REPORT

Mangroves as a protection from storm surges in a changing climate

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Abstracts Adaptation to climate change includes addressing sea-level rise (SLR) and increased storm surges in many coastal areas. Mangroves can substantially reduce vulnerability of the adjacent coastal land from inundation but SLR poses a threat to the future of mangroves. This paper quantifies coastal protection services of mangroves for 42 developing countries in the current climate, and a future climate change scenario with a 1-m SLR and 10 % intensification of storms. Findings demonstrate that while SLR and increased storm intensity would increase storm surge areas, the greatest impact is from the expected loss of mangroves. Under current climate and mangrove coverage, 3.5 million people and GDP worth roughly US \$400 million are at risk. In the future climate change scenario, vulnerable population and GDP at risk would increase by 103 and 233 %. The greatest risk is in East Asia, especially in Indonesia and the Philippines as well as Myanmar.

Keywords Climate change · Coastal protection · Mangroves · Storm surge

INTRODUCTION

Adaptation to climate change will require living with Sea-Level Rise (SLR) and increased storm surges in many coastal areas (e.g., Bamber and Aspinall 2013; IPCC 2013;

Hansen et al. 2015; Hay et al. 2015). Coastal protection from storm surge and flooding is partly provided by built infrastructure (Dasgupta et al. 2010; Nicholls et al. 2010). Mangroves¹ are a form of natural infrastructure that also provides coastal protection in tropical regions. The protective role of mangroves and other coastal forests and trees against coastal hazards has received considerable attention in the aftermath of the 2004 Indian Ocean tsunami. This paper describes the extent of coastal mangroves forests in developing countries with previous exposure to tropical cyclones, how mangroves will be affected by climate change, the geographic area and human resources at risk due to loss of coastal protection from mangroves in a changing climate, and the potential for adaptation.

The idea that mangroves may protect coastal communities from coastal hazards (coastal erosion, tidal bores, wind and salt spray, cyclones, etc.) is well known in tropical coastal ecology and increasingly by coastal managers (UNEP-WCMC 2006). Various modeling and mathematical studies have shown that mangrove forests can attenuate wave energy (Massel et al. 1999; Mazda et al. 2006; Quartel et al. 2007; Barbier et al. 2008; Zhang et al. 2012; Pinsky et al. 2013; McIvor et al. 2015). However, these studies indicate that the magnitude of the energy absorbed strongly depends on forest density, diameter of stems and roots, forest floor shape, bathymetry, the spectral characteristics of the incident waves, and the tidal stage at which the wave enters the forest. Even though additional studies are needed to define specific details and limits of this protective function, experts and scientists agree that coastal forest belts, if well designed and managed, have the

Authors' names are in alphabetical order. The findings, interpretations, and conclusions expressed in this paper are entirely those of the authors. They do not necessarily represent the views of the International Bank for Reconstruction and Development/World Bank and its affiliated organizations, or those of the Executive Directors of the World Bank or the governments they represent.

¹ Mangroves are salt-tolerant evergreen forests found along sheltered coastlines, shallow-water lagoons, estuaries, rivers or deltas in 124 tropical and subtropical countries and areas.

potential to act as bioshields for the protection of people and other assets against above-mentioned coastal hazards and some tsunamis (FAO 2007). Awareness of the role of mangroves in coastal protection has led to large-scale programs to rehabilitate and replant mangroves in countries like Vietnam and the Philippines as well as small programs in many other countries. A review of 53 nature-based defense projects (including 12 mangrove projects) found that mangroves could be 2–6 times less expensive than the commonly used alternative, submerged breakwaters, for relatively low waves (Narayan et al. 2016).

However, the latest global estimates of the total area of mangroves range only from approximately 137 000 sq. km (Giri et al. 2010) to 150 000 sq. km (Spalding et al. 2010). Over the past century, mangrove forest cover has declined significantly. Although figures are not available for global mangrove forest cover loss over the century, estimates indicate the amount of loss to approximately 35 600 sq. km from 1980 (FAO 2007; Spalding et al. 2010) with an average annual loss rate of 1.04 per cent from 1980 to 2000 and 0.66 per cent from 2000 to 2005. Rates of average loss may have stabilized or declined further between 2000 and 2012 with a few exceptions, mainly in Southeast Asia (Hamilton and Casey 2014).²

Most of this loss is a result of mangrove clearing for aquaculture, tourism, industrial/urban development, or overexploitation of mangrove timber. In addition, urban and industrial pollution has contributed to degradation. While significant losses due to human actions are likely to continue in the future, it is projected that stresses on mangroves may be further aggravated in the twenty-first century due to climate change. Continuation of the present rate of global warming may even threaten the survival of mangroves. Climate change poses a number of threats to mangroves: SLR, rise in atmospheric CO₂, rise in air and water temperature, change in frequency, and intensity of precipitation/storm patterns due to climate change (discussed in Alongi 2008). Among these threats from climate change, SLR has been identified as the greatest challenge (McLeod and Salm 2006).

Historically, mangroves have shown considerable resilience to fluctuations in SLR (Alongi 2008). However, their adaptation to future SLR depends on their success in landward progression and is conditioned by the availability of adequate and suitable space for expansion/migration, continued supply of sediment and nutrients from freshwater inflows, and a rate of SLR that is not greater than the rate at which mangroves can migrate (McLeod and Salm

2006). The ability of mangroves to migrate landward, in turn, is determined by local conditions, such as topography (e.g., steep slopes) and, perhaps more importantly, infrastructure (e.g., roads, agricultural fields, dikes, urbanization, seawalls, and shipping channels). If inland migration or growth cannot occur fast enough to compensate for the rise in sea level, then mangrove areas will become progressively smaller with each successive generation and may perish.

