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Mangroves as Protection from Storm Surges in a Changing Climate

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Abstract

Adaptation to climate change includes addressing sea level rise and increased storm surges in many coastal areas. Mangroves can substantially reduce the vulnerability of the adjacent coastal land from inundation and erosion. However, climate change poses a large threat to mangroves. This paper quantifies the coastal protection provided by mangroves for 42 developing countries in the current climate, and a future climate change scenario with a one-meter sea level rise and 10 percent intensification of storms. The benefits of the coastal protection provided by mangroves are measured in terms of population and gross domestic product at a reduced risk from inundation; the loss of benefits under climate change is measured as the increased population and gross domestic product at risk. The findings demonstrate that although sea level rise and increased storm intensity would increase storm surge areas and the amounts of built resources at risk, the greatest impact is the expected loss of mangroves. Under current climate and mangrove coverage, 3.5 million people and roughly $400 million in gross domestic product of are at risk. In the future climate change scenario, the vulnerable population and gross domestic product at risk would increase by 103 and 233 percent, respectively. The greatest risk is in East Asia, especially in Indonesia, the Philippines, and Myanmar.

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1. Introduction

Adaptation to climate change will require living with sea level rise and increased storm surges in many coastal areas (IWTC 2006; IPCC 2013; Rahmstorf 2007; ADB 2008; ScienceNow 2008; Dasgupta and Meisner 2009a; WMO 2010; World Bank 2010a, World Bank 2010b). Coastal protection from storm surge and flooding is partly provided by built infrastructure (Dasgupta et al. 2010; World Bank 2010c; Nicholls et al. 2010). Mangroves[2] 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 mangrove 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 (Chapman, 1976; UNEP-WCMC, 2006; Doney et al. 2012; Waite et al. 2014). Various modeling and mathematical studies have shown that mangrove forests can attenuate wave energy (Brinkman et al., 1997, Mazda et al. 1997, 2006; Massel et al., 1999; Quartel et al., 2007, Barbier et al. 2008, Gedan et al. 2011; Zhang et al. 2012; McIvor et al. 2013; Liu et al. 2013; Pinsky et al. 2013). However, these studies indicate that the magnitude of the energy absorbed strongly depends on forest density, diameter of stems and

[2] 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 (Tomlinson 1986; Ellison and Stoddart 1991). A "mangrove" has been defined as a "tree, shrub, palm or ground fern, generally exceeding more than half a meter in height, and which normally grows above mean sea level in the intertidal zones or marine coastal environments, or estuarine margins" (Duke 1992). The term 'mangrove' describes both the ecosystem and the plant families that have developed specialized adaptations to live in this tidal environment. The mangrove ecosystem represents an inter phase between terrestrial and marine communities, which receive a daily input of water from the ocean (tides) and freshwater, sediments, nutrients and silt deposits from upland rivers. Mangroves may grow as trees or shrubs according to the climate, salinity of water, topography and edaphic features of the area in which they exist.

roots, forest floor shape, bathymetry, 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 the specific details and limits of this protective function, experts and scientists agree that coastal forest belts, if well designed and managed, have the potential to act as bioshields for the protection of people and other assets against the above mentioned coastal hazards and some tsunamis (FAO, 2007; Das and Vincent, 2009; Arkema et al. 2013).

The latest global estimates of the total area of mangroves range 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 be approximately 35,600 square kilometers from 1980 (FAO 2007; Spalding et al 2010), with an average annual loss rate of 1.04 percent from 1980 to 2000, and 0.66 percent 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).[3]

Most of this loss is a result of mangrove clearing for aquaculture, tourism, industrial/urban development, and overexploitation of mangrove timber. In addition, urban and industrial pollution has contributed to degradation. (For example, see Tanaka 1995; Primavera 1997; Wolanski et al. 2000; Saito and Alino 2008; Giri et al. 2008; Feka and Ajonina 2011; Shahbudin et al. 2012; Munji et al. 2014; Nguyen 2014.) 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 21st 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: rise in sea level, rise in atmospheric CO_2, rise in air and water temperature, and change in frequency and intensity of precipitation/storm patterns due to climate change (discussed in Alongi 2008). Among these threats from climate change, sea level

[3] Data for extended periods are available for some countries. For example, coastal development in the Philippines has led to more than a 50 percent loss of mangroves since 1900, mainly due to conversion for aquaculture (Primavera 2005, Primavera et al., 2014). Vietnam's mangrove forests declined about 75% from 1950 to 2000, falling from roughly 400,000 hectares to 100,000 hectares (MONRE 2002).

rise (SLR) has been identified as the greatest challenge (Field 1995; Nicholls et al. 1999; McLeod and Salm 2006).

