TECHNICAL REPORT: BUILDING COASTAL RESILIENCE WITH MANGROVES. THE CONTRIBUTION OF NATURAL FLOOD DEFENSES TO THE CHANGING WEALTH OF NATIONS

The Changing Wealth of Nations 2021

Managing Assets for the Future

WORLD BANK GROUP

THE CHANGING WEALTH OF NATIONS 2021

Managing Assets for the Future

TECHNICAL REPORT

BUILDING COASTAL RESILIENCE WITH MANGROVES: THE CONTRIBUTION OF NATURAL FLOOD DEFENSES TO THE CHANGING WEALTH OF NATIONS

WORLD BANK GROUP

Cover design: Florencia Micheltorena

Building Coastal Resilience with Mangroves:

The Contribution of Natural Flood Defenses to the Changing Wealth of Nations

Michael W. Beck[1], Pelayo Menéndez[1,2], Siddharth Narayan[1,3], Saul Torres-Ortega[2], Sheila Abad[2], Iñigo J. Losada[2]

[1] Coastal Resilience Lab, Institute of Marine Sciences, University of California, 115 McAllister Way, Santa Cruz, CA 95060, USA
[2] Instituto de Hidráulica Ambiental-IHCantabria, Universidad de Cantabria, Santander, Cantabria 39011, Spain
[3] Department of Coastal Studies, East Carolina University, Wanchese, NC 27891

Contents

Executive Summary

There is growing recognition that natural capital represents real value to nations and that these assets have been under appreciated in national economics. As coastal risks grow from storms and climate change, the needs for coastal defenses are rising. Mangroves and coral reefs provide critical coastal protection services that have been valued in recent global studies using risk-industry models (Beck et al. 2018, Menendez et al. 2020). These natural coastal protection services have not been included in the World Bank's Changing Wealth of Nations in the past. We address that gap in this report for both reefs and mangroves with a particular focus on the change in mangrove wealth over time.

We apply peer reviewed models of flood risks and habitat benefits to assess the value of these natural capital assets and their contribution to the wealth of (sub) tropical nations. We develop and use a combined set of process-based storm and hydrodynamic models: (i) to identify the area and depth of flooding; (ii) using model scenarios with and without reefs and mangroves; (iii) for five storm frequency events, 1 in 5, 10, 25, 50, 100-yr driven by local storm data. We overlay these flood extent and depth data on historical data on populations and the value of assets (Penn World Table 9.1), adjusted to 2018 dollars, downscaled to 90 x 90 meters to identify a probabilistic distribution of flood damages (risk) and avoided damages (habitat benefits). We ran all models for three years with data on the historical distribution of mangroves (1996, 2010, 2015) to assess changing flood risks and the benefits of mangroves as natural defenses.

We assessed risks and mangrove benefits for more than 75 nations covering approximately 700,000 km of (sub) tropical coastlines. We summarize results by country but these models and values can be used to understand risks and benefits within countries at the provincial and even municipal level. These are fully quantitative risk models in comparison to other index-based approaches for assessing coastal vulnerability and ecosystem services.

The present value of the flood reduction benefits from mangroves (100-year asset at a 4% discount rate) in 2018 is $589 billion. The countries with the greatest present value of mangroves for flood reduction are China, Vietnam, Australia and Indonesia. The present value of coral reefs as a flood reduction asset globally is $355 billion with the greatest values in Mexico, Indonesia, the Philippines, Malaysia and Cuba.

Annual flood risk on mangrove coastlines in 2018 is greatest in China, Vietnam, United States, The Philippines, Indonesia, Taiwan, India, Brazil and Australia. Each of these countries have more than 168,000 people exposed to coastal flooding every year and more than $1.1 billion in assets at risk from flooding annually on mangrove coastlines.

The change (increase) in the wealth of mangroves for flood risk reduction from 1995-2018 is estimated to be over $348 billion dollars. The countries receiving the greatest increases in wealth in absolute values ($) were China, Vietnam, India and Indonesia, and in relative values (%) were Iran, St. Vincent and the Grenadines, Comoros and Egypt.

Annual flood damages will grow 5-fold by 2100 even under significant mangrove restoration scenarios and by seven-fold if mangroves are lost. The flood reduction benefits of mangroves will also grow by at least four-fold by 2100 as long as present mangrove distributions are conserved. Flood reduction benefits could grow by eight-fold with some restoration.

The period from 1996-2010 covers the time with some of the greatest losses of mangroves in recorded history from the rapid expansion of shrimp aquaculture in the 2000's and the more consistent losses from coastal development. The global loss of mangroves was 4% from 1996-2010 but was >25% in some countries, such as Aruba, Benin, Netherlands Antilles and Anguilla. Total mangrove loss in hectares was greatest in Indonesia, Mexico, Myanmar, Brazil, and Mozambique over this time period.

From 1996-2010 annual coastal flood risk to people and property increased dramatically by 32% and 118% respectively. Multiple factors contributed to this increase including mangrove loss (4%) and increases in population (20%) and stock (56%) in these countries. Despite the loss of mangrove habitats their flood reduction benefits (i.e., their value to national wealth) increased significantly. Mangroves protected 22% more people and 50% more stock value in 2010 as compared to 1996, because of the increases in populations and asset values. The countries receiving the greatest increase in mangrove flood reduction benefits to national wealth from 1996 to 2010 were Vietnam, China, India, and Indonesia.

From 2010-2015, the annual coastal flood risk to people and stock increased by 14% and 34% globally. The countries with the most significant increases in people at flood risk were China, the Philippines, India and Vietnam (> 190,000 people flooded/year/country). The countries with greatest increases in economic risk were China, United States, Indonesia and Vietnam (> $650M/year/country).

Mangrove cover declined globally from 2010-2015 but the losses were small overall. Global mangrove benefits to people and stock increased in this time period by 9.5% and 38% respectively. China, Vietnam, United Arab Emirates and Bangladesh experienced the greatest increase in people protected by mangroves (>29,000 people/year/country). Some countries experienced declines in people protected by mangroves including the Philippines, Myanmar, Malaysia and Colombia. China, Vietnam, Australia and Indonesia all saw increases in mangrove flood protection benefits of more than $250M/year. The Philippines, the USA, United Arab Emirates, Guyana and Malaysia experienced decreases in mangrove benefits (>$19M/year/country) in annual expected flood protection benefits from mangroves.

There is growing interest in nature-based defenses for risk reduction, adaptation, storm recovery and resilience building. By valuing these natural assets and their change over time we hope to inform efforts to use natural defenses in disaster risk management, climate adaptation, land use planning and development. These defenses can be used to maintain and build resilience naturally and cost effectively and their values can be more readily incorporated in national economic accounts and decisions.

Introduction

The Changing Wealth of Nations (CWON) applies wealth accounts to analytics for three areas of major policy concern: the linkages between natural capital and human capital, climate change, and sustainability. It strengthens the measurement of wealth through expanded coverage and improved quality of all assets, notably natural capital and human capital. Wealth accounts consist of five categories of assets: produced capital and urban land; fossil fuels and minerals; renewable natural capital; human capital and net foreign assets. In past wealth estimates, renewable natural capital was limited to agricultural land, forests, and protected areas, due to data constraints. CWON 2021 will include new and expanded coverage of renewable natural capital: marine fisheries, renewable energy, and additional ecosystem services from forests, notably mangroves.

Mangrove forests and coral reefs are key missing natural capital assets. Coral reefs have not previously been included in CWON. As a type of forest, partial mangrove asset values are implicitly included in CWON forest asset accounts already. However, this forest asset value was based only on timber value, other forest products, watershed services and recreation services. The important coastal protection services of mangroves were not considered.

Mangroves and coral reefs provide critical coastal protection services that have been valued in recent global studies using coupled ecological, engineering and economic models (Beck et al. 2018, Menendez et al. 2020). In 2016, the World Bank developed Guidelines for rigorously assessing the coastal protection benefits of coral reefs and mangroves (World Bank 2016). These Guidelines were implemented and advanced at the national scale for mangroves in the Philippines and Jamaica (Menendez et al. 2018, Beck et al. 2019) and these approaches have now been advanced to identify these values for reefs and mangroves globally (Beck et al. 2018, Losada et al. 2018, Menendez et al. 2020).

Mangroves protect coastlines by decreasing the risk of flooding and erosion. The aerial roots of mangroves retain sediments and prevent erosion, while the roots, trunks and canopy reduce the force of oncoming wind and waves and reduce flooding. A 500-meter wide mangrove forest can reduce wave heights in general by 50-100% (World Bank 2016) and cyclone wave heights by 60 to 90% (Narayan et al., 2010). In low lying areas, even relatively small reductions in water levels can reduce flooding and prevent property damage. In the long term, mangroves increase sedimentation, decrease erosion, and maintain tidal channels. Mangroves can also support livelihoods and reduce social vulnerability by providing resources to support fisheries, building materials, ecotourism and trade.

Coral reefs serve as natural, highly efficient submerged breakwaters that provide flood reduction benefits through wave breaking and wave energy attenuation (Lowe et al., 2005; Monismith, 2007). Coral reefs can reduce incoming wave energy by 97% (Ferrario et al. 2014) and without reefs the costs of storms could double globally (Beck et al. 2018).

These habitats act as natural defenses that protect people and property from storms. Yet these benefits are often not fully accounted for in policy and management decisions, and these habitats continue to be lost. At present, the value of renewable natural capital is underestimated, the losses from mangroves and coral reefs are not accounted for, and the benefits from management or restoration of coastal natural capital remains hidden.

Using new data on historical distributions of mangroves, we assess changes in the value of coastal protection benefits from mangroves over time. We also provide a static measure of current coral reef wealth for 60+ nations as historical data do not exist for reefs globally.

Mangroves have been lost at an alarming rate; 19% of the world's mangroves were lost between 1980-2005 (Spalding et al. 2010). Although the rate of loss has slowed over the past decade, mangroves are still under threat. If mangroves are degraded or destroyed, the coast line becomes more exposed and vulnerable to the destructive impacts of waves and storm surge, and is at higher risk of coastal flooding and erosion. The result is more people and property directly at risk from the impacts of storms, floods, and sea level rise.

By rigorously valuing flood reduction benefits and by identifying where these natural coastal defenses provide the greatest benefits, this work informs policies for adaptation, sustainable development, and environmental restoration. These are relevant to national and multi-national decisions as coastal development and climate change are dramatically increasing the risks of flooding, erosion, and extreme weather events for millions of vulnerable people, important infrastructure, and trade. Governments worldwide are dedicating billions of dollars to reduce risks from disasters and climate change. Most of our current investments in coastal protection support "grey infrastructure", such as seawalls and breakwaters, that remain vulnerable to coastal risks and fail to adapt to changing environments (McCreless and Beck 2016). However, the interest in nature-based defenses is growing for example with significant interest from key international bodies such as the UNFCCC, UNISDR, EU and national and multi-national agencies and organizations such as the Army Corp of Engineers, the World Bank, and Inter-American Development Bank.

Methods

Methods in Brief

In this section we describe the methods and data sources for estimating flood risk, flood protection benefits and the asset value of mangroves locally, nationally and globally. The flood protection benefits provided by mangroves are assessed as the flood damages avoided to people and property by keeping mangroves in place (Losada et al. 2017, Beck et al. 2017, Menendez et al., 2020). We couple offshore storm models with coastal process and flood models to measure the flooding that occurs: (i) with and without mangroves (ii) under cyclonic and non-cyclonic storm conditions (iii) by storm frequency (return period), across the globe. These flood extents and depths are used to estimate the annual expected flood damages to people and property and hence the expected benefits of mangroves in social (people protected) and economic terms (value of property protected). Our estimates are based on a set of global statistical models, hydrodynamic process-based models and socioeconomic data. All these processes are grouped into 5 steps following the Averted Damages (Expected Damage Function) approach, commonly used in engineering and insurance sectors and recommended for the assessment of coastal protection services from habitats (**Figure 1**). Many aspects of these models such as connections between wind, waves, run-up and flooding have been extensively validated.