On the other hand, as the climate changes during the twenty-first century, larger storm surges are expected in cyclone-prone coastal areas (Bender et al. 2010; Knutson et al. 2010; Lin et al. 2012; Knutson et al. 2013; Lin and Emanuel 2016). The scientific evidence indicates that cyclone-induced storm surges will intensify for two reasons. First, they will be elevated by a rising sea level as thermal expansion and ice-cap melting continue.³ Second, the current scientific consensus holds that a warmer ocean is likely to intensify cyclone activity and heighten storm surges.⁴ As storm surges increase, they will create more damaging flood conditions in coastal zones and adjoining low-lying areas. If mangroves can migrate inland with a possible retreat of the coastline, then they will still provide coastal protection even in a changing climate. However, if mangroves cannot migrate inland or if migration of mangroves is at a risk, then they may not continue to provide coastal protection services in a changing climate.

In this paper, we present coastal mangrove area estimates by country, quantify coastal protection services of mangroves in the current climate, and under a future climate scenario out to 2100 with a 1-m SLR and 10 % intensification of storms. The impact of climate change is compounded by the loss of mangroves due to SLR and the inability of some mangroves to migrate to suitable higher ground. We also estimate the coastal population and GDP at risk due to loss of coastal protection from mangroves, and the potential for adaptation. It should be noted that previous studies on climate change and the future of the world's mangrove forests did not quantify the exposure area and human resources at risk from the loss of

² Data for extended periods are available for some countries. For example, coastal development in the Philippines has led to more than a 50 % loss of mangroves since 1900, mainly due to conversion for aquaculture (Primavera 2005).

³ For example, see Jacob et al. (2012). The most recent evidence suggests that sea-level rise could reach 1 m or more during this century (Gillet-Chaulet et al. 2012; Hansen et al. 2015; Hay et al. 2015; DeConto and Pollard 2016).

⁴ Cyclones get their power from rising moisture, which releases heat during condensation. As a result, cyclones depend on warm sea temperatures and the difference between temperatures in the ocean and the upper atmosphere. At present, an increase in sea-surface temperature is strongly evident at all latitudes and in almost all ocean areas. If global warming increases temperatures at the earth's surface but not the upper atmosphere, it is likely to provide tropical cyclones with more power (Emanuel et al. 2008). A sea-surface temperature of 28 °C is considered an important threshold for the development of major hurricanes of categories 3, 4 and 5 (Knutson and Tuleya 2004).

mangroves' cyclone protection function in a changing climate (for example see Quartel et al. 2007; McIvor et al. 2012; Sheng et al. 2012; Zhang et al. 2012). This paper is a step forward in that direction.

The focus of our analysis is on the most vulnerable countries where coastal protection from mangroves is potentially the most important. Hence the scope of the paper is restricted to developing countries in four regions—East Asia–Pacific, South Asia, Africa and Latin America, and Caribbean—where most mangroves occur, and in those regions, only to those countries with previous exposure to tropical cyclones. This coverage accounts for more than 50 % of global mangroves.⁵

MATERIALS AND METHODS

Data

For our analysis, we have used the best available spatially disaggregated global datasets from various sources, including Giri et al. (2010), National Aeronautics and Space Administration (NASA), the Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise (DINAS-Coast) project, Land Scan 2005 and UNISDR (2011). In particular:

- Information was provided by Giri et al. (2010) on the extent and distribution of mangroves from the global mangrove databases of the USGS: Earth Resources Observation and Science Center. In this database, the status and distributions of mangroves were mapped using the 30-m resolution global land survey (GLS) data for 2000 supplemented by the Landsat archive.
- In order to estimate coastal mangrove areas by country, we extracted vector coastline masks from Shuttle Radar Topography Mission (SRTM) version 2 Surface Water Body Data provided by NASA, and used the country and region identifiers used by the World Bank. Country boundaries along with mangrove data were used to estimate the extent of coastal mangrove forests, by country. We restricted our analysis to countries with previous exposure to tropical cyclones.⁶ A total of 46 countries meet the criteria for inclusion in this study (For country coverage, see Table 1). While other countries have mangrove forests, the absence of

cyclones makes their storm protection service less important.

- In order to estimate the impact of SLR on mangroves and the potential for adaptation, we use the wetland migratory potential (WMP) characteristic in the DIVA database from the DINAS-COAST project (Vafeidis et al. 2008). WMP indicates the potential for wetlands, including mangroves, to migrate landward in response to a 1-m rise in SLR. The migratory potential is based on a few geophysical characteristics of the coastline: coastal type, topography, tidal range, and other information when available (e.g., whether mangroves are associated with an island or mainland coast), as described in Hoozemans et al. (1993).⁷ Five possible responses to SLR, or categories of wetland migratory potential (WMP), were defined for the DIVA database:
 - WMP1: No change or no significant change;
 - WMP2: A retreat of the coastline with inland migration of coastal ecosystems;
 - WMP3: A retreat of the coastline without the possibility of inland migration;
 - WMP4: A possible retreat of the coastline but increase of flooding area behind the coastline (“ponding”); and
 - WMP5: Total loss of the coastal ecosystem.
- The assessment of population and economic activity at risk from storm surges and loss of mangroves in a changing climate, extracts databases at the 1 km level of population from Landsat 2005 (Bright et al. 2006) and of GDP 2005 from the UNISDR (2011). The population estimates are the result of a spatial allocation of population derived from census and other covariates (for details see Dobson et al. 2000). The GDP data are the result of a spatial allocation model that combines subnational GDP at the administrative level that includes over 74 countries with Landsat population data. Within a subnational or national administrative unit with GDP, the total subnational GDP is allocated on a per capita basis with rural and urban strata, assuming the latter to have a higher GDP per capita (for details see UNISDR 2011).⁸

