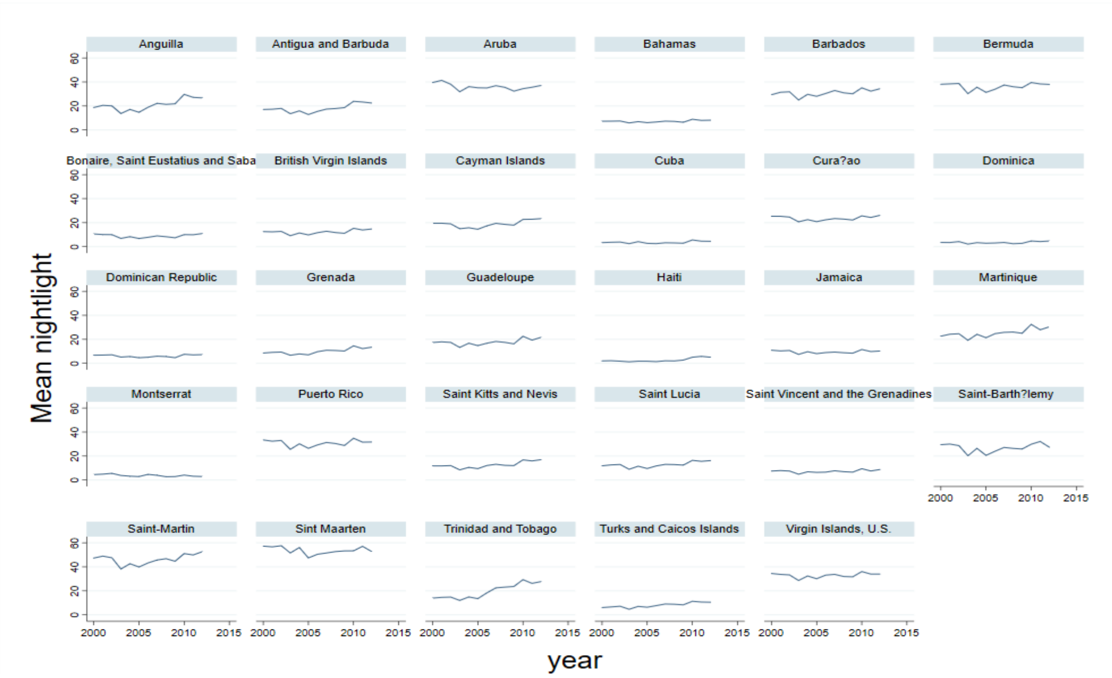
7. Annexes

Annex 1. Mean nightlight



Note: Nightlight value represent the mean of light intensity per year, with values ranging from 0 to 63.
Source: Authors' calculations based on the NOAA's Global DMSP-OLS Nighttime Lights Time Series 2000–12.

Annex 2. Mean hurricane damage index

Note: Mean hurricane damage index correspond to f=0.2 (wind speed of 203 kilometers per hour).
Source: Authors' calculations based on windstorm hazard model outcomes (see sections 2.2 and 3.1).

Annex 3. Hurricanes in the Caribbean, by category number (2000–12)

Country/area		Hurricane category number (Saffir-Simpson Scale)					
	0	**1**	**2**	**3**	**4**	**5**	**Total**
Anguilla	5	4	4	3	1	2	19
Antigua and Barbuda	8	5	4	2	2	1	22
Aruba	10	1	1	1	1	2	16
Bahamas, The	11	8	8	7	8	6	48
Barbados	12	5	3	1	1	0	22
Bermuda	3	4	3	2	4	4	20
Bonaire, Sint Eustatius and Saba	12	6	2	3	5	3	31
British Virgin Islands	6	6	5	3	3	2	25
Cayman Islands	7	2	2	3	3	4	21
Cuba	11	11	9	9	8	6	54
Curaçao	0	0	0	0	0	0	0
Dominica	13	2	2	1	0	0	18
Dominican Republic	10	10	8	7	5	2	42
Grenada	10	4	2	2	2	2	22
Guadeloupe	13	6	2	1	0	0	22
Haiti	10	10	10	10	4	3	47
Jamaica	6	4	4	5	4	5	28
Martinique	11	2	1	1	1	1	17
Montserrat	9	7	3	0	0	0	19
Puerto Rico	8	6	6	6	3	1	30
St. Kitts and Nevis	8	7	3	3	2	0	23
St. Lucia	11	3	1	2	2	2	21
St. Vincent and the Grenadines	11	6	5	3	2	1	28
St. Barthélemy	0	0	0	0	0	0	0
St. Martin	5	6	5	1	1	2	20
Sint Maarten	5	5	5	1	1	2	19
Trinidad and Tobago	13	3	1	2	2	1	22
Turks and Caicos Islands	8	1	2	2	2	3	18
Virgin Islands (U.S.)	6	5	5	5	3	2	26

Source: Authors' calculations.

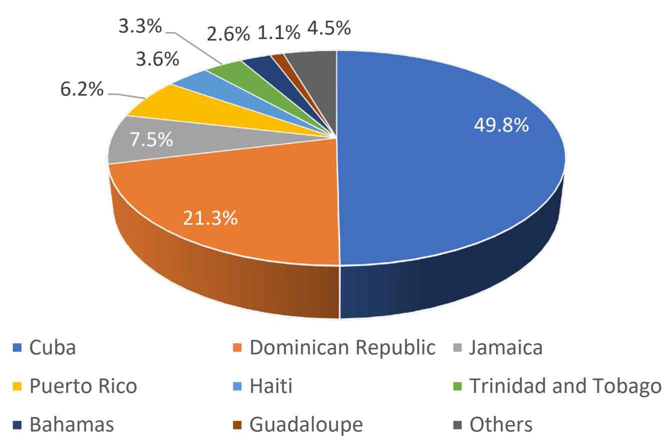
Annex 4. Descriptive statistics

Variable	Description	Mean	Standard deviation	Minimum	Maximum
Luminosity Index (nightlight)	Intensity of nightlights, on scale that ranges zero (no light) to 63 (maximum light)	7.66	12.72	0.00	63.00
f index (203)	Emanuel f index (2011) with V_H = 203 kph	0.21	0.31	0.00	0.97
Low elevation	LECZ indicator	0.19	0.39	0.00	1.00
Old mangrove	Areas that have historically supported mangrove habitats	0.03	0.16	0.00	1.00
Mangrove width	Sum of line segments with mangrove areas on the shortest path to the coast	0.25	0.74	0.00	20.67
Distance to coast	Distance from the centroid of the cell of nightlights to the coast	23.45	16.90	0.01	82.10

Source: Authors' calculations.
Note: Number of observations in raw data = 2,310,113.

Annex 5. Relative observations per country (percentage of total number of observations)

The initial number of observations is equivalent to 2,310,113 and includes all 29 countries and territories. It is important to note, however, that, due mainly to a greater territorial extension, some countries present a greater concentration of observations. Cuba, for example, comprises 49.8 percent of observations, the Dominican Republic 21.3 percent, Jamaica 7.5 percent, Puerto Rico 6.2 percent and Haiti 3.6 percent.



Source: Authors' calculations.