We first developed and validated key mangrove-specific aspects of the flood models in the Philippines, a country with over 36,000 km of heavily populated coastlines, high risks from cyclones, and more than 200,000 hectares of coastal mangroves. We use these models to generate a dataset of several thousand simulations to describe the physical relationships between tropical cyclones, offshore wave climate, mangrove extent and geometry and extreme water levels (i.e., flood height) along the shoreline for five storm frequency events (1 in 5, 10, 25, 50, 100-yr) driven by local storm data. This dataset is then used to estimate how mangroves modify extreme water levels for every kilometer of mangrove shoreline globally. Global flood depths and extents are then estimated by intersecting the global extreme water levels with 90-meter SRTM-DTM (Shuttle Radar Topography Mission). Finally, we overlay the resulting maps of flood depths and extents on socioeconomic asset information downscaled to 90 x 90 meters. Flooded socioeconomic assets are then assessed by flood depth to identify flood damages (risk) and avoided damages (mangrove benefits).

Global Mangrove Watch (www.globalmangrovewatch.org/datasets) has just recently posted spatial mangrove distribution data for the following years: 1996, 2007, 2008, 2009, 2010, 2015, 2016. We assessed flood risk and mangrove benefits using these historical mangrove databases for the years 1996, 2010, and 2015.

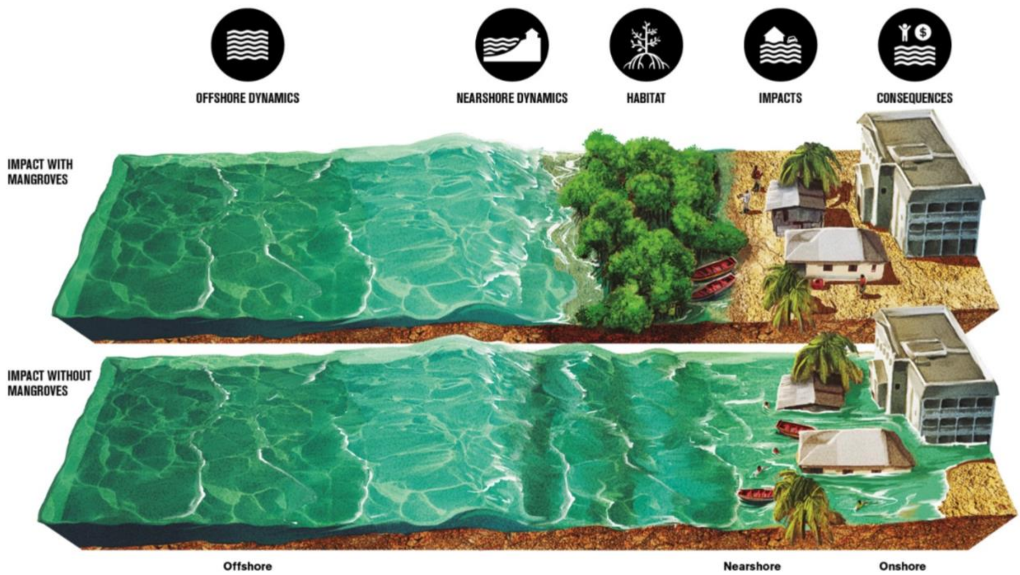


Figure 1: Key steps and data for estimating the flood protection benefits provided by mangroves. Offshore Dynamics: Oceanographic data are combined to assess offshore sea states. Nearshore Dynamics: Waves are modified by nearshore hydrodynamics. Habitat: Effects of mangroves on wave run-up are estimated. Impacts: Flood heights are extended inland along profiles (every 1 km) for 1 in 5, 10, 25, 50, 100-yr events with and without mangroves. Consequences: The land, people and built capital damaged under the flooded areas are estimated. Adapted from World Bank 2019.

Benefits of the Averted Damages Approach

The Averted Damages Approach (also referred to as the Expected Damages Function Approach) provides a rigorous foundation for estimates of flood risk and habitat benefits (van Zanten et al. 2014, Barbier 2015, World Bank 2016, Pascal et al. 2016). We have chosen this approach over others because it is (a) quantitative in contrast to other approaches, which use indicator (expert) scores to assess shoreline vulnerability (e.g., Silver et al. 2019), (b) it uses process-based models and statistical tools to assess hydrodynamics, (c) it uses the methods and tools of risk agencies, insurers and engineers (Narayan et al.

2016, 2017, Reguero et al. 2018), (d) it is consistent with approaches for national accounting (World Bank 2016), and (e) it accurately captures impacts of extreme events.

Study Domain Description

This global study covers 700,000 km of mangrove coastlines. For computational purposes, we divided the global domain at three levels (**Figure 2**). The first level is the division into five macro-regions, corresponding to the five ocean basins of tropical cyclone generation (Knapp et al., 2010): East Pacific, North Atlantic, North Indian, South Indian, West Pacific and South Pacific (**Figure 2**a). The second level divides the 700,000 km of coastline into 68 sub-regions considering coastline transects of similar coastal typology (e.g. islands and continental coasts) and similar ecosystem characteristics (**Figure 2**b). The third level is at the national scale, defining country-side units (**Figure 2**c). Within these nationwide units, we create cross-shore profiles perpendicular to the mangrove habitats for each kilometer of coastline, totaling 700,000 profiles (**Figure 2**d).

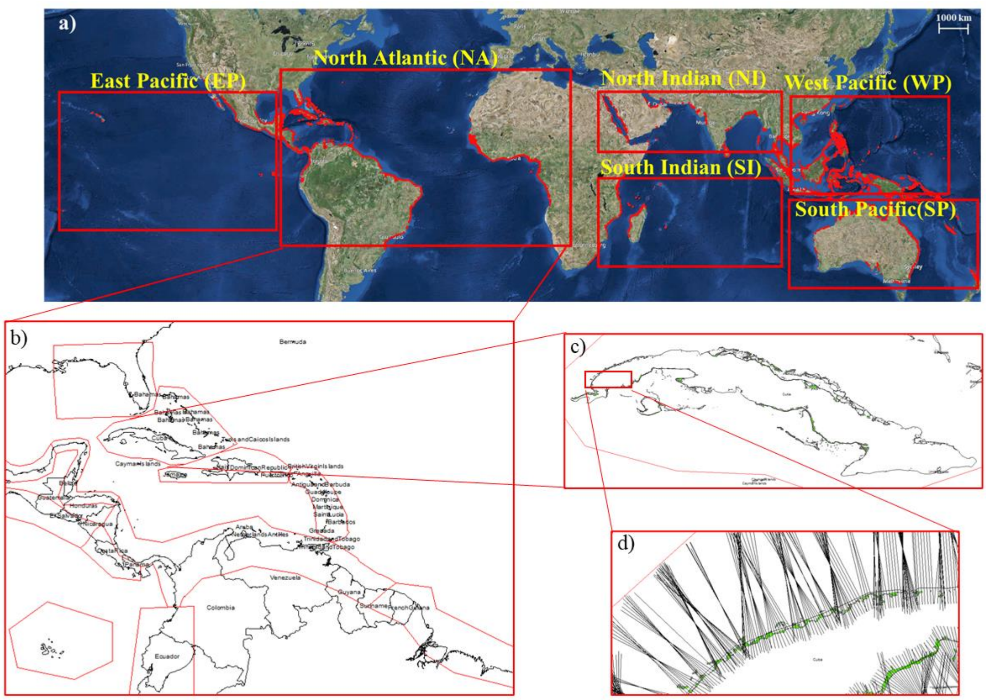


Figure 2: The geographic subdivisions for hydrodynamic models. (a) Macro-regions with the global mangrove cover in red, (b) Sub-regions in the Atlantic Ocean basin, (c) Local study units every 20 km of coastline in the Northern Caribbean Sub-region, (d) Profiles every 1 km of coastline in the North of Cuba.

The Philippines: Baseline case to build global models

We chose the Philippines as the baseline case to develop the global statistical models of the relationships between tropical cyclone parameters, oceanographic variables, and on-shore flood extents and depths on mangrove coastlines. There are three main reasons that make the Philippines an excellent pilot case for valuation of the coastal protection ecosystem service provided by mangroves. First almost 10% (548 events) of the global tropical cyclone records from the International Best Track Archive for Climate Stewardship (IBTrACS) database affected the Philippines (Knapp *et al.*, 2010). Second the islands of the Philippines present high climatic variability and are at particularly risk from natural hazards like typhoons and regular storms, which are the cause of 80% of the total losses from disasters (National Economic and Development Authority, 2017). Third, the Philippines ranks in the top 15 most mangrove habitat-rich countries, with 2,630 km^2 in 2010, representing 2% of the world total (Giri *et al.*, 2011). Fourth, these mangrove habitats show extensive variation in both cross-shore width (0.1 km and 8 km wide) and average depth (Menendez et al., 2018).

We valued the flood protection service of mangroves in the Philippines by using the numerical model Delft3D considering both cyclonic and non-cyclonic storm conditions, for scenarios with and without mangroves. We use these results to build two global statistical models. The first, a "Cyclone Model", was developed to describe specific offshore and nearshore ocean dynamics produced by tropical cyclones (wave height, peak period, storm surge and storm duration), and the second, a "Mangroves & Flood Height Model", estimates how the presence and profile of mangrove habitats influences the total water level during storm conditions on the shoreline. Further details about the Philippines-based developed models can be found in Menéndez *et al.* (2018, 2020) and the two models are summarized here:

<u>"Cyclone Model": Offshore and nearshore dynamics generated by tropical cyclones:</u> Offshore waves and storm surge generated by tropical cyclones were numerically simulated in the Philippines by using Delft3D modules "Flow" ('Delft3D-FLOW user manual', 2006) and "Wave" ('Delft3D-WAVE user manual', 2000). Both modules were run simultaneously in a 2-dimensional grid of 5 km cell-size with a time step of 30s, forced with hourly wind data and sea level pressure fields in a model which considers the non-linear interaction processes of tide, wind setup, inverse barometers and wave setup. The model was validated by comparing the storm surge generated by typhoon Rammasun, in Legaspi and Subic Bay. We use tidal gauges registers from the Global Sea Level Observing System (GLOSS, *http://www.gloss-sealevel.org*) for validation.

Using the results of the numerical simulations carried out with the Delft3D model in the Philippines we look for statistical relationships between cyclone parameters and oceanographic variables to create a new predictive model, where the key oceanographic variables that affect on-shore flooding (wave height, wave period, storm tide and duration of the storm peak) are predicted based on cyclone parameters (distance, wind speed, track velocity, wind angle of incidence). In the Philippines, we simulated 548 storm events creating a database of 58 million results. We randomly select 90% of the generated results to build our predictive model and use the other 10% for validating the predictive models. We examined the correlation between the physical tropical cyclone parameters and the oceanographic variables for two coastal area typologies: areas directly exposed to tropical cyclones and areas protected from the direct impact of tropical cyclones. Based on these variables, we then developed a best fit regression model to predict the oceanographic variables.