⁵ 58 % if the Giri et al. (2010) estimate of global mangroves is used and 53 % if the Spalding et al. (2010) estimate is used.

⁶ The Tropical cyclones surges (1975–2007) data are available for download from UNEP-PREVIEW, Genève (2009) at: <http://preview.grid.unep.ch>.

⁷ The migratory potential of mangroves also depends on a wide range of additional factors that are site-specific and highly variable; such as the continued flow of sediment and nutrients from inland stream. Such detailed information was not available on a global scale.

⁸ We agree with the anonymous reviewer of the paper that HDI, genuine savings/wealth are alternative indicators of human well-being, however these indicators are not currently available for all countries at a subnational level. Once these data are available at a subnational level, the methodology can be extended to include new indicators of human well-being in the future.

Table 1 Name and number of countries in regions that met the criteria for this study

Region	Countries
East Asia and Pacific (18)	China, Fiji, Hong Kong SAR, Indonesia, Macao SAR, Micronesia, Myanmar, Palau, Papua New Guinea, Philippines, Samoa, Solomon Islands, Taiwan (China), Thailand, Timor-Leste, Tonga, Vanuatu, Viet Nam
Latin America (20)	Antigua and Barbuda, Belize, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Grenada, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, Rep. Bol. De Venezuela
South Asia (4)	Bangladesh, India, Pakistan, Sri Lanka
Sub Saharan Africa (4)	Comoros Islands, Madagascar, Mozambique, Seychelles

Methods

Our analysis primarily uses geographic information system-based techniques.

Estimates of coastal area

In order to estimate coastal mangrove areas by country, we extracted vector coastline masks from SRTM version 2 surface water body data provided by NASA, and used the country and region identifiers used by the World Bank. Country boundaries along with mangrove data provided by Giri et al. 2010 were used to estimate the extent of coastal mangrove forests, by country.

Coastal protection service of mangroves

The flow of water through the mangrove forest during natural disaster is obstructed by the matrix of roots/trunks of the mangrove trees, which creates bed resistance. Hence, mangroves can substantially reduce vulnerability and risk from wind waves and storm surges,⁹ providing “natural protection.” Factors affecting the decline of wave height include cross-shore distance, tree density, stem and root diameter, shore slope, bathymetry, spectral characteristics of incident waves, and tidal stage upon entering the forest (For example, see Alongi 2008; Massel et al. 1999). In a cross-country study like the one presented in this paper, specifying location-specific bathymetry, mangrove species (their allometric characteristics: trunk width, root system and leaf area, which determines the extent of bed resistance to the flow of water from storm surges), forest density, and forest width is beyond the scope of the analysis. Instead, we estimated the coastal protection services of mangroves using the algorithm described below:

1. The storm surge inundation zone protected by mangroves is derived from the inundation zone modeled

for an extreme 100-year return period storm surge¹⁰ with mangroves and a storm surge zone without mangroves (the counterfactual). The inundation area protected by mangroves (mangrove protection zone) is only calculated upstream of an area of mangroves greater than 3 arc seconds (90 sq. m) that matches the resolution of the global SRTM.

$$SS_PA = SS * wave_n - SS * wave_m$$

where SS_PA refers to the storm surge inundation area that is protected, SS refers to the 1 in 100 surge height in meters, *wave* refers to the wave attenuation function, *n* refers to without mangrove and *m* refers to with mangrove.

2. For storm surge areas without mangroves, a linear distance decay of waves of 6.3 cm/km, where *d* is the distance in meters, was adapted from observational data summarized in McIvor et al. (2012) for salt marsh:

$$wave_n = \left(\frac{0.063 \text{ m}}{1000 \text{ m}} \right) * d$$

3. For areas with mangroves, using estimates from Zhang et al. (2012), the wave reduction is derived from the following:

$$wave_m = 80 * \exp(-0.3375 * d) + 16.75$$

4. The total of the cumulated wave reduction in meters calculated from step 2 and step 3 above and elevation above sea level was subtracted from the storm surge wave height. If the result is positive, it is marked as an area of inundation.
5. The above-mentioned computation was conducted for each grid cell.
6. Finally, the GIS modeling approach in ESRI ArcGIS used a cost-distance (path distance) function that accumulates the least-cost path planimetrically across each cell (wave height) to adjust for direction and elevation.

⁹ Storm surge refers to the temporary increase in the height of the sea level due to extreme meteorological conditions: low atmospheric pressure and/or strong winds (McIvor et al. 2015).

¹⁰ A 100 year storm surge has a 1 % chance of occurring in any given year.

