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Supplementary Information for

Mangroves shelter coastal economic activity from cyclones

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Supplementary Information Text
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Supporting Information
Data Sources and Geospatial Processing

Mangrove Areas

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. This database is itself a synthesis of the landsat driven Global Forest Change (GFC) database (1), the landsat driven Mangrove Forests of the World (MFW) database (2), and the expertly delineated Terrestrial Ecosystems of the World (TEOW) database. CGMFC-21 tracks mangrove forest cover at 1 arc-second resolution globally for the 21st Century. Each 1 arc-second pixel measure contains a mangrove canopy cover estimate in square meters for each year. This database is known to omit some small mangrove forests in-and-around the Pacific atolls.

Administrative Units

Mangrove areas were then aggregated to the Lowest Level Administrative Units (LLA) of each country with mangrove holdings, using the Global Administrative Areas Database v2.7. Off-shore mangroves outside of a country boundary were assigned to their closest LLA via a process of spatial allocation. This process provides annual mangrove area estimates for each LLA globally. Administrative areas smaller than 2 km^2 were discarded due to a lack of inputs feeding into each pixel, and LLAs with no region closer than 50 km to the coast were also excluded as we considered these non-coastal LLAs. The 2 km^2 rejection rule appeared to only alter data for the Philippines in any meaningful manner, which had numerous LLAs smaller than 2km^2. LLAs further north or south than 50° were excluded due to being outside of the maximum mangrove latitudinal range (2). Although many of the datasets such as mangrove cover, population, and raw elevation are at 1 arc-second resolution; or approximately 30 m^2 at the equator, the minimum mapping unit or data resolution of this analysis is best defined as the smallest administrative unit for each country globally that has land within 50 km of the coastline and an area greater than 2 km^2 and all more resolute datasets are aggregated to this larger unit.

Protected Mangroves

Within each LLA we calculated not only the mangrove canopy area annually but also the amount of this mangrove area that was in a protected area within each LLA. The protected areas were obtained from the World Database of Protected Areas (WDPA*)* and were not only applied spatially to each LLA but annually as well dependent on the year the protected area came online (3). For example, if a protected area came online in an LLA in 2005 the relevant mangrove area would show as protected in 2005 but not in 2004.

Population Counts

Population counts from 2000 to 2012 for each LLA were calculated from the Landscan population database (4). This dataset is based on census data obtained at the highest possible resolution which is then remapped using dasymmetric mapping and modelling techniques to a 30 arc-second resolution, or 1 km^2 at the equator. Although individual population measures from Landscan have high levels of uncertainty, the average LLA is greater than 530 km^2, resulting in 530 Landscan population counts feeding into the average LLA, this aggregation increases the reliability of the population measures.

Mean Elevations

The average elevation of each LLA was calculated using Shuttle Radar Topography Mission (SRTM) data at 3 arc-seconds, or approximately 90 m^2 at the equator (5). These data were merely averaged for each LLA to provide a mean elevation across the LLA. As the elevation data is at 90 m^2 resolution and the smallest allowable LLA is 2 km^2, this results in at least 22,222 elevation measures feeding into each LLAs average calculation thus ensuring that individual pixel elevation anomalies will have a limited influence on the overall LLA average. The average elevation of all LLAs across the entire study was slightly under 150 m, reflecting the coastal nature of the analysis. The SRTM data used has been pre-interpolated, or used in conjunction with ancillary data, to fill known voids in the data and these voids are generally in mountainous areas such as the Himalayas so the coastal regions are less affected. Canopy interference is known to be an issue in some regions but again should have limited influence at the scales presented.

Coastline Lengths

A standard scale coastline is required to make sure that LLAs digitized to a higher resolution did not exhibit a longer coastline than those digitized from a coarser resolution when the actual coastline may not be longer. This fractal-based feature of natural geographic features is well known with the geographic and physics literature and results in the use of manually digitized lengths of natural boundaries, such as coastlines, exhibiting vastly differing lengths due to the input data utilized and not the actual length of the physical feature (6). Coastlines are particularly vulnerable to this problem (7). For this reason, the 2017 version of the Global Self-Consistent, Hierarchical, High-Resolution Shoreline Database (GSHHS) as utilized to provide the coastline length of each LLA (8). The GSHHS was merely constrained by the global mangrove latitudinal extent and divided into 100 m segments. Each 100-m segment was then applied to the LLA to which it was closest to, or the majority of it was closest to, this process was used to the alignment issues inherent when working with shorelines and administrative polygons. The LLA coastline length was then calculated to be the sum of all the 100 m segments of coastline for which it was attributed.