<u>"Mangroves & Flood Height Model": The role of coastal habitats in nearshore dynamics:</u> The "Mangroves & Flood Height Model" predicts the effects of mangrove forest characteristics on flood heights at the shoreline. Coastal vegetation provides resistance to the energy and flow of waves and water as they come

onshore which is modeled by using a friction factor based on the Manning coefficient (n). We assigned different friction factors to sandy soil (n=0.02), mangroves (n=0.14) and coral reefs (n=0.05) (Zhang *et al.*, 2012)(Prager, 1991). One-dimensional numerical propagations, on cross-shore profiles perpendicular to the mangrove shoreline, were carried out using the Delft3D model to obtain flood heights along the coast. We use these numerical results to create two interpolation tables for cyclonic and non-cyclonic storm conditions that correlate the oceanographic information at the seaward side of the profile (wave height, wave period, weather storm tide and storm peak duration) and the characteristics of the mangrove profiles (width and slope) with the flood height. These tables contain 37,500 tropical cyclone simulations (50 cyclones x 750 profiles) and 90,000 non-cyclonic climate simulations (120 sea states x 750 profiles).

Methods in detail for quantifying global mangrove benefits

Stage 1: Offshore Tropical Cyclone and non-cyclonic climate sea states: The offshore hydrodynamic conditions (wave height, wave period, storm surge and astronomical tide) were subdivided in two groups: (1) those produced by less intense local climate or extreme climate generated far away from the study area (regular climate or non-cyclonic conditions) and (2) those produced by local extreme events (tropical cyclones or cyclonic conditions).

1A. Non-cyclonic Climate: Deep water ocean dynamics produced by any other climate condition different from tropical cyclones is analyzed as non-cyclonic climate. Non-cyclonic climate is defined by different datasets within the period 1979-2010: a global wave reanalysis (Reguero et al. 2012, Perez et al. 2017), a global storm surge reanalysis (Cid et al. 2017), astronomical tide (Pawlowicz et al. 2002, Egbert & Erofeeva 2002), and mean sea level compiled from historical numerical reconstruction and satellite altimetry (Church et al. 2004). Waves and sea level conditions due to tropical cyclones are excluded and studied separately to avoid double counting, resulting, finally, in 32 years' time series of only non-cyclonic climate. The 32-year long time series of wave data (1979 -2010) includes 280,000 sea states (1 sea state represents 1-hour of wave height, peak period and total water level). We reduce the number of sea-state propagations by considering only the 3,787 non-repeated combinations of wave height, peak period and total water level and, then, applying the Maximum Dissimilarity Algorithm to identify 120 sea states to be propagated with the Snell law and shoaling equation across coastal profiles. For future analyses, it will be possible to look at data beyond 2010 but a few more years of data on storms and sea-states will only have small (but real) effects on the overall storm frequency distributions (i.e., extreme value distribution). All of the models and data in the "non-cyclonic climate" analysis including waves and storm surge have been globally validated (e.g., Reguero et al. 2012, Perez et al. 2017, Cid et al. 2017). The "non-cyclonic climate" analysis covers most of the storm and flood risk conditions globally (including tropical depressions and storms) except for cyclone conditions, which represent comparatively small (spatio-temporally) but locally intense conditions.

1B. Tropical Cyclones: Tropical cyclones are considered separately from non-cyclonic climate if the 10-minute sustained wind speeds (W_{10m}) exceed 118 km/h. Tropical depressions ($W_{10m} \leq 62$ km/h) and tropical storms (63 km/h $\leq W_{10m} \leq$ 118 km/h) are included in the non-cyclonic climate models. For historical tropical cyclones, we use the IBTrACS database (Knapp et al. 2010), which provides 6-hourly data of wind speed, atmospheric pressure and track position and contains regularly updated storm data (https://www.ncdc.noaa.gov/ibtracs/).

Stage 2: From offshore dynamics to shallow water: We obtain ocean hydrodynamics on the seaward side of each cross-shore profile cyclonic and non-cyclonic conditions. Waves interact with the bottom and other obstacles (e.g., islands) as they approach the coast and modify height and direction through shoaling, refraction, diffraction and breaking processes.

2A. Non-cyclonic Climate: For non-cyclonic climate, several thousand offshore ocean parameters representing non-extreme sea states are clustered into 120 representative sea states using a Maximum Dissimilarity Algorithm (MDA, (Camus *et al.*, 2011; Camus, Mendez and Medina, 2011)). Wave and water level conditions at the seaward point of each profile are then associated with the nearest non-cyclonic climate sea state. From this, a regression model is created that equates offshore non-cyclonic climate sea states with wave and water level conditions at the seaward end of a profile.

2B. Tropical Cyclones: We used the "Cyclone Model" described above to estimate key nearshore parameters from cyclones including wave height (Hs), peak period (Tp), Storm Surge (SS) and the time duration of the meteorological tide (T_{ss}).

Stage 3: Modeling the role of coastal habitats in nearshore dynamics, flood height. We used the "Mangroves & Flood Height Model" (described above) to estimate Flood Height given mangrove length and depth, significant wave height, peak period and total water level at the head of each cross-shore profile. Once we have calculated the historical time series of Flood Height (1979-2010), we apply a extreme value analysis to obtain 1-in 5, 10, 25, 50 and 100 year extreme sea levels in coast. To do that, we select maximum values over a threshold (minimum 1 event every 5 years) and then adjust these values to a Generalized Pareto-Poisson distribution. This one-dimensional model is commonly used even in site-based models (Beck et al. 2018). The consideration of non-linear effects is only possible using computationally expensive phase resolving models (e.g., XBeach) at local scales (e.g., bays). This modeling approach is not feasible at the global scale because of computational capacity and the lack of high-resolution bathymetric data and especially if risk is to be evaluated probabilistically across multiple events and scenarios (Beck et al. 2018). In our coral reef work, we have shown that the wave propagation approach in the flooding model performs very well when considered against the results of one of these phase resolving models (Beck et al. 2018).

Stage 4: Calculating impacts: Flooding maps: To estimate flooding, we use a modified bathtub flooding model which includes a hydraulic connectivity requirement for flooding connected points across the coastal topography. To obtain flood maps by means of uncoupling propagation (stages 1, 2 and 3) and coastal flooding (stage 4), it requires: (i) Flood Height along the coast with high longshore resolution; (ii) a good topography data identified with a Digital Terrain Model (DTM); and (iii) a flooding method consistent with the other steps of the analysis (Menéndez *et al.*, 2019). Here we use 1-in- 5, 10, 25, 50- and 100-years Flood Height every 1 km of coastline, a global topography dataset, at 90 m horizontal resolution, from the Shuttle Radar Topography Mission (STRM) (Farr et al., 2007) and a bathtub method for flooding based on hydraulic connectivity. The final outcome of this stage are global flood maps for different return periods (1-in- 5, 10, 25, 50- and 100-years), different storm conditions (cyclonic and non-cyclonic) and different mangrove extent (1996, 2010, 2015 and without mangroves).

Stage 5: Assessing global flood consequences in areas protected by mangroves: The expected flood risk and benefits provided by mangroves are presented in social and economic terms. From the flooding levels and flooding extent, we calculated the total area of land affected and damages. We intersect the flood maps with population data from GHS-POP (https://ghsl.jrc.ec.europa.eu/ghs_pop2019.php) and built stock data from the Penn World Table version 9.1 (https://www.rug.nl/ggdc/productivity/pwt/).

We follow a multi-step approach to obtain coastal damage and risk:

- *Step 1. Global population and stock distribution*: The distribution and density of population is obtained from the spatial raster GHS-POP. This dataset contains global residential population estimates at 250 m resolution for 1975, 1990, 2000 and 2015. These global population rasters provided by CIESIN GPWv4.10 were disaggregated from census or administrative units to 250 m grid cells, and informed by the distribution and density of built-up as mapped in the Global Human Settlement Layer (GHSL) global layer per corresponding epoch. We used the four years (1975, 1990, 2000, and 2015) to adjust 1996 and 2010 scenarios, which are the target years of this analysis. Global grid population from 1996 was adjusted by interpolation of 1990 and 2000 population distribution. Global grid population from 2010 was adjusted by interpolation of 2000 and 2015 population distribution. Then we calibrate both, 1996 and 2010 interpolated grids, with nationwide population statistics from the World Bank (World Bank Data) The calibration consists of adjusting the total people per country from the interpolated grids to the World Bank data. Global stock is calculated using Penn World Table, version 9.1 (PWT 9.1). This version is a database with information on relative levels of income, output, input and productivity. The table includes 182 countries and 68 years, between 1950 and 2017.

  For our analyses of global stocks we used the national data of Capital Stock at constant 2018 national prices. Then, we calculate the stock per capita at each country and multiply these national values by the population located at each grid cell. We finally obtain a global stock distribution raster at 250 meters resolution.

- *Step 2. Resampling population and stock grids to flood maps resolution (90m)*: To overlay flood and assets maps, both must be at the same horizontal resolution. We decided to downscale socioeconomic data rather than upscaling flood grids. Global population and stock rasters at 250 meters are resampled to the same horizontal resolution as the flood maps (90 m). We use ArcGIS toolbox to carry on the spatial redistribution of population and stock grids. Then we calibrate the new rescaled rasters, by adjusting the total population and total stock per country at 90 m resolution to those at 250 m.

- *Step 3. Exposure. People and stock in flooded areas*: Here we calculate the number of people and the stock exposed to coastal flooding in 1996, 2010 and 2015 with and without mangroves. We first reclassify the flooding raster into 1 and 0 values. We assign 1 to flooded pixels with water, and 0 to dry pixels. Then we multiply population and stock rasters by the reclassified flood raster and obtain the global distribution of people and stock exposed to coastal flooding. The exposure layers will inform how many people and assets are in flooding areas, but not the real damage to people and the real economic loss (Risk). Calculating flood risk requires that we estimate flood damages using damage functions, that relate flood damages at a location to the flood depth at that location (see Box 1).

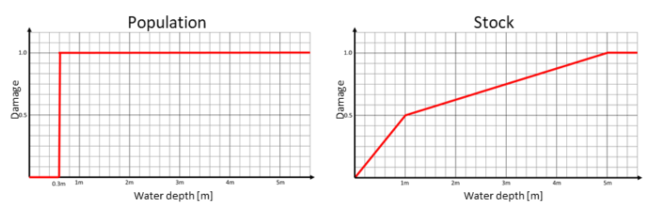
- *Step 4. Damage coefficients*: Flood damage depends on the water depth and the type of asset (**Error! Reference source not found.**). We use different damage functions for population and stock. For people we use a damage function that assumes that, in a grid cell, people are not affected by water below 30 cm in depth and all people are affected by flood water depths greater than 30 cm. This a commonly used threshold in civil protection services to decide when people must be evacuated.

- For stock, we combined data from JRC and Hazus depth damage curves (see Box 1). The best combination of these curves globally results in a damage function that ramps up linearly from 0 to 50% of damage when water depth is below 1 m. Then damage increase at a slower rate from 50% at 1 m water depth to 100% at 5 m. We use these curves to calculate global rasters of damage coefficients to people and stock. In prior work, we tested the use of various damage curves (including complex damage functions) for population, residential and industrial stock from Hazus in the Philippines (Menéndez *et al.*, 2018), and we found that the results were not significantly different from approaches using simpler curves such as those in **Error! Reference source not found.**.