Assessing the impact of SLR on mangroves

We use the WMP characteristic of the coastline from Vafeidis et al. (2008) to estimate the impact of SLR on mangroves and the potential for adaptation. Among the five WMP categories, mangroves in WMP category 3 cannot migrate landward in response to a 1-m rise in SLR. Mangroves in category WMP 4 are at great risk and will be severely degraded and may perish if the flooding behind the coastline is severe and persists long enough to seriously disrupt the flow of freshwater and nutrients to mangroves. Therefore, to assess the expected loss of mangroves due to 1-m rise in SLR, our focus is on mangroves in categories WMP 3 and WMP 4.

For the Geographic overlays of mangroves with the WMP characteristics, we had to make the following adjustments: (i) Due to mismatch of coastline boundaries in DIVA and SRTM, the DIVA database was spatially joined to watersheds delineated from HydroSHEDS (Lehner et al. 2008) to allow the connection between the DIVA coastline and SRTM coastline; (ii) For more complete coverage, the HydroSHEDS-adapted DIVA data are extended via the closest HydroSHEDS grid cell (via the ESRI ArcGIS Expand command) in areas with mangroves and areas where the 450 sq. m grid of HydroSHEDS and the 90 m coastline do not overlap; (iii) In some areas due to a data constraint, the mangroves are well outside the HydroSHEDS coastline and given a WMP value of NA; (iv) Elevation of mangroves is considered 0 m above sea level.

Coastal protection services of mangroves at a risk in a changing climate

Climate change is likely to expand the storm surge inundation areas due to a combination of three effects: (i) SLR, (ii) heightened surges from more powerful storms, and (iii) loss of protection (wave attenuation) from mangroves. In order to understand the specific impacts of SLR, storm intensification and loss of mangroves on surge inundation, we conducted our computation in two steps.

In step 1, we estimated the impacts of 1-m SLR and a 10 % increase in storm intensity (*assuming no loss of existing mangroves*) on the surge inundation area using data and methods described in Dasgupta et al. (2011) and Brecht et al. (2012) as follows:

- Storm surge zones are defined as locations that would be inundated by a given wave height, assuming the SRTM value represents ground elevation and there are no coastal protection measures.
- In the absence of a scientific consensus on where tropical storms will or will not intensify, and by how

much, we follow Nicholls (2010) and Hanson et al. (2011), with a baseline assumption of a 10 % increase in storm surges/extreme water levels for the 1-in-100 year event.¹¹

- In the calculation of storm surges (wave heights or extreme sea levels), we follow the method outlined by Hanson et al. (2011) where future storm surges are calculated as follows:

$$\begin{aligned}\text{Future storm surge} = & S100 + SLR \\ & + (\text{UPLIFT} * 100 \text{ year})/1000 \\ & + \text{SUB} + S100 * x\end{aligned}$$

where S100 is the 1-in-100-year surge height (m), SLR is the sea-level rise (1 m), UPLIFT is continental uplift/subsidence in mm/year, SUB is 0.5 m (applies to deltas only), and x is 0.1 (increase of 10 %) applied only in coastal areas currently prone to cyclone/hurricane.

- Finally, we apply the wave height calculated for the coastline segment closest to a drainage basin outlet to inland areas within that basin. We use mangrove and non-mangrove wave attenuation functions in estimating wave height for inland cells.

Thereafter in step 2, we estimated the additional impact on inundation area due to loss of mangroves with geographic overlays of the surge zone from step 1 with decline in storm surge protection associated with mangroves WMP 3 and WMP 4 categories.

To assess the vulnerability of population and GDP within a coastal zone from storm surges under climate change—in the areas where mangroves may provide some protection—we overlay information on the number of people from Landsat 2005 and GDP for 2005 from the UNISDR (2011) databases with the geographic area vulnerable to storm surges due to the loss of mangroves.¹² At the outset, it should be noted that no projections were made of population or GDP for 2100 in coastal zones; the analysis of human resources protected by mangroves uses baseline 2005 data. The estimates also do not include the additional areas and resources at risk that are not upstream of any mangroves.

¹¹ We acknowledge that the assumption of 10 % increment is conservative, as a review of the regional studies of storm surges reveals predictions of storm surge height in 1-in-100 year events that are generally above 10 %. See Brecht et al. (2012) for sensitivity analysis.

¹² We used ESRI ArcGIS 10.1 Geographic Information Systems (GIS) to extract the sum of the values of the population and GDP models that intersect the storm surge exposure areas.

RESULTS

Area estimates of coastal mangroves in developing countries with previous exposure to tropical cyclones

Our estimates indicate mangroves in developing regions with previous exposure to tropical cyclones covered an area of 79 756 sq. km during 1997–2000. The largest area of mangrove was in East Asia & Pacific (57 %), followed by the Latin America and Caribbean (26 %), South Asia (11 %), and Sub-Saharan Africa (6 %). The top 10 out of the 46 countries account for a total of 80 % of mangroves area (See Table 2). Indonesia has by far the single largest mangrove area (33 % of the total); the remaining top 10 countries account for fewer than 10 % each.

We compared our country-level estimates (which are aggregated from 30 to 90 m) with the country-level mangrove estimates of the Mangrove Atlas (Spalding et al. 2010). All our estimates were within 95 % range.