Tropical Storms

Tropical storm locations for all years were recreated from the International Best

Track Archive for Climate Stewardship (IBTrACS) Annual Tropical Cyclone Best Track Database (9). The proximity of exposure was determined by calculating the distance of an LLA to each cyclone's eye as depicted in IBTrACS. The distance measure uses the LLA polygonal boundary that is closest to the track of the storm within the calculation. The process was conducted annually and iteratively for each LLA, and each storm with storms crossing an annual boundary applied to the year of origin. This dataset has the major caveat that many historic storms do not a measure for wind speed or pressure so all tropical storms are considered equal in intensity when clearly certain storms likely have a far larger impact than others.

Nighttime Lights

Defense Meteorological Satellite Program – Operational Linescan System (DMSP-OLS) Nighttime Lights Time Series v.4 (NLU) were obtained for 2000 to 2012 (10). These data were processed at 30 arc-second resolution, or approximately 1 km^2 at the equator, and averaged across the LLA. An average NLU value obtained for each LLA / year was then calculated. The smallest LLA had only 4 NLU inputs into the calculation, but such small LLAs are an extreme outlier with an average 363 NLU measures feeding into each LLA.

Data Repository

In the interests of scientific replication and data transparency, all spatial and tabular data are stored in a long-term publicly accessible Harvard Dataverse account (doi redacted for review but data provided to reviewers and doi to be added here upon publication) in free and open formats. The repository includes all geographies, all attributes utilized, all attributes calculated but not used, all metadata, and all code developed. These data, code, and metadata are available for use under a non-commercial creative commons license.

Software Utilized

Geographic Data Abstraction Library (GDAL) v9 for raster data transformation and analysis.

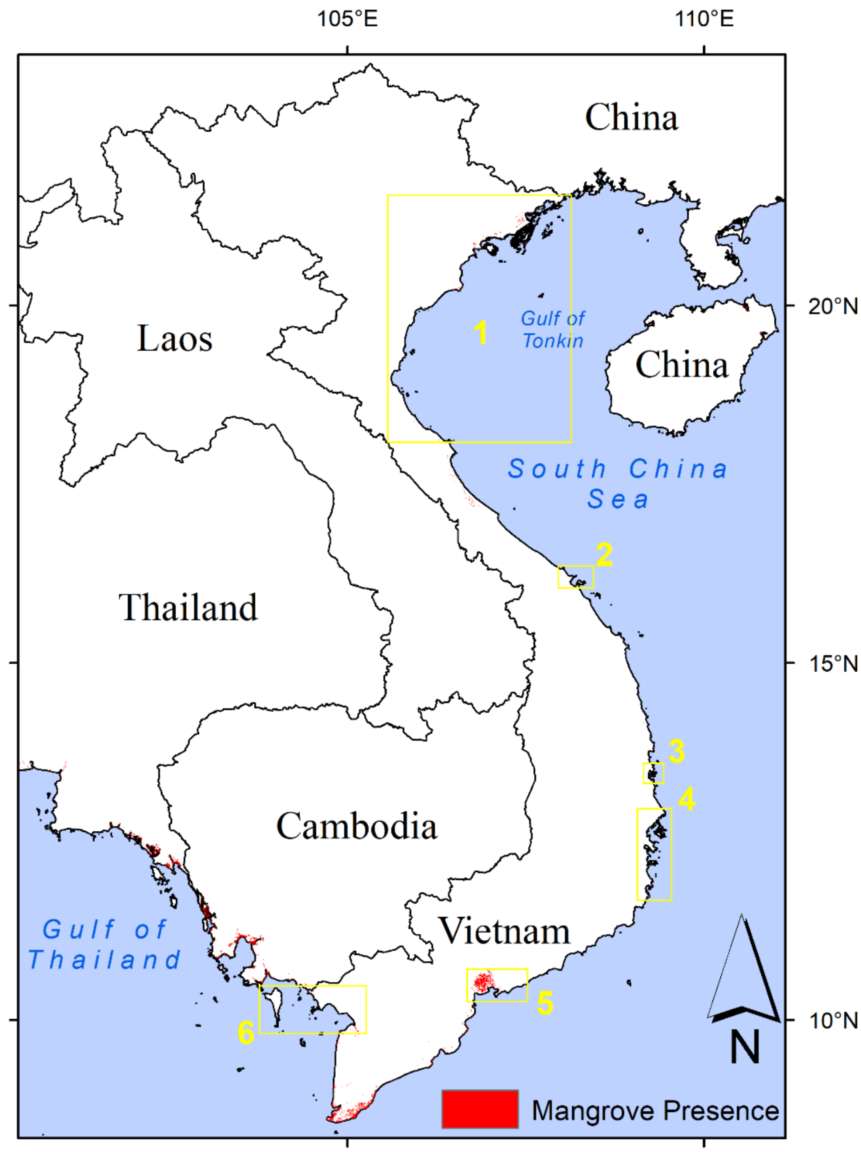
QGIS v2.8.9 for vector data transformation and analysis.