Box 1: Damage Functions

Global Flood Depth-Damage functions are needed to evaluate the sensitivity of people and property to be damaged for different flood levels. A new report from the EU Joint Research Centre (JRC) collected data from Africa, Asia, Oceania, North America, South America and Central America and proposed damage functions for residential and industrial stock in each region (Huizinga et al. 2017). We refer to these hereafter as JRC damage functions. These damage functions are a new alternative to damage curves from FEMA Hazus (Scawthorn et al. 2006), which were based only on US collected data but frequently extrapolated for use in other geographies. JRC damage functions aim to address flooding effects on property globally, developing a consistent database of depth-damage curves. We used both, JRC and Hazus to calculate stock damages (**Error! Reference source not found.**). Stock damage results from the integration of global JRC damage functions (LINK), calibrated with Hazus damage curves for different building types.

The damage curve for people was built based on a commonly used threshold in civil protection services to decide when people must be evacuated. It indicates no people affected in areas with less than 30 cm water depth, and 100% of people affected in areas with water depth above 30 cm (**Error! Reference source not found.**).



- *Step 5. Risk- People and stock damaged by coastal flooding*: To calculate risk, we multiply damage coefficient rasters by global population and stock distribution layers create 120 risk maps for the different conditions and scenarios (see Table 1).

- *Step 6. Nationwide aggregation results*: Risk to people and stock is aggregated at national scale. We first create a 10 km external buffer at each country and find the pixels that lay into each country buffer boundary. We calculate the total number of people and the total stock value on each country under each scenario.

- *Step 7. Annual Expected Risk and Benefits*: In addition to assessing risk for specific events (e.g., 100-year storm event), we also examined average annual expected damages and benefits provided by mangroves. To estimate annual risk, we integrated the values under the extreme value distribution curves that compare stock damaged or people affected, by storm return period, i.e., the integration of the expected damage with the probability of the storm events.

- *Step 8. 100-year asset value calculation*: We calculated the Present Value of mangrove benefits over a period of 100 years (**Figure 4**). We assumed a constant benefit flow and 4% discount rate to obtain the 100-year asset value (Eq. 2).

$$PV = \sum_{i=1}^{i=100} \frac{AEB}{(1+r)^i} \qquad (2)$$

Where *PV* is the Present Value, *AEB* are the Annual Expected Benefits, *r* is the discount rate (4%) and *"i"* is each year within the life cycle period (i=1-100 years).

Table 1: Risk maps summary table

Years	Assets	Mangrove scenario	Storm condition	Return Period
1996 2010 2015	People Stock	With mangroves Without mangroves	Cyclonic (Tropical Cyclones) Non-Cyclonic (Regular Climate)	1-in-5-years 1-in-10-years 1-in-25-years 1-in-50-years 1-in-100-years

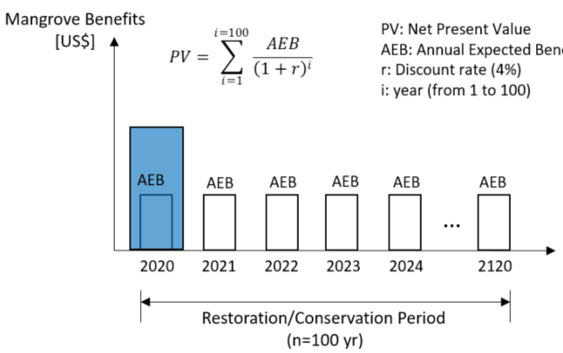


Figure 4: Present Value calculation over a 100-year time period with 4% discount rate

Projections of Future Flood Risk and Mangrove Benefits

We examined recent trends in flood risks by country to estimate the range of potential future flood risk and the values of mangroves as flood protection assets. We have shown that most of the change in flood risk and mangrove benefits are driven by socio-economic changes (i.e., in populations and wealth by country) and the values and benefits are driven much less by changes in the abundance of mangroves.

To estimate future mangrove values, we assume that flood risk will grow by country at the same rate as in the past (1996-2015) and will be driven primarily by changes in population (size and distribution) and wealth (GDP per capita). In these analyses we are using past relationships to predict potential future patterns; we are not trying to account for any future acceleration in changes do to SLR or storminess; so, our estimates should be conservative.

For each country, we have identified the correlation coefficients describing the relationships for changes in risk and benefits with changes in assets and mangroves (ha). We used these correlation coefficients to project future risk and mangrove benefits in 2050 under several different scenarios for changes in mangrove abundance with respect to 2015, covering mangrove loss (-100%, -50%, -20%, -5%), conservation (0%) and restoration (5%, 10%, 20%). The 0% is a no change or conservation scenario (i.e., the 2015 distributions are held constant).

In just the 15-year period from 1996-2010, there were some countries that lost more than 20% of their mangroves so we assume that even higher rates were possible over the 30-year period to 2050. Our restoration scenarios cover a slightly larger range than Worthington and Spalding (2018) who identified that mangrove restoration potential in a few key countries is 10-15% of existing mangrove cover based on analyses of mangrove loss and the land use factors that underlie that loss.

Data and Model Assumptions

Mangrove Data

Global Mangrove Watch (GMW, Bunting *et al.*, 2018) (www.globalmangrovewatch.org/datasets), has just recently posted spatial mangrove distribution data for the following years: 1996, 2007, 2008, 2009, 2010, 2015, 2016. The GMW has generated a global baseline map of mangroves for 2010 using ALOS PALSAR and Landsat (optical) data, and changes from this baseline for seven epochs between 1996 and 2017 derived from JERS-1, ALOS and ALOS-2. Annual maps are planned from 2018 and onwards. The primary objective of the GMW has been to provide countries with mangrove extent and change maps, to help safeguard against further mangrove forest loss and degradation.

Population Data

Global exposure data for people was obtained from GHS-POP GRID dataset, from the European Commission (https://ghsl.jrc.ec.europa.eu/ghs_pop2019.php). This new package provides estimates of global populations and their distribution for 1975, 1990, 2000 and 2015. The global distribution of population is at 250 m resolution. Residential population estimates for target years 1975, 1990, 2000 and 2015 provided by CIESIN GPWv4.10 were disaggregated from census or administrative units to grid cells, informed by the distribution and density of built-up as mapped in the Global Human Settlement Layer (GHSL) global layer per corresponding epoch.

Capital Stock Data

This study uses data from the Penn World Table version 9.1 from the Groningen Growth and Development Center (https://www.rug.nl/ggdc/productivity/pwt/). This version is a database with information on relative levels of income, output, input and productivity. The table covers 182 countries and 68 years, between 1950 and 2017. We particularly used the nationwide data of Capital Stock at constant 2011 national prices and transformed into constant 2018 national prices. Then, we calculate the stock per capita at each country and multiply these national values by the population located at each grid cell. We finally obtain the global stock distribution at 250 meters resolution. There were 22 tropical nations that had mangroves but were not included in the Penn World Table; we filled most of these gaps with national data from the World Bank. There were a few remaining countries and territories that we were not able to include in the analyses due to the lack of economic data, including are Eritrea, French Guiana, New Caledonia, Micronesia, Palau, Somalia, Guadelupe, Martinique, Timor Leste, Mayotte, Samoa, Netherlands Antilles, US Virgin Islands, Saint Martin and American Samoa.

Gross Domestic Product

World Development Indicators from the World Bank (https://datacatalog.worldbank.org/dataset/world-development-indicators) were used to obtain GDP data for each country involved in this study (World Bank 2017). GDP information is available from 1960 to 2016.

Model Limitations and adjustments

Our efforts represent state of the art process-based assessments of flood risk and mangrove benefits globally. For most countries with mangroves, these represent the best data and models for even mangrove benefits, and for many of these countries the best national level estimate of flood risk. For this global study, we have developed a dataset of several thousand simulations to describe how mangroves modify extreme water levels at the shoreline, for every kilometer of mangrove coastline in the world. This approach is computationally highly efficient and allows us to efficiently estimate coastal flood risk globally for new scenarios of mangrove presence and extent.

Applying the model described above at global scale requires use of much less accurate data than would be used for assessment at a local level and introduces potential inaccuracies. For mangrove coverage, we have only the extent of mangroves, for example, not the age structure, density, species, degree of degradation and other factors which can affect the capacity of mangroves to reduce flooding.

The greatest sources of uncertainty in coastal flood risk modeling are estimates of topography and bathymetry (e.g., Menendez et al. 2019). Given that flooding and damage from tropical storms are among the greatest risks to people and property, better elevation and depth data is urgently needed. Fortunately, in the past decade there has been a substantial increase in the availability of high-resolution coastal elevation data through the widespread use of LIDAR. Nearshore bathymetry, however, remains a major gap, though there are advances in remote sensing that could help.

Our coastal flooding analyses have several significant, combined improvements over other recent global flooding analyses including the downscaling to a 90m resolution; consideration of hydraulic connectivity in the flooding of land; the use of 30 years of wave, surge, tide and sea level data; reconstruction of the flooding height time series and associated flood return periods. Our global flood risk models also include ecosystems for the first time, which represents a critical advance in the assessment of flood risk. Major remaining constraints for global coastal flooding models include the consideration of flooding as a one-dimensional process and the difficulty in representing flooding well in smaller islands.

There are more than 100 countries with some mangroves. Our preliminary review of the results for the benefits of mangroves, identified that a handful of countries had very high values of benefits per hectare (up to millions per hectare). This problem was largely addressed by removing from consideration countries with less than 100 ha of mangroves. These countries had too few mangroves to reliably estimate benefits from a global model that assesses nearshore flooding initially every 1km. This excluded 15 countries in total including Bahrain, Singapore, and Benin. This also excluded eight Caribbean Small Island Developing States.

We do not account for changes in sea level in this time period; these effects would be small in this time period and would have only very minor impacts in flooding. We also calculate the (local) distributions of extreme sea levels across this entire time period; we do not adjust the distributions within this time period. That is, we are assuming that the 30-year historical data of waves and cyclones is applicable to 1996, 2010 and 2015. Adjustments within the time period would drastically shorten the data record, which is not a standard approach for risk and flood modeling.

RESULTS

Mangrove Cover

The cover of mangroves changed substantially between 1996, 2010 and 2015. It declined overall from 1996-2010 with a 4% loss globally, from 151,000 km2 to 145,000 km2 in the Global Mangrove Watch database (Figure 6, Figure 7 Figure 7). Many countries saw double digit losses in the percent cover of mangroves with dozens of km^2 of losses not uncommon (Figure 6 and Figure 7). A very few countries saw gains in mangroves in this period, most of them located in Africa (e.g. Suriname, Guinea Bissau, Gambia, Guyana, Senegal, Sierra Leona, Cameroon and Guinea). There was much less change in mangrove from 2010 to 2015 and many countries saw gains in mangrove hectares (e.g. Mexico, French Guiana, Belize and the Philippines) though not to the levels observed in 1996. The global mangrove decline observed between 2010 and 2015 was 0.4% (Figure 6 and Figure 7).

The patterns in mangrove change are spatially variable (Figure 7). Even within countries that saw significant losses of mangroves from 1996 to 2010 such as Mexico, Belize and Honduras there were still numerous stretches of coastline where mangrove increased (Figure 8). Our high-resolution models account for this spatial variability in mangroves as well as in storms, people and stock even though we mostly summarize by country in this report.