Coastal protection service of mangroves

The estimates of area benefiting from storm surge attenuation by mangroves are expected to vary among the 46 countries due to variations between countries in (i) the 1-in-100 storm surge height, (ii) the extent of mangroves, and (iii) elevation of the vulnerable zone. Our findings indicate that the surge protection benefits from mangroves are more evenly distributed among regions than the distribution of the mangroves (Fig. 1). For example, while

East Asia has 56 % of mangroves in our study area, 29 % benefit from storm surge attenuation from mangroves. On the other hand, South Asia has 11 % of the mangroves but 36 % benefit from surge protection.

For the top 10 countries with mangroves listed in Table 2, estimates of area that would be subject to storm surge if there were no mangroves and the reduction in surge area due to the presence of mangroves are summarized in Table 2.

Assessing the impact of SLR on mangroves

In the DIVA database, no mangroves occur in areas with the most extreme responses, WMP 1 or WMP 5 (other wetlands may fall in these categories). Geographic overlays of mangroves with the WMP characteristics of the coastlines from the DIVA database indicates across our study area, the vulnerability of mangroves varies a great deal by region and by country. South Asia has 93 % and Sub-Saharan Africa has approximately 100 % of mangroves that are in WMP category 2, with great potential for migration. In East Asia & Pacific, most mangroves (77 %) have the potential to migrate and survive, but in Latin America & Caribbean, only 43 % of mangroves have the potential to migrate; most are extremely vulnerable, with 29 % in WMP3 and 28 % in WMP4, and likely to be lost.

Table 3 shows vulnerability of mangroves to SLR in the 10 tropical cyclone-prone countries with the largest mangrove area. Our estimates assign the highest vulnerability to Mexico, where SLR is likely to destroy 100 % of coastal mangroves. Other countries where climate change will

Table 2 Coastal protection from storm surges due to mangroves in the top 10 mangrove countries under current climate conditions. *Source* Table and authors estimates described in the text

Countries	Mangrove area (sq km)	Percent of total area (%)	Storm surge area without mangroves (sq km)	Storm surge area with mangroves (sq km)	Reduction in area subject to storm surge due to mangroves (%)
Indonesia	26 705	33	37 904	27 865	27
Mexico	6 358	8	12 819	6 478	50
Myanmar	4 935	6	7 873	5 612	29
Papua New Guinea	4 705	6	5 123	4 763	7
Bangladesh	4 290	5	4 849	4 365	10
Cuba	4 241	5	5 724	4 463	22
India	3 821	5	7 875	4 159	47
RB Venezuela	3 309	4	3 928	3 398	14
Mozambique	2 891	4	4 076	3 071	24
Philippines	2 482	3	3 947	2 849	28
Remaining 36 countries	16 019	20	23 952	16 856	30
Total	79 756	100	118 070	83 879	29

Fig. 1 Distribution of total mangrove area and distribution of total area protected by mangroves by region *Source* Figure 1 and authors estimates described in the text.

Table 3 Mangrove area and wetland migratory potential in top 10 mangrove countries. *Source* Authors' estimates as described in the text

Rank and Region	Total mangrove area (sq km)	Mangrove area by Wetland migratory potential (percent of total mangrove area)	
		Percent of mangroves in WMP2 (%)	Percent of mangroves in WMP 3 & 4 (%)
1 East Asia & Pacific	45 119	77	23
2 Latin America & Caribbean	20 636	43	57
3 South Asia	8 803	93	7
4 Sub-Saharan Africa	5 197	~100	<1
Total	79 756	71	29
Rank and Country			
1 Indonesia	26 705	83	17
2 Mexico	6 358	0	100
3 Myanmar	4 935	73	27
4 Papua New Guinea	4 705	69	31
5 Bangladesh	4 290	99	1
6 Cuba	4 241	99	1
7 India	3 821	91	9
8 RB Venezuela	3 309	41	59
9 Mozambique	2 891	100	0
10 Philippines	2 476	15	85
... All other countries	16 019	71	29

Notes Mangroves in WMP 2 are potentially capable of migration; those in WMP 3 & 4 are not able to migrate

severely threaten the existence of mangroves include Philippines (85 %), Venezuela (59 %), Papua New Guinea (31 %) and Myanmar (27 %).

It should be noted that due to the spatial differences in the datasets, approximately 4 % could not be reliably mapped into WMP categories (2, 3 or 4) directly, so the remaining mangroves are allocated to the country level by proportions.

Coastal protection services of mangroves at a risk in a changing climate

The joint impacts of SLR and increased storm intensity on inundation area in a changing climate are summarized in Table 4. Estimates indicate relatively modest increase in the inundation area from 84 222 to 86 257 sq. km, or by 2

Table 4 Impact of climate change on storm surge area: increase due to SLR, storm intensification, and loss of mangroves. *Source* authors' estimates as described in the text