Geographic Resources Analysis Support System (GRASS) GIS for spatial data analysis.

ESRI ArcGIS v10.4.1 for spatial data analysis and database creation.

Python v 2.7 for hurricane proximity calculations.

Fig. S1. Vietnam case study excluding Gulf of Tonkin and coastal villages with sheltered bays.



Six areas with sheltered bays excluded from analysis corresponding to “excluded locations” in Table S5.

Table S1. Annually averaged and aggregated summary statistics for geographic indicators (2006-2010).

Country	Income	Region	Basin	Provinces (count)	LLAs (count)	Area (ha)	Coastline (km)	Mean Elev. (m)
Bahamas	H	LA&C	Atlantic	14	14	320,000	1413	7.5
Belize	UM	LA&C	Atlantic	2	2	540,000	473	13.5
China	UM	EA&P	NW Pacific	5	58	7,400,000	5500	45.4
Colombia	UM	LA&C	Atlantic	6	13	752,000	563	41.8
Costa Rica	UM	LA&C	Atlantic	1	1	55,400	32	73
Cuba	UM	LA&C	Atlantic	14	49	2,320,000	1669	38.9
Dominican Republic	UM	LA&C	Atlantic	8	14	486,000	320	51.7
El Salvador	LM	LA&C	Atlantic	6	12	206,000	230	44.6
Fiji	UM	EA&P	Australian/SW	1	1	42,800	78	81
Guatemala	LM	LA&C	Atlantic	5	12	580,000	267	41.8
Haiti	Low	LA&C	Atlantic	3	6	31,800	39	32
Honduras	LM	LA&C	Atlantic	4	9	248,000	305	49.2
Hong Kong	H	EA&P	NW Pacific	2	2	27,800	32	80.5
India	LM	SA	North India	8	138	11,720,000	6120	27
Japan	H	EA&P	NW Pacific	2	40	196,800	663	55.7
Madagascar	Low	SSA	SW Indian	3	9	51,600	109	28.2
Mexico	UM	LA&C	Atlantic	11	62	10,520,000	4880	25.7
Mozambique	Low	SSA	SW Indian	7	13	330,000	295	31.6
Nicaragua	LM	LA&C	Atlantic	2	4	206,000	188	47.8
Philippines	LM	EA&P	NW Pacific	57	920	432,000	1772	25.7
Trin. and Tob.	H	LA&C	Atlantic	8	8	242,000	209	28.8
United States	H	NA	Atlantic	3	66	14,880,000	8840	14.8
Vietnam	LM	EA&P	NW Pacific	22	475	738,000	2140	16.6
LOW				13	28	413,400	442	31.3
LM				104	1,570	14,130,000	11,023	26.8
UM				48	200	22,116,200	13,515	43.5
EA&P				89	1,496	8,837,400	10,185	43.6
LA&C				84	206	16,507,200	10,588	34.0
NA				3	66	14,880,000	8,840	14.8
SA				8	138	11,720,000	6,120	27.0
SSA				10	22	381,600	404	31.2
Developed				29	130	15,666,600	11,157	20.5
Developing				165	1,798	36,659,600	24,980	34.7
Total				194	1,928	52,326,200	36,136	33.1