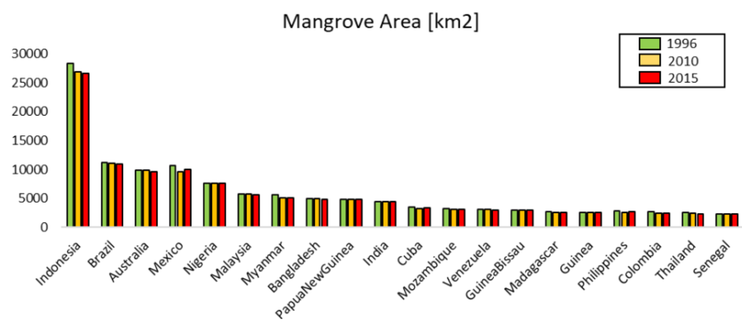


Figure 5: Change in the coverage of mangroves from in 1996, 2010 and 2015 (top 20 countries shown).

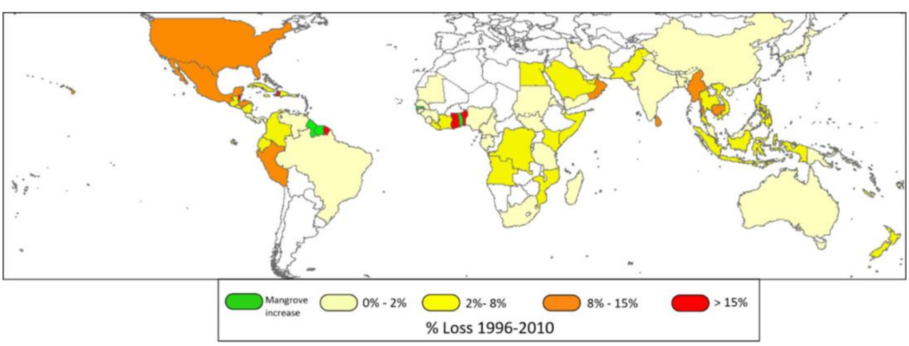


Figure 6: Global change by country in mangrove cover from 1996-2010

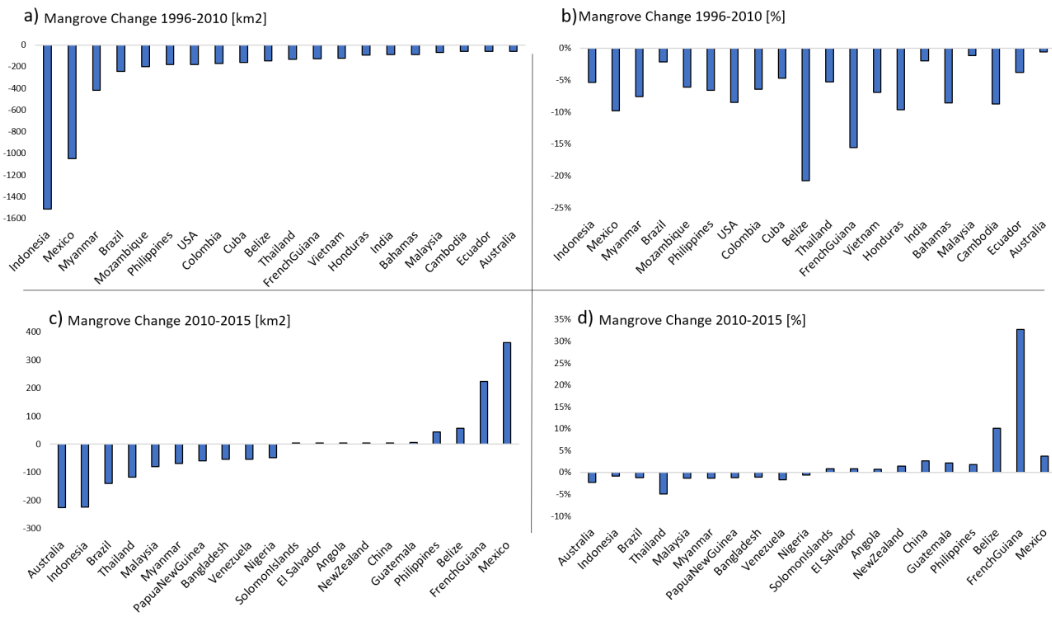


Figure 7: Countries with the greatest overall changes in mangrove area from 1996-2010 in total value (a) and percent (b); and from 2010-2015 in total value (c) and percent (d).

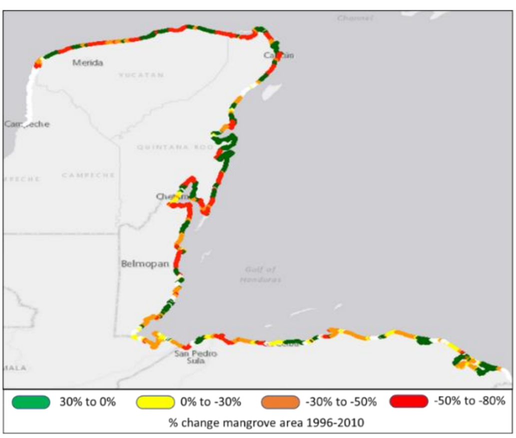


Figure 8: Spatial variability in mangrove change from 1996-2010 across the Caribbean coasts of Mexico, Belize, Guatemala and Honduras.

Flood Risk

Overall flood risk increased substantially from 1995 – 2018 (1996, 2010, 2015). This increase in risk was driven by population and economic growth in coastal areas and countries as well as from increase in flooding due to mangrove loss on many coastlines. For example, from 1996-2010, there was an overall population growth of +20% and an increase in stock (economic growth) of +56% in countries with mangroves and a global mangrove loss of 4%.

Annual flood risk on mangrove coastlines in 2018 is greatest in China, Vietnam, United States, The Philippines, Indonesia, Taiwan, India, Brazil and Myanmar. All of these countries have more than 168,000 people exposed to coastal flooding every year and more than $525 million in assets at risk from flooding annually on mangrove coastlines.

From 1996-2010, the annual flood risk to people increased by 32% (Figure 9) (i.e., 32% more people were predicted to be flooded annually on mangrove coastlines). The countries with the most people annually affected by coastal flooding in 2010 were China, Vietnam, India, Philippines and Indonesia; all five countries had more 450,000 people at risk of flooding annually. The countries with the greatest % increase in annual flood risk to people from 1996-2010 were Eritrea, Angola, Tonga, Qatar and Thailand rank the highest. All these countries have doubled their risk in 15-year period (1996-2010).

From 1996-2010, the annual flood risk to stock increased by 118% (Figure 10) (i.e., 118% more stock was predicted to be flooded annually on mangrove coastlines). In 2010, annual flood risk to stock on mangrove coastlines was greatest in China, US, Taiwan and Vietnam with annual expected flood losses above 2 US$ billion.

The greatest absolute increase in annual flood risk to stock between 1996 and 2010 was observed in China, Vietnam, Indonesia, Taiwan, India, and Australia. The annual flood losses in each of these nations increased by more than 293 US$ million. The greatest % of annual flood risk to stock between 1996 and 2010 was in developing countries such as Turks and Caicos, Sudan, Tonga, Djibouti, Suriname and Myanmar.

From 2010-2015, the annual flood risk to people increased by 14% globally with the most significant increases in people at flood risk in China, the Philippines, India and Vietnam, all with annual increases in people flooded > 190,000 people/year. From 2010-2015, the annual flood risk to stock increased by 34% globally. The countries with the highest economic risk increases were China, US, Indonesia and Vietnam (> $650M/year).

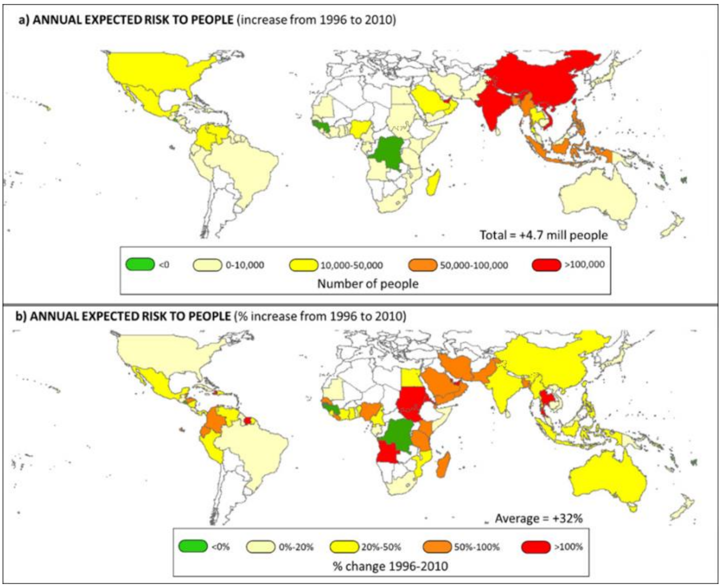


Figure 9: Change in Flood Risk to People from 1996 to 2010. The change in the annual expected number of people flooded in total (a) and as a percent change (b) across the time period.

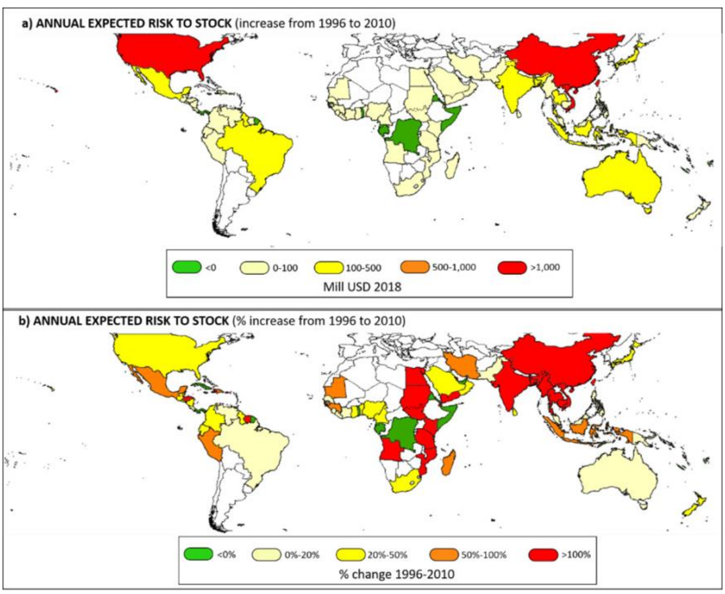


Figure 10: Change in Flood Risk to Stock from 1996 to 2010 (in 2018 $US million dollars). The change in the annual expected stock loss in (a) total and (b) as a percent change.

Change in Mangrove Flood Reduction Benefits & Wealth

At a global level, mangrove benefits and contributions to wealth increased substantially in each time period (1996-2010, 2010-2015) and across the entire time from 1995 to 2018.

The change in the coverage of mangroves is spatially variable and this affects the protection provided by mangroves first by affecting flood height at the shore (Figure 11). This effect on flood height is the best way to examine how mangrove loss (and gain) effects flooding before combining this flood hazard with changes in the exposure of people and property over time.

The period from 1996-2010 saw a substantial loss of mangroves but even across this period there was a gain in the value of benefits for flood risk reduction (Figure 12, Figure 13). Despite mangrove losses, nearly 1 million more people received flood reduction benefits annually in 2010 as compared to 1996, which represents an increase of 22% more people protected (Figure 12). Vietnam, India and Brazil saw the greatest increase in benefits to people. Countries such as Thailand, Guyana and Haiti saw overall decreases in people protected.

The overall increase in flood protection benefits to stock were even greater across this time period (1996-2010). Despite mangrove losses, annual flood protection benefits to stock increased by more than $5 billion from 1996 to 2010 representing a 50% increase (Figure 13). Vietnam, China, India and Indonesia saw the greatest increase in benefits to stock. Countries such as Thailand and the USA saw overall decreases in stock protected; mangrove losses coupled with coastal economic growth puts much more wealth at risk.