	Area exposed to storm surge, Sq km			
	Area exposed under current climate and mangrove cover (1)	Area exposed due only to SLR plus storm intensification (2)	Area exposed due to all climate change effects: SLR, storm intensification, and partial loss of mangroves due to the lack of migratory potential (3)	Percent increase in storm surge area under all climate change effects (4)
Regions				
Sub-saharan Africa	5 483	5 605	5 647	3 %
East Asia & Pacific	48 090	48 849	57 380	19 %
Latin America & Caribbean	21 237	22 078	34 263	61 %
South Asia	9 412	9 727	12 927	37 %
Total	84 222	86 259	110 218	31 %
Top 10 Mangrove countries				
Indonesia	27 865	28 177	30 203	8 %
Mexico	6 478	7 115	17 675	173 %
Myanmar	5 612	5 722	7 147	27 %
Papua New Guinea	4 763	4 774	5 027	6 %
Bangladesh	4 365	4 411	4 520	4 %
Cuba	4 463	4 572	4 572	2 %
India	4 159	4 303	7 108	71 %
RB Venezuela	3 398	3 423	3 630	7 %
Mozambique	3 071	3 181	3 181	4 %
Philippines	2 849	2 978	4 782	68 %
Subtotal	67 023	68 656	87 845	31 %
All other countries	17 199	17 603	22 373	30 %
Total	84 222	86 259	110 218	31 %

Note Column 1 represents the area under current climate condition with all the mangroves intact. Column 2 is a partial estimate of the impact of climate change that takes into account SLR and storm intensification but it does not include the likely loss of mangroves due to the lack of migratory potential described in “Discussion” section. Column 3 is the full impact of climate change on inundation area taking into account SLR and storm intensification (column 2) plus the likely loss of flood protection as mangroves in categories WMP 3 and 4 fail to migrate. Column 4 is calculated from Columns 1 and 3

% globally (Table 4). No region is severely impacted from SLR and increased storm intensity alone, although relative vulnerabilities of the countries differ. For example, surge inundation area of Mexico is estimated to increase by 10 %.

However, the vulnerability from SLR and the increased storm intensity increase dramatically when we estimate the combined impacts of all three climate change effects: SLR, storm intensification and loss of mangroves from the lack of migratory potential (WMP3 and WMP4) (Table 4, column 3). For the 46 countries considered in this study, the total storm surge inundation area is expected to increase by 31 % from 84 222 to 110 218 sq. km, and all the regions will be adversely affected. Among the regions, Latin America and Caribbean are the most affected: the inundation area is expected to increase by 61 %. Among the countries, once again a wide variation of impacts is observed: increase ranging from Cuba (2 %), Bangladesh

and Mozambique (4 %), Papua New Guinea (6 %) to India (71 %), and Mexico (173 %). Therefore, our estimates clearly point out that while in a changing climate, SLR and increased storm intensity will affect storm surge areas, the greatest impact is expected from the loss of mangroves.

Our estimates further indicate that under current climate and mangrove coverage, 3.5 million people and GDP worth roughly US \$400 million are at risk, partially protected by mangroves. Under the future impacts of climate change, resources at risk increase significantly, where GDP at risk increases nearly threefold and population at risk more than doubles (Table 5; Fig. 2). These risks are especially acute in Latin America and Caribbean and East Asia. Densely populated South Asia has an increase of 60 and 70 % for population and GDP, respectively. Although the top ten countries have a large share of the current total exposure of resources at risk, the exposure under the future impacts of

Table 5 GDP and population exposed to storm surges under current climate and future climate change effects (GDP: estimates value of production in thousand constant US\$ in 2005; Population: number of persons in 2005). *Source* authors' estimates as described in the text

	Exposure under current climate and mangrove cover		Exposure under all climate change impacts: SLR, storm intensification and loss of some mangroves		Percent increase under climate change effects	
	GDP	Population	GDP	Population	GDP (%)	Population (%)
Region						
Sub-saharan Africa	724	31 037	805	34 236	11	10
East Asia & Pacific	286 211	2 757 953	1 015 435	5 726 135	255	108
Latin America and Caribbean	84 748	275 198	280 265	617 656	231	124
South Asia	33 498	487 176	52 957	832 433	58	71
Total	405 181	3 551 364	1 349 461	7 210 461	233	103
Top 10 Mangrove countries						
Indonesia	123 281	1 519 155	148 176	1 877 974	20	24
Mexico	33 120	70 801	199 557	325 256	503	359
Myanmar	1 888	110 040	5 854	298 858	210	172
Papua New Guinea	1 337	33 464	1 576	40 311	18	20
Bangladesh	922	30 052	1 762	62 613	91	108
Cuba	5 872	17 512	6 207	18 632	6	6
India	27 585	376 498	43 127	656 620	56	74
RB Venezuela	21 813	53 750	35 057	83 693	61	56
Mozambique	497	21 446	528	22 771	6	6
Philippines	28 819	447 748	106 925	1 355 247	271	203
Subtotal	245 134	2 680 466	548 769	4 741 975	124	77
All other countries	160 047	870 898	800 693	2 468 486	400	183
Total	405 181	3 551 364	1 349 461	7 210 461	233	103

climate change for the remaining countries increases nearly fourfold for population and more than doubles for GDP. Among the top ten countries, the population of Indonesia and the Philippines are most at risk under all climate change impacts, but Mexico and Myanmar along with the Philippines will also experience large increases in vulnerability of population and GDP.