The sample includes all mangrove-holding LLAs within those 22 countries and 1 territory (Hong Kong) that passed within 100km of a cyclone's "eye" from 2006 to 2010. The panel spans from 2000 to 2010 and sample statistics are reported for 2006 to 2010, which remain in-sample using our lagged specification. Income group aggregates are presented based on the 2016 world bank classifications. Low income countries (LOW) have a gross national income (GNI) per capita<$1,025, lower middle-income countries (LM) between $1,026 and $4,035, upper-middle income countries (UM) between $4,036 and $12,475. Developing countries include all LOW, LM and UM income countries and developed countries have a GNI per capita of $12,476 or more. East Asia and Pacific (EA&P), Latin America and Caribbean (LA&C), North America (NA), South Asia (SA) and Sub-Saharan Africa (SSA) regional aggregates are also presented based off of world bank categorizations.

Table S2. Cumulative effects of cyclone exposure (excl. mangrove-distance interactions in equation 1).

Column: Key Regressors in model	1 – AR0 Cumulative effects	2 – AR4 Cumulative effects
Cyclone (binary):		
Forward Lag 2	-0.0194***	0.0012
+ Forward Lag 1	-0.0191**	0.0073***
+ Lag 0 - Impact year	-0.0497***	0.0109**
+ Lag 1	-0.0645***	0.0006
+ Lag 2	-0.0635**	-0.0162***
+ Lag 3	-0.0664*	-0.0373***
+ Lag 4	-0.1002**	-0.0548***
+ Lag 5	-0.1148**	-0.0682***
+ Lag 6	-0.1097*	-0.0716***
N	8,826	8,826
Countries	23	23
Provinces	194	194
LLAs	1,928	1,928

Note: All LLAs with a coastline and average elevation below 100m are included in the sample. Cumulative effects represent the linear summation of coefficient estimates following the storm event. Administrative unit, year and country-year fixed effects are included along with control variables for the LLA's area, length of coastline, distance from centroid to coastline, mean elevation, elevation-distance interaction, the log of nighttime lights in the base year as a proxy for level of economic development and the unit's population growth rate in the exposed year. *p<0.10, **p<0.05, ***p<0.01.

Table S3. Cumulative effects of cyclone exposure (including mangrove-distance interactions).

Column: Key Regressors in model	Cumulative Effects AR0 (OLS)	Cumulative Effects AR0 (2SLS)	Cumulative Effects AR4 (OLS)	Cumulative Effects AR4 (2SLS)
Cyclone (binary) β $vector$				
Forward Lag 2				
+ Forward Lag 1	0.0008	-0.0216***	0.0008	0.0003
+ Lag 0 - Impact year	0.0071***	-0.0204***	0.0071**	0.0071**
+ Lag 1	0.0113**	-0.0546***	0.0113**	0.0089**
+ Lag 2	-0.0001	-0.0785***	-0.0001	-0.0050
+ Lag 3	-0.0196***	-0.0853***	-0.0196***	-0.0268***
+ Lag 4	-0.0443***	-0.0957***	-0.0443***	-0.0524***
+ Lag 5	-0.0636***	-0.1426***	-0.0636***	-0.0731***
+ Lag 6	-0.0764***	-0.1601***	-0.0764***	-0.0878***
	-0.0795***	-0.1555***	-0.0795***	-0.0918***
	Cumulative Effects AR0 (OLS)	Cumulative Effects AR0 (2SLS)	Cumulative Effects AR4 (OLS)	Cumulative Effects AR4 (2SLS)
Cyclone x Mangrove (m) α $vector$				
Lag 0 - Impact year	-0.0000	0.0008**	-0.0000	0.0004
+ Lag 1	0.0003	0.0025***	0.0003	0.0010***
+ Lag 2	0.0007	0.0038***	0.0007	0.0018***
+ Lag 3	0.0013**	0.0048**	0.0013**	0.0024***
+ Lag 4	0.0016***	0.0069**	0.0016**	0.0029***
+ Lag 5	0.0014***	0.0071*	0.0014*	0.0030***
+ Lag 6	0.0012***	0.0067	0.0012	0.0029**
N	8,826	8,826	8,826	8,826
Countries	23	23	23	23
Provinces	194	194	194	194
LLAs	1,928	1,928	1,928	1,928