The period from 2010-2015 saw some small declines in mangrove cover globally and overall gains in mangrove benefits to people, stock and wealth.

From 2010-2015, the annual flood benefits to people increased by 9.5% globally. Overall China, Vietnam, United Arab Emirates and Bangladesh experienced the greatest increases in people protected by mangroves (>29,000 people/year per country). However, not all the countries had increases in mangrove benefits. The Philippines, Myanmar, Malaysia and Colombia all saw significant declines in people protected from flooding by mangroves.

From 2010-2015, the annual flood benefits of mangroves to stock increased by 38% globally. Many countries saw significant increases in their annual expected flood protection benefits. For example, China, Vietnam, Australia and Indonesia all saw increases in their benefits of more than $250M/year. On the other hand, some countries saw decreases; The Philippines, USA, United Arab Emirates, Guyana and Malaysia all saw decreases of more than $19M apiece in annual expected flood protection benefits from mangroves.

Not surprisingly, the economic benefits per hectare are strongly dependent on the income status of countries (Figure 14). The value of assets protected per hectare was 10-fold smaller in low income countries than in all three of the other country income categories.

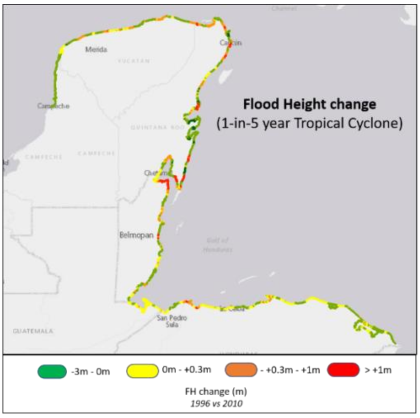


Figure 11: Effects of Mangrove Change on Flood Hazards from 1996 to 2010 along the Mesoamerican coastline under 1-in-5-year return period event.

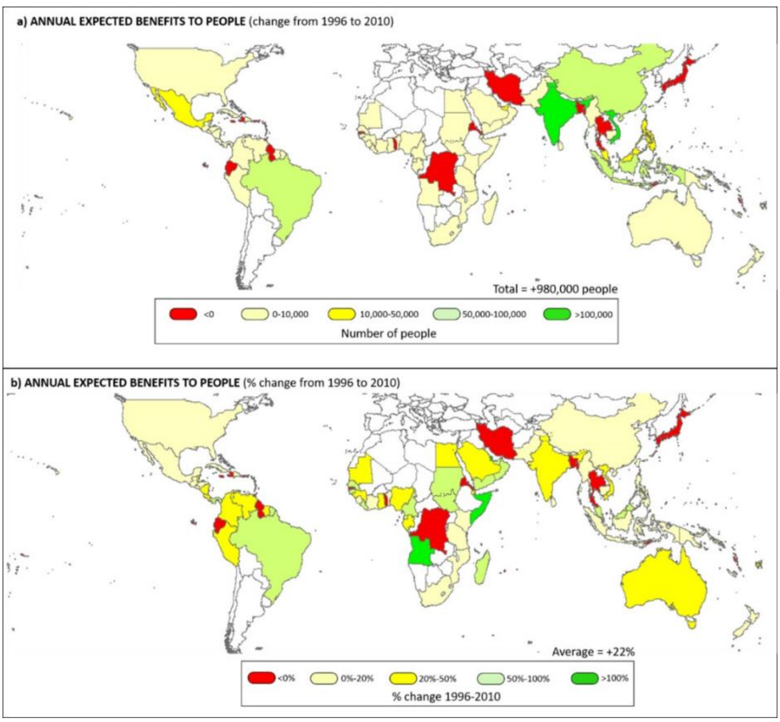


Figure 12: Change in Flood Reduction Benefits of Mangroves to People from 1996 to 2010. The change in the annual expected number of people receiving flood protection benefits from mangroves in total and as a percent change across the time period.

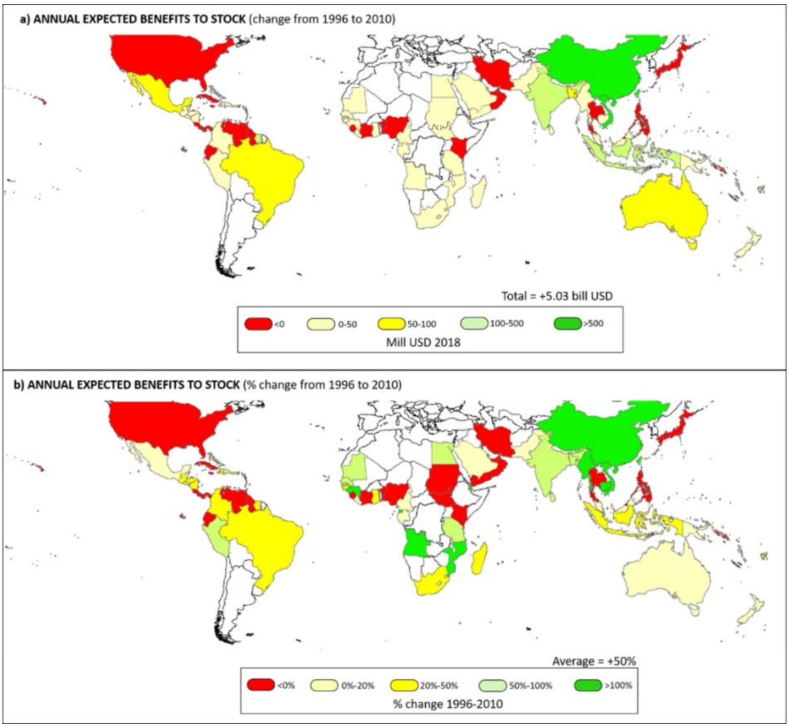


Figure 13: Change in Flood Reduction Benefits of Mangroves to Stock from 1996 to 2010 (in 2018 dollars). The change in the annual avoided damages to stock due to mangroves in total and as a percent change across the time period.

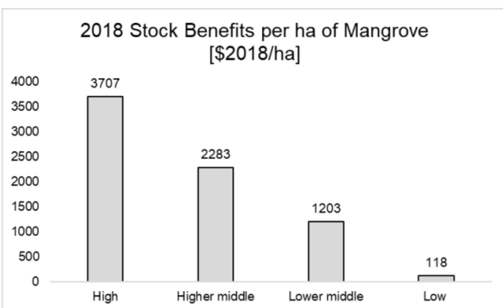


Figure 14: Annual expected benefits per hectare of mangrove in 2018 (in 2018$). The graph shows results averaged across countries in the four different income categories: high, higher middle, lower middle and low.

Mangrove Asset Value and Changing Wealth

For the Changing Wealth of Nations, we are interested not the just in the annual benefits from mangroves but in the asset value of mangroves. Some assets, like manufactured capital, are traded in markets and a market price has been established. The market price is taken as the value of the asset. But mangroves and the services they provide, like much of natural capital, are not traded in markets and do not have observable market prices.

For assets like mangroves that do not have market prices, we rely on the economic definition of asset value: the discounted sum of the services mangroves can be expected to generate over their lifetime. This approach has two major components, i) estimation of the value of services using non-market valuation techniques like the expected damage function that was applied to estimate annual flood protection benefits, and ii) projections of the generation of these services in the future.

The previous sections described how coastal protection services are measured and valued; we now turn to the second component of asset valuation, projections about the generation of protection services by mangroves in the future. This requires the following information:

- A discount rate: 4% is used to discount all other assets in CWON so we will apply 4% to mangroves.
- Lifetime over which coastal protection services will be valued. Following approaches recommended by the UN and UK for natural capital accounts, we have assumed a 100-year 'project' lifespan for these coastal habitat assets (SEEA 2012; UK Natural Capital Accounts *– get ref from GM*), which is consistent with other infrastructure assets. Given that these habitats have survived for millennia in these environments (and many past sea levels) that is not unreasonable. Of course, it will be increasingly a management choice to help keep these natural defenses in place over this time period.

Our analyses assume that the protection services from mangroves is consistent over the next 100 years with the present annual value of flood reduction benefits discounted by 4% per year over this time period. The Present Value (Eq. 1) is used to estimate the current asset value of mangrove assuming constant distribution of Annual Expected Benefits over 100 years with a 4% rate of discount (Figure 4) as follows:

$$PV = \sum_{i=1}^{i=100} \frac{AEB}{(1+r)^i}$$

Where *PV* is the Present Value, *AEB* is the Annual Expected Benefits, *r* is the discount rate (4%) and "*i"* is each year within the life cycle period (i=1-100 years).

The present value (2018) of the global flood reduction benefits from mangroves (100-year asset @ 4% discount rate) is $589 billion. The countries with the greatest present value of mangroves for flood reduction are China, Vietnam, Australia and Indonesia (**Table 2**, Figure 15).

The change (increase) in the wealth of mangroves for flood risk reduction from 1995-2018 is estimated to be over $348 billion dollars (**Table 2**). The countries receiving the greatest increases in wealth in absolute values ($) are China, Vietnam, Indonesia and India, and in relative values (%) were Iran, St. Vincent and the Grenadines, Comoros and Egypt.

Despite mangrove losses, most countries still saw increases in the asset value or wealth of mangroves for flood risk reduction largely because of overall increases in flood risk (growth of people and assets on coastlines). However, some nations saw overall losses in mangrove wealth for flood risk reduction including most notably Thailand and the Philippines.

The present value of coral reefs as a flood reduction asset globally is $355 billion (Table 3). The countries where reefs have the highest asset value for flood reduction are Indonesia, the Philippines, Malaysia, Mexico and Cuba.

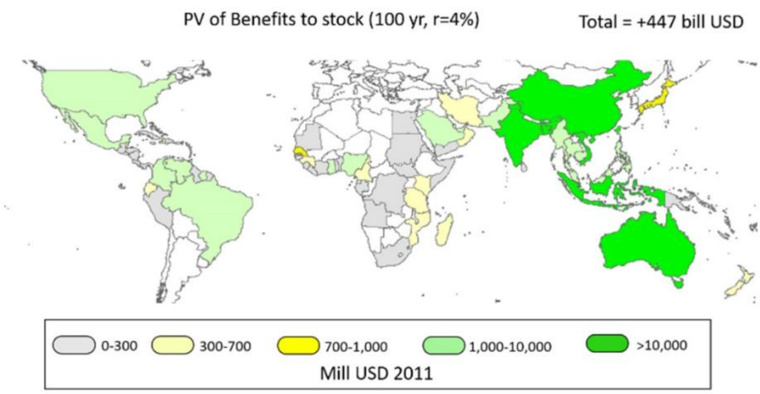


Figure 15: Present value of Mangrove Assets in 2018 (100 years at 4% discount rate).

Table 2: Mangrove Benefits for Flood Protection. Top 15 Countries in Mangrove Asset Value (100yrs at 4% discount) and Annual Expected Benefit for Flood Protection. Values in the table are in $US millions in 2018 dollars. Countries are ranked by Annual Expected Benefit in 2015. We have noted four additional nations with negative changes in present value from 1995-2018.