DISCUSSION

Overall, our findings are in line with the common wisdom that mangroves can substantially reduce vulnerability of the adjacent coastal land from storm surge inundation.¹³ As expected, we also find areas benefiting from storm surge

attenuation by mangroves vary across countries due to variations in the storm surge height, the extent of mangroves and elevation of the vulnerable zone between countries. Our estimates for the 1-in-100 storm surge height for 46 countries with previous exposure to cyclones covered in this study further indicate that extensive mangrove coverage does not always result in wide coastal protection. Although most of the countries with extensive mangroves benefit from significant reductions in storm surge that can be attributed to their mangrove forests, there are several notable exceptions where mangroves reduce the inundation area by less than 15 %. Papua New Guinea (7 %), Bangladesh (10 %), and Venezuela (14 %) are illustrative examples. In contrast, while not in the top 10 of mangrove coverage, there are a number of additional countries with significant mangrove coverage (at least 1000 sq. km) and benefit considerably achieving at least a 25 % reduction in the surge inundation. China (84 %), Vietnam (54 %), Pakistan (58 %), Nicaragua (45 %), and Honduras (35 %) are illustrative examples. These findings illustrate the importance of careful review of the site selection for mangrove plantation to achieve effective coastal protection, as well as careful consideration in converting existing mangroves to other land uses.

¹³ Some researchers, who are skeptical about the ability of mangroves to protect against tsunamis, have noted that mangroves might be more capable of protecting against tropical storm surges (Chatenoux and Peduzzi 2007). Storm surges differ from tsunamis in having shorter wavelengths and relatively more of their energy near the water surface (McIvor et al. 2015). Theoretical models indicate that mangroves attenuate shorter waves more than longer waves (Masset et al. 1999); and field experiments confirm that relatively narrow strips of mangroves can substantially reduce the energy of wind-driven waves (Mazda et al. 2006).

Fig. 2 Increase in storm surge area, GDP, and population at risk under climate change by region *Source* Tables 4 and 5

In the past, a number of studies have predicted the future of the world's mangrove forests in a changing climate with local, regional, and global forests ranging from extinction to no or little change in area coverage. Our estimates confirm significant loss of mangroves in many countries with 1-m rise in the sea level. In our study, we used the WMP characteristics of the coastlines (Vafeidis et al. 2008) to quantify the impact of SLR on mangroves and their potential for adaptation. Geographic overlays of mangroves with the WMP characteristics indicate across our study area, 71 % of the mangroves fall under WMP 2 (57 003 sq. km), where there is a potential for mangroves to migrate inland with a 1-m SLR. Another 29 % of mangroves fall into categories WMP3 and WMP4 (22 753 sq. km), in which climate change will seriously compromise the existence of mangroves. Category 4 mangroves account for the 18 % of mangrove area where survival of mangroves is possible but at risk depending on local conditions. Category 3 mangroves account for the remaining 9 %; these mangroves are the most vulnerable to SLR and are likely to be lost. However, we acknowledge that as pointed out by many previous research—understanding the location-specific impact of SLR on mangroves must take into account local factors that affect the ecological dynamics of the ecosystem, such as the history of sea levels in regard to development of coastal gradients, relative geomorphic and sedimentologic homogeneity of the coast, coastal processes including tidal range and its stability, density of mangroves, availability of freshwater and sediment, and salinity of soil and groundwater (Kumura et al. 2010). Our knowledge from the cross-country analysis like the one presented in this paper with the wetland migratory potential of the publicly available DIVA database remains far from

complete and quantification of location-specific loss deserves further analyses.

Even though quantification of the expected vulnerability is especially critical, previous studies did not quantify the exposure area and the human resources at risk from the loss of mangroves' cyclone protection function in a changing climate. As it is virtually certain that SLR will continue beyond 2100 even if greenhouse gas emissions are stabilized today, this paper is a step forward in that direction.

The change in vulnerability of GDP and population to storm surge across countries also depends on many local factors, especially on the extent of coastal development. Our findings indicate although the increase in the storm surge area in a changing climate is relatively similar for all regions—between 50 and 100 % (Table 4)—the increase in GDP affected ranges from 11 % in Africa to more than 250 % in East Asia, and vulnerable population increases by 10 % in Africa and by 124 % in Latin America (Table 5).

At the outset, we acknowledge the following limitations in this analysis; some may have led to an overestimation of the coastal protection service, while other results may have led to an underestimation or an unknown bias. Factors that may overestimate coastal protection include the likely loss of mangroves since the reference year 2000 and the lack of local characteristics in the mangrove presence and absence database.

Conversely, factors that may underestimate coastal protection and resources at risk include geographic limitations of the data, elevation measurement error, a lack of GDP and population estimates to 2100, and the conservative estimates from direct exposure. With regards to geographic limitation, some small-island nations in Africa,

Asia and the Pacific, and Latin America are not included in our analysis due to lack of data. The elevation data (SRTM) has measurement error due to signal interference from surface features such as dense canopy (or high forest cover percent see Shortridge and Messina 2011) and built-up environments, which would under estimate risk by overestimating height. For exposure estimates, we used 2005 data for population and GDP in absence of reliable country-specific projections of coastal population and GDP out to 2100; we did not consider potential growth in the coastal economies over time. Direct exposure estimates for calculating vulnerable population and GDP are also conservative estimates and do not consider the losses from proximity or network effects due to mangroves at risk (e.g., the economic loss generated from the flows on the impacted transportation network).

Finally, we do not know if there is any positive or negative bias introduced by the following: rounding of elevation data, spatial allocation methods, and the functional form of the distance decay function. The unit of measurement for the SRTM data is meters and the rounding may introduce a positive or negative bias. Spatial allocation methods used for estimating population and economic activity in coastal areas have infrastructure and land cover information in the model (e.g., Bright et al. 2006) and may have bias at the local level. The literature has limited information on the functional form of the distance decay function of waves and it was adapted from available sources for mangroves and salt marshes.