Note: 2SLS estimates instrument mangrove distance variables using mangrove distance that is protected. All LLAs with a coastline and average elevation below 100m are included in the sample, which contains annual data from 2000 to 2012 while dropping those observations before 2006 because mangrove data begins in 2000. Columns 3 and 4 include 4 autoregressive lags whereas columns 1 and 2 exclude autoregressive lags. Cumulative effects represent the linear summation of coefficient estimates following the storm event. Administrative unit, year and country-year fixed effects are included along with control variables for the LLA's area, length of coastline, distance from centroid to coastline, mean elevation, elevation-distance interaction, the log of nighttime lights in the base year as a proxy for level of economic development and the unit's population growth rate in the exposed year. *p<0.10, **p<0.05, ***p<0.01.

Table S4. Comparison of the physical characteristics in exposed and unexposed Vietnamese coastal villages.

Variable:	Exposed (<=100km)	Unexposed (>100km)
2006		
Number of villages	213	220
Average coastline length (km)	5.6	4.0
Average elevation (m)	19.6	13.2
2007		
Number of villages	888	894
Average coastline length (km)	19.8	20.5
Average elevation (m)	25.2	25.7
2008		
Number of villages	1,153	643
Average coastline length (km)	18.1	23.6
Average elevation (m)	26.3	23.9
2009		
Number of villages	591	1,140
Average coastline length (km)	17.4	22.8
Average elevation (m)	24.1	26.2
2010		
Number of villages	680	1,057
Average coastline length (km)	20.9	20.9
Average elevation (m)	24.0	26.4

Note: Summary statistics of average village physical characteristics shown for the primary OLS-AR4 specification (Column 3 of Supplementary Table 2). All LLAs with a coastline and average elevation below 100m are included in the sample, which contains annual data from 2000 to 2012 while dropping those observations before 2006 because mangrove data begins in 2000.

Table S5. Vietnam case study replication of primary regression specification excluding Gulf of Tonkin and coastal villages with sheltered bays.

Column: Key Regressors in model	Full Sample	Excluding Gulf of Tonkin	Excluding Gulf of Tonkin and Sheltered Bays
Cyclone (binary) β $vector$	(1)	(2)	(3)
Forward Lag 2			
+ Forward Lag 1	-0.0074	-0.0371**	-0.0361*
+ Lag 0 - Impact year	-0.0222	-0.0512	-0.0678
+ Lag 1	-0.0472*	-0.0742	-0.1111
+ Lag 2	-0.0948**	-0.0951	-0.1550
+ Lag 3	-0.1371***	-0.1137	-0.1658
+ Lag 4	-0.1929***	-0.1647	-0.1855
+ Lag 5	-0.2302***	-0.1960	-0.1762
+ Lag 6	-0.2387***	-0.2317	-0.1944
	-0.2520***	-0.2924*	-0.2379
Cyclone x Mangrove (m) α $vector$			
Lag 0 - Impact year			
+ Lag 1	-0.0003	0.0007	0.0015*
+ Lag 2	-0.0002	0.0010	0.0022*
+ Lag 3	-0.0004	0.0017*	0.0037*
+ Lag 4	0.0009	0.0030**	0.0063*
+ Lag 5	0.0017	0.0038***	0.0077*
+ Lag 6	-0.0004	0.0041**	0.0081*
	-0.0009	0.0052*	0.0110*
N	2,229	934	623
Provinces	22	16	13
LLAs	475	208	143
Sample summary statistics			
Total sample coastline (km)	10,730	5,653	3,632
Dep: Mean mangrove dist (m)	3.19	5.61	4.21

Excluded locations	**Laterals**
Column 2	
+ (#1) Gulf of Tonkin	>18.18
Column 3	
+ (#2) Ganh Rai Bay	10.30 to 10.50
+ (#3) Cam Ranh Bay & Nha Trang Bay & Nha Phu Bay & Vân Phong Bay	11.75 to 12.90
+ (#4) Vung Lam Bay & Xuan Dai Bay & Cu Mong Estuary	13.36 to 13.56
+ (#5) Da Nang Bay & Chan May Bay	16.07 to 16.34
+ (#6) Rạch Giá & Cây Dương	> 9.85 (western coast)

Note: *p<0.10, **p<0.05, ***p<0.01. Numbers of excluded locations (#1-#6) correspond to areas in Figure S1.

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