Country	Annual Expected Benefit 2015	Present Value 1995	Present Value 1996	Present Value 2010	Present Value 2015	Present Value 2018	Change in Present Value 1995-2018
China	5,665	20,714	22,831	58,900	138,839	186,802	+166,088
Vietnam	4,231	18,686	21,245	80,233	103,700	117,780	+99,094
Australia	3,089	42,188	43,531	45,676	52,164	56,058	+13,870
United States	1,087	29,357	30,133	28,441	26,652	25,579	-3,778
Indonesia	1,073	12,822	14,039	20,139	26,299	29,996	+17,174
India	767	9,671	10,196	17,922	23,566	26,952	+17,281
Mexico	676	11,784	12,051	14,299	16,574	17,939	+6,155
Brazil	553	9,339	9,631	12,052	13,575	14,489	+5,150
Suriname	420	5,735	5,831	8,598	10,300	11,321	+5,586
Taiwan	417	2,937	3,183	6,051	10,226	12,731	+9,794
Bangladesh	327	2,040	2,147	4,249	8,031	10,236	+8,196
UAE	288	8,901	9,119	8,352	7,058	6,283	-2,618
Guyana	278	8,097	8,153	7,476	6,821	6,428	-1,669
Japan	182	1,108	1,145	869	4,464	6,622	+5,514
Philippines	181	10,788	11,239	11,112	4,437	432	-6,468
Thailand	87	4,077	4,485	2,094	2,123	2,140	-1,937
Cuba	37	1,437	1,406	1,001	907	850	-587
Jamaica	45	1,337	1,362	1,176	1,095	1,047	-290
Ecuador	49	1,416	1,425	1,011	1,204	1,320	-96
Global total	**20,710**	**241,573**	**244,935**	**368,141**	**507,494**	**589,857**	**348,284**

Table 3: Coral Reef Benefits for Flood Protection. Top 15 Countries in Coral Reef Present Value (100yrs at 4% discount) and Annual Expected Benefit for Flood Protection. Values are in $US millions in 2011 dollars from Beck et al. (2018) and in 2018 dollars as in Table 2. *In 2011 dollars.

Country	Annual Expected Benefit (2011 $Millions)	Present Value (2018 $Millions)
Indonesia	639	$17,536
Philippines	590	$12,866
Malaysia	452	$10,632
Mexico	452	$22,041
Cuba	401	$9,826*
Saudi Arabia	138	$2,941
Dom. Republic	96	$3,081
United States	94	$9,373
Taiwan	61	$2,196
Jamaica	46	$4,812
Vietnam	42	$637
Myanmar	33	$177
Thailand	32	$964
Bahamas	14	$1,440
Belize	9	$273
Global Total	**4,182**	**$355,418**

Projections of Future Flood Risk and Mangrove Flood Reduction Benefits

Future flood risk on mangrove coastlines is predicted to grow substantially because of increasing growth in coastal populations and assets (Figure 16). Annual flood damages will grow 5-fold by 2100 even under significant mangrove restoration scenarios and by seven-fold if mangroves are lost. These should be considered to be conservative estimates as they do not account for increases in sea levels or storminess.

The flood reduction benefits of mangroves will also grow by at least four-fold by 2100 as long as present mangrove distributions are conserved (Figure 17). Flood reduction benefits could grow by eight-fold with some restoration. It will be challenging to maintain mangrove distributions in to the future given increases in sea level and storminess. Mangroves can keep pace with some increases in sea level, but not with the extreme rates of sea level rise that could occur later in the century (Saintilan et al. 2020).

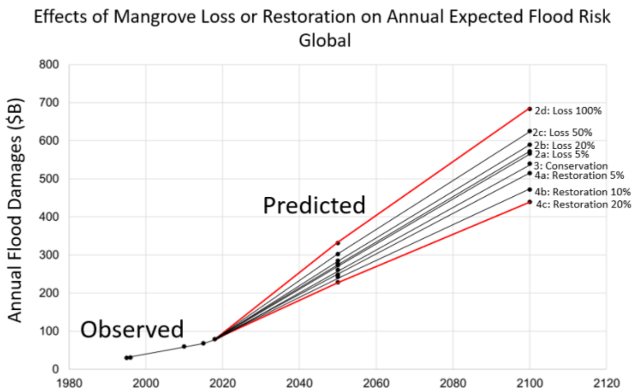


Figure 16: Future annual expected flood risk and the effects of mangrove loss and restoration.

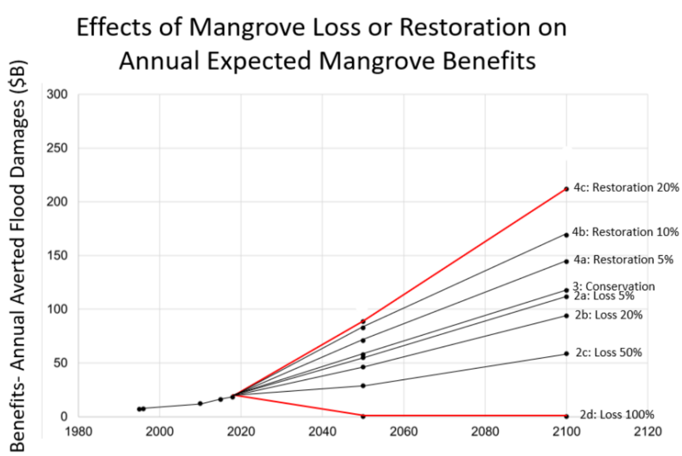


Figure 17: Future benefits of mangroves for flood risk reduction under loss and restoration scenarios.

Discussion

Conventional approaches to measuring wealth and economic development focus only on built capital and fail to account for the value of all goods and services provided by natural capital. Currently, only a subset of the extractive benefits provided by natural ecosystems, such as fish and timber harvests, are valued. Many critical services, such as flood protection and climate mitigation, which rely on keeping ecosystems intact, are rarely valued (Narayan et al. 2016, World Bank 2016). This lack of consideration encourages short-term over-exploitation and degradation, reducing the quantity and quality of the goods and services provided. To halt the loss of our natural capital and to ensure the provision of critical ecosystem services, these values must be accounted for in policy and management decisions. Better valuations can inform decision-makers as they strive to meet risk reduction and environmental management objectives.

Our analyses show that the value of mangroves for flood risk reduction increased substantially from 1995-2018 even though there was an overall loss of mangroves in this period. This increase in the wealth of mangroves is due first and foremost to the fact that global flood risk increased substantially on mangrove coastlines in this time period. Coastal flood risk in this period nearly doubled because of increases in populations and stock and thus the exposure to flooding. The increases in coastal populations have been well documented, but the changing effects on flood risk have not been quantified so clearly.

The increase in wealth despite overall losses of mangroves is also likely due in part to increases in the marginal value of the remaining mangroves. For example, the first 10's to 100's of meters at the seaward front of mangrove forests provide some of the most important benefits for reducing waves in particular but also surge. Thus, remaining mangroves particularly on highly developed coastlines can provide very high benefits per hectare in flood risk reduction.

China is estimated to have the highest current wealth of mangroves for flood risk reduction and the greatest growth in their wealth from 1995-2018. Much of these benefits are related to the overall increases in both population and wealth on Chinese coastlines particularly over the last decade. Flood exposure on Chinese coastlines is also difficult to model well because there are substantial populations at very low elevation; small changes in flood height or improvements in elevation models can have dramatic effects on populations flooded on these coasts.

Vietnam is estimated to have the second highest wealth of mangroves for flood risk reduction and the second greatest growth in their wealth from 1995-2018. Most of this increase in wealth also arises from the increasing populations and assets on Vietnamese coastlines, which contributes to substantial increases in flood risk and mangrove benefits. Though Vietnam has been a champion of mangrove restoration with tens of thousands of hectares restored (e.g., IFRC 2011), the data for 1996-2015 show overall national losses in mangrove cover. The most important flood reduction benefits arise from the mangroves just southeast of Ho Chi Minh city in the Can Gio Mangrove Biosphere Reserve, and this has been an area of significant protection and restoration efforts.

A number of countries saw decreases in wealth including most notably Thailand, the Philippines, and Jamaica. Most of these countries oversaw significant declines in their mangrove forests as the primary contributing factor to declines in wealth. There was also some evidence that population densities and thus overall flood risk decreased on some of the coastlines most exposed to tropical cyclones.

Our estimates are based on a global process-based model that identifies the annual expected benefits of mangroves for flood risk reduction (Losada et al. 2018, Beck et al. 2018a, Menendez et al. 2020). First, we develop and use a set of combined hydrodynamic and economic models to identify (i) the area and depth of flooding, (ii) for mangrove coastlines, (iii) in model runs with and without mangrove, (iv) for four storm frequency events, 1 in 10, 25, 50, 100 yr driven by local storm data. Finally, we overlay these data on economic asset information downscaled to 90 x 90 meters and assessed by flood depth to identify flood damages (risk) and avoided damages (mangrove benefits).

This works applies state of the art engineering approaches in global flood risk modeling. These are fully quantitative models in comparison to other qualitative, index-based approaches for assessing coastal vulnerability and coastal protection ecosystem services. Nonetheless there are still a number of limitations for quantitative regional and global modeling efforts. Areas where the greatest improvements are feasible are: (i) going from one dimensional flood model that assess dynamics from offshore to onshore to two dimensional models that also account for alongshore flow; (ii) continued improvements in asset data; and (iii) and improvements in the spatial resolution of coastal bathymetry and topography data. These would improve all flood risk models (including those by the risk industry). While acknowledging limitations, our assessment of mangrove (and reef) benefits are based on robust models, using peer reviewed approaches for assessing flood risk reduction and adaptation benefits.

There are many factors that could influence the future value of mangroves, which includes ecological, social, economic and climatological factors. The future distribution of mangroves is likely affected by a number of factors and in particular future sea level and sediment supply (particularly from watersheds). Sea level will affect mangroves if they do not have room to migrate inland or opportunities to build land upwards. Mangroves are good land builders, better than other wetlands. Under some scenarios, mangroves can keep pace with increasing sea levels as long as there is sufficient supply of (upland) sediments usually riverine which mangroves can trap and use to build upwards. However, some models predict that later in the century, sea levels could rise faster than mangrove forests can accumulate sediments and grow vertically (Saintilan et al. 2020).

As long as mangroves can be managed (as they have in recent years) to be maintained or restored, then their value to national wealth will likely grow substantially. Under most social, economic and climatological scenarios there will be increases in coastal assets and risks to them. Continued increases in populations and stocks on coastlines coupled with increasing sea levels and storminess from climate change, will lead to major increases in flood risk on most coastlines. The value of flood reduction and adaptation strategies such as mangrove conservation and restoration will also increase substantially.

Mangroves and other natural solutions for flood risk reduction and climate adaptation have been shown to be cost effective on many coastlines for example across the Caribbean (Beck et al. 2020). As the wealth of these assets increases, their cost effectiveness will also likely continue to grow.

The present value of mangroves and reefs for direct flood damage reduction (i.e., avoided damages to property) is greater than $850 billion dollars. The indirect losses from flooding (e.g., business interruption) are usually more than two times larger than direct flood losses. For example, one global insurer indicates that all large property insurance claims now include a major business interruption element, which typically accounts for most of the loss;
recent business interruption claims have been 139% larger than direct property loss claims (Allianz 2019). If we consider the direct and likely indirect benefits of mangroves and reefs for flood risk reduction, then the present value of these two tropical habitats for avoided flood damages is could be $1.7 to 2 trillion dollars.

Recommendations for Policy and Practice

The coastal protection services of mangroves can be rigorously valued. These values inform the policy and practice of development, aid, and conservation and help identify sustainable and cost-effective approaches for adaptation and risk reduction. By valuing these coastal protection benefits in terms used by finance and development decision-makers we can inform adaptation, development and environmental conservation decisions.