The other major limitation of this approach is that the potential for migration is only the first step toward understanding whether mangroves will actually migrate or not. Mangroves are already under severe pressure from conversion for aquaculture and tourism, overcutting, pollution, and other factors. Mangroves have been lost in many areas and are severely degraded in others. Many mangrove forests may not survive to 2100, regardless of the impact of climate change. For those forests that do survive, demographic, economic, and other factors may block migration, even where the ecological conditions would make it possible. Coastal areas are the most densely populated parts of the globe, with many large, rapidly expanding urban areas; competition for space is fierce. Also, many of the rural poor live in the low-elevation coastal zone (Barbier 2015). Therefore, preserving and cultivating mangroves as a source of coastal defense will require addressing competing land uses, which is beyond the scope of this study.

CONCLUDING REMARKS

This paper estimates the contribution of mangroves to coastal protection from cyclonic storm surges in many

tropical countries at risk. We quantified the exposure of coastal areas to population and GDP from SLR, increased storm intensity, and loss of mangroves. The results show that while in a changing climate SLR and increased storm intensity will affect storm surge areas, the greatest impact is expected from the loss of mangroves. By 2100, in a changing climate with 1 m SLR, approximately 29 % of mangroves are likely to be lost, but 71 % may migrate and continue to provide coastal protection.

Even though the threat of mangrove loss is substantial with climate change, the potential for adaptation of mangroves to SLR by natural or assisted migration is also considerable. Historical evidence suggests mangroves generally adapt to gradual SLR (Alongi 2008). However, the recent rapid growth of population and economic activities in coastal regions poses challenges for mangroves to migrate. Natural migration will be successful only if mangroves are not blocked by other land uses and SLR is not faster than the natural migration rate. In other areas where natural migration of mangroves is not feasible, assisted migration, afforestation, replanting and rehabilitation of mangroves in appropriate places are feasible alternatives.

Experiences to date of assisted migration of mangroves can inform decision makers into the successes and challenges of these activities such as site selection and design, cost and land use. Although past efforts at replanting or rehabilitating mangroves have had mixed success,¹⁴ there have been many successful attempts to plant or rehabilitate mangroves in Asia and East Africa, including a large-scale effort in many countries affected by the 2004 tsunami (UNEP-WCMC 2006). In the past, many afforestation or restoration and rehabilitation efforts failed because of the selection of inappropriate species and poor site selection. Mangroves were often planted in lower intertidal or subtidal zones, where mangroves do not naturally occur, because more suitable land was not available (Lange et al. 2010). Project failures in the past will offer insight into what to avoid in the future. In general, site-specific design improves the likelihood of successful mangrove interventions (IWM 2000).¹⁵ These studies indicate that the forest site must be planned carefully with the consideration of mangroves in combination with “hard” infrastructure, because site-specific characteristics greatly influence the extent of storm protection.

The costs of afforestation and replanting mangroves can also vary significantly. For example, Primavera and Esteban (2008) report average planting costs in the Philippines

¹⁴ For example, Primavera and Esteban (2008) found mixed results reviewing efforts in the Philippines.

¹⁵ For a list of mangrove resilience factors that inform site selection, see McLeod and Salm (2006, pp. 20–21).

that are over US \$500/ha and do not include the costs of purchasing land. The Ramsar Secretariat, which is quoted in Gilman and Ellison (2007), reported a range of costs per hectare from US \$225 to US \$216 000, depending on the amount of rehabilitation needed.

We acknowledge that one major obstacle to assisted mangrove migration may come from competing land uses. Large areas of mangrove forests, especially in Asia, were converted for aquaculture, mainly shrimp farming over the past few decades. Many of these farming operations were abandoned after about five years due to disease and loss of profitability, and the operators moved onto new sites (Barbier 2009). Rehabilitation of abandoned aquaculture sites or shrimp ponds (if they are in areas identified as WMP 2) may be suitable for restoring mangroves, because these areas originally had the natural conditions for mangrove habitat. However, one should keep in mind that abandoned shrimp ponds are usually highly degraded with poor quality, compacted acidic soil (Wolanski 2006), and mangroves will not naturally re-colonize these areas until the land is rehabilitated. Barbier (2009) reported costs of US \$8 812–\$9 318 per hectare for rehabilitation, replanting, and maintaining mangrove seedlings.

These costs may seem high yet one should keep in mind that in addition to coastal protection services as highlighted in this paper, mangroves provide many benefits that include the provision of food, timber, wood fuel, medicine, habitat, and nurseries for fish and other wildlife. Mangroves also trap sediment, nutrients, and contaminants to maintain water quality and protect coral reefs (which in turn support fisheries, tourism, and can be even more effective than mangroves for coastal protection). It has also been recognized that mangroves store a much higher amount of carbon per equivalent area than terrestrial forests. Therefore, there is an increasing likelihood that carbon storage by mangroves could be included under REDD+. It is important to take into account all the multiple benefits of mangroves for an appropriate cost benefit comparison of mangrove rehabilitation.

One of the important observations arising from our analysis is the significant variability in the coastal protection services of mangroves due to local conditions. Careful consideration of the location of mangrove protection and mangrove afforestation programs will be critical to achieve maximum benefits. Policy makers and investment planners will benefit considerably from further empirical research on location-specific coastal protection and other services from mangroves.

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