This cost effectiveness of mangroves for flood risk reduction opens many opportunities to finance their conservation and restoration including through blue bonds, infrastructure bonds, disaster management and recovery, and insurance among others (e.g., Airoldi et al., 2021). By showing the variation of the flood protection benefits provided by mangroves, we can identify the places where mangrove management may yield the greatest returns. We point to a few key recommendations and opportunities.

- Existing mangroves should be conserved as they contribute substantially to national wealth and their value has and will grow.
- Mangrove restoration efforts should expand and they can be particularly cost effective.
- Governments should require that mangroves, reefs and other nature-based solutions be considered as alternatives in formal (cost effectiveness) assessments for coastal defense.
- Mangrove restoration for risk reduction has been done at large scales over hundreds of thousands of hectares in places such as Vietnam, Philippines and Guyana (World Bank 2016). While best practices are still evolving, current approaches are well advanced.
- These valuations enable the prioritization of adaptation funding (e.g. Green Climate Fund) and identify priority sites for mangrove coastal protection, either as 'stand-alone' solutions, or part of hybrid approaches that combine mangrove natural defenses with built infrastructure.
- Mangroves provide a wide suite of additional benefits from fisheries to carbon mitigation, which can also be valued and combined with these flood reduction values to bolster the case for cost effective investments in mangrove conservation and restoration.
- Rigorous valuations support innovative finance opportunities for mangrove restoration. For example, these results can be considered in insurance industry models to lower premiums.
- These values can also support the development of catastrophic hazard bonds, resilience bonds, and blue bonds that could use the risk reduction benefits of mangroves to support habitat conservation and restoration.
- Accounting for mangrove flood reduction benefits as natural asset values – and ultimately as natural infrastructure – can also inform disaster recovery plans and spending.

References

Allianz. 2019. Allianz Risk Barometer: Top Business Risks for 2019. Allianz Global Corporate and Specialty, Munich, Germany.

Airoldi, L., Beck M. W., Firth L. B., Bugnot A., Steinberg P., Dafforn K. A. 2020. Emerging solutions to return nature to the urban ocean. Annual Review of Marine Science.

Beck, M.W., S. Narayan, D. Trespalacios, K. Pfliegner, I. J. Losada, P. Menendez, A. Espejo, S. Torres, P. Diaz, F. Fernandez, S. Abad, P. Mucke, L. Kirch. 2018a. The global values of mangroves for risk reduction. Summary Report. The Nature Conservancy, Berlin.

Beck MW, Losada IJ, Menéndez P, Reguero BG, Díaz-Simal P, Fernandez F. 2018b. The global flood protection savings provided by coral reefs. Nature Communications. 9:2186.

Beck, M. W., S. Narayan, I. J. Losada, A. Espejo, S. Torres. 2019. The Flood Protection Benefits and Restoration Costs for Mangroves in Jamaica, *In* Castaño-Isaza, J., Lee, S., Dani, S. (eds.). Forces of nature: assessment and economic valuation of coastal protection services provided by mangroves in Jamaica. World Bank, Washington.

Beck, M. W., N. Heck, S. Narayan, P. Menéndez, S. Torres, I. J. Losada, M. Way, M. Rogers, L. McFarlane-Connelly. 2020. Reducing Caribbean Risk: Opportunities for Cost-Effective Mangrove Restoration and Insurance. The Nature Conservancy.

Barbier, E. B. 2015. Valuing the storm protection service of estuarine and coastal ecosystems. Ecosystem Services11:32–38

Barbier, E. B. 2018. How to pay for saving biodiversity. Science 360: 486-488.

Bayas, J.C.L., Marohn, C., Dercon, G., Dewi, S., Piepho, H.P., Joshi, L., van Noordwijk, M. and Cadisch, G., 2011. Influence of coastal vegetation on the 2004 tsunami wave impact in west Aceh. *Proceedings of the National Academy of Sciences*, *108*(46), pp.18612-18617.

Church JA, White NJ, Coleman R, Lambeck K, Mitrovica JX. 2004. Estimates of the regional distribution of sea level rise over the 1950-2000 period. J Clim. 17:2609–25.

Cid A, Camus P, Castanedo S, Méndez FJ, Medina R. 2017. Global reconstructed daily surge levels from the 20th Century Reanalysis (1871–2010). Glob Planet Change. 148:9–21.

Colgan, C. S., M. W. Beck, S. Narayan, 2017. Financing Natural Infrastructure for Coastal Flood Damage Reduction. Lloyd's, London.

De Bono A, Chatenoux B. 2015. A global exposure model for GAR 2015. UNEP-GRID, GAR.

Desai B, Maskrey A, Peduzzi P, De Bono A, Herold C. 2015. Making Development Sustainable: The Future of Disaster Risk Management, Global Assessment Report on Disaster Risk Reduction.

Egbert GD, Erofeeva SY. 2002. Efficient inverse modeling of barotropic ocean tides. J Atmos Ocean Technol. 19:183–204.

Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, et al. The Shuttle Radar Topography Mission. 2007;(2005):1–33

Hochard, J. P., S. Hamilton, E. B. Barbier. 2019. Mangroves shelter coastal economic activity from cyclones. *Proceedings of the National Academy of Sciences*, *116*:12232-12237.

Huizinga J, De Moel H, Szewczyk W. 2017. Global flood depth-damage functions - Methodology and the database with guidelines. JRC Working Papers JRC105688, Joint Research Centre (Seville).

Knapp KR, Kruk MC, Levinson DH, Diamond HJ, Neumann CJ. 2010. The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data. Bull Am Meteorol Soc. 91:363–76.

Losada, I., P. Menéndez, Beck, M. W., D. Trespalacios, S. Narayan. 2017. Technical Report- Valuing the Protection Services of Mangroves in the Philippines. World Bank, Washington, DC.

Losada, I. J., P. Menéndez, A. Espejo, S. Torres, P. Díaz-Simal, S. Abad, M. W. Beck, S. Narayan, D. Trespalacios, K. Pfliegner, P. Mucke, L. Kirch. 2018. The global value of mangroves for risk

reduction. Technical Report. The Nature Conservancy, Berlin.
McCreless and Beck 2016. Rethinking our global coastal investment portfolio. Journal of Ocean & Coastal Economics 3:1-19.
Menéndez, P., Losada, I. J., M. W. Beck, S. Torres-Ortega, A. Espejo, S. Narayan, P. Díaz-Simal, GM Lange. 2018. Valuing the Protection Services of Mangroves at National Scale: The Philippines. *Ecosystem Services* **34**:24-36.
Menéndez, P., Losada, I. J., M. W. Beck, S. Torres-Ortega, A. Toimil. 2019. Assessing the effects of using high-quality data and high-resolution models in valuing flood protection services of mangroves. PLoS ONE 14(8): e0220941.
Menéndez, P., Losada, I. J., S. Torres-Ortega, S. Narayan, M. W. Beck. 2020. Global flood protection benefits of mangroves. *Scientific Reports* 10:4404.
Muis, S., Verlaan, M., Winsemius, H.C., Aerts, J.C. and Ward, P.J., 2016. A global reanalysis of storm surges and extreme sea levels. *Nature Communications, 7, p.11969.*
Narayan, S., Suzuki, T., Stive, M.J., Verhagen, H.J., Ursem, W.N.J. and Ranasinghe, R., 2010. On the Effectiveness of Mangroves in Attenuating Cyclone Waves. Coastal Engineering.
Narayan, S., M. W. Beck, B. G. Reguero, I. J. Losada, B. Van Wesenbeeck, N. Pontee, J. N. Sanchirico, J. C. Ingram, G-M. Lange , K. Burkes-Copes. 2016. The benefits, costs and effectiveness of natural and nature-based coastal defenses. PLoS ONE 11(5): e0154735.
Narayan, S., M.W. Beck, P. Wilson, C. Thomas, A. Guerrero, C. Shepard, B. G. Reguero, G. Franco, C. J. Ingram, D. Trespalacios. 2016. Coastal Wetlands and Flood Damage Reduction: Using Risk Industry-based Models to Assess Natural Defenses in the Northeastern USA. Lloyd's Tercentenary Research Foundation, London. DOI:10.7291/v93x84kh.
Narayan, S., M.W. Beck, P. Wilson, C. Thomas, A. Guerrero, C. Shepard, B. G. Reguero, G. Franco, C. J. Ingram, D. Trespalacios. 2017. The value of coastal wetlands for flood damage reduction in the northeastern USA. Scientific Reports 7:9463.
Narayan, S., C. Thomas, J. Matthewman, C. C. Shepard, A. Birch, L. Geselbracht, K. Nzerem, M. W. Beck. 2019. Valuing the Flood Risk Reduction Benefits of Florida's Mangroves. The Nature Conservancy, Arlington, VA.
Pawlowicz R, Beardsley B, Lentz S. Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. Comput Geosci. 2002;28(8):929–37.
Perez J, Menéndez M, Losada IJ.2017. GOW2: A global wave hindcast for coastal applications. Coast Eng. 124:1–11.
Reguero BG, Menéndez M, Méndez FJ, Mínguez R, Losada IJ. 2012. A Global Ocean Wave (GOW) calibrated reanalysis from 1948 onwards. Coastal Engineering. **65**:38–55. Thresholds of mangrove survival under rapid sea level rise
Saintilan, N., N. S. Khan, E. Ashe, J. J. Kelleway, K. Rogers, C. D. Woodroffe and B. P. Horton. 2020. Thresholds of mangrove survival under rapid sea level rise. Science 368: 1118-1121.
Scawthorn C, Flores P, Blais N, Seligson H, Tate E, Chang S, et al. 2006. HAZUS-MH Flood Loss Estimation Methodology. II. Damage and Loss Assessment. Nat Hazards Rev. 7:72–81.
System of Environmental-Economic Accounting. 2012. Experimental Ecosystem Accounting Revision. UN.
Silver JM, Arkema KK, Griffin RM, Lashley B, Lemay M, Maldonado S, Moultrie SH, Ruckelshaus M, Schill S, Thomas A, Wyatt K and Verutes G. 2019. Advancing Coastal Risk Reduction Science and Implementation by Accounting for Climate, Ecosystems, and People. *Frontiers in Marine Science* 6:556
Spalding, M., M. Kainuma, L. Collins. 2010. World Atlas of Mangroves. London: Earthscan.
Storlazzi, C.D., Reguero, B.G., Cole, A.D., Lowe, E., Shope, J.A., Gibbs, A.E., Nickel, B.A., McCall, R.T., van Dongeren, A.R., Beck, M.W. 2019. Rigorously valuing the role of U.S. coral reefs in coastal hazard

risk reduction. USGS Open-File Report 2019–1027.
UNISDR 2011. Global assessment report on disaster risk reduction revealing risk, redefining development. United Nations Office for Disaster Risk Reduction.
UNISDR. 2015. Making development sustainable: the future of disaster risk management, global assessment report on disaster risk reduction. United Nations Office for Disaster Risk Reduction.
van Zanten, B. T., P. J.H. van Beukering, A. J.Wagtendonk. 2014. Coastal protection by coral reefs: A framework for spatial assessment and economic valuation. Ocean & Coastal Mgmt 96:94-103.
World Bank, 2011. The changing wealth of nations: measuring sustainable development in the new millennium, Environment and development. World Bank, Washington, D.C.
World Bank. 2016. Managing Coasts with Natural Solutions: Guidelines for Measuring and Valuing the Coastal Protection Services of Mangroves and Coral Reefs. Beck MW., Lange GM (eds). Washington DC; 2016.
Worthington, T., & Spalding, M. (2018). Mangrove Restoration Potential: A global map highlighting a critical opportunity. The Nature Conservancy, Virgina.