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 (Woodroffe 1990; Aksornkaoe and Paphavasit 1993; Pernetta 1993; UNEP 1994; Semeniuk 1994; Snedaker 1995; Miyagi et al. 1999; Alongi 2002; Gilman et al., 2006; Mcleod and Salm 2006; Cavanaugh et al. 2013; Osland et al. 2013).[4] However, these studies did not quantify the geographic area and human resources at risk from the loss of mangroves' cyclone protection function in a changing climate. This paper is a step forward in that direction.

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-meter sea level rise and 10 percent intensification of storms. The impact of climate change is compounded by the loss of mangroves due to sea level rise 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. This paper will focus on the most vulnerable countries where coastal protection from mangroves is potentially 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 & 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 percent of global mangroves.[5]

The paper is structured as follows: In Section 2, we estimate the coastal mangrove areas in the countries of our interest; in Section 3, we present the methodology and estimates of coastal protection services of mangroves in the current climate; in Section 4, we assess the

[4] The differences in assessment are mainly due to site differences in coastal position (open coast versus lagoon) and tidal (micro- versus macro-tide) regime (Alongi 2008).

[5] 58 percent if the Giri et al. (201) estimate of global mangroves is used and 53 percent if the Spalding et al. (2010) estimate is used.

vulnerability of mangroves due to sea level rise in a changing climate; in Section 5, we address the coastal protection services of mangroves at risk in a changing climate; and in Section 6, present the limitations of our analysis. Section 7 concludes with a brief discussion of the results.

2. Area Estimates of Coastal Mangroves in Developing Countries with Previous Exposure to Tropical Cyclones

For our analysis, we used information 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 Landsat archives. The GLS 2000 mosaics were prepared using images acquired from 1997 to 2000. Landsat imagery from the USGS archives was used if GLS data were cloudy. While mapping, each image was normalized for variation in solar angle and earth-sun distance by converting the digital number values to the top-of-the-atmosphere reflectance. The results were validated with other existing global, regional and local data sets (for details, see Giri et al. 2010). The USGS database includes a presence or absence grid cells showing the exact location, size, and shape of the mangroves.

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 were used to estimate the extent of coastal mangrove forests, by country. We restricted our analysis to countries with previous exposure to tropical cyclones (UNEP/GRID 2009). A total of 46 countries meet the criteria for inclusion in this study (for country coverage, see Box 1). While other countries have mangrove forests, the absence of cyclones makes their storm protection service less important.

Box 1:

East Asia and Pacific (18): China; Fiji; Hong Kong SAR, China; Indonesia; Macao SAR, China; the Federated States of Micronesia; Myanmar; Palau; Papua New Guinea; Philippines; Samoa; Solomon Islands; Taiwan, China; Thailand; Timor-Leste; Tonga; Vanuatu; Vietnam.

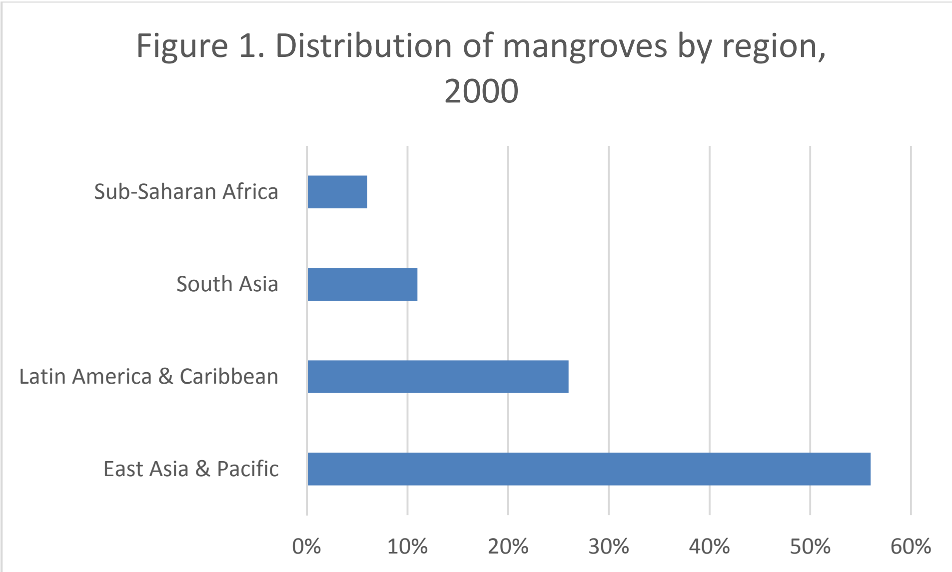
Latin America (20): Antigua and Barbuda, Belize, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Grenada, Guatemala, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Trinidad and Tobago, República Bolivariana de Venezuela.

South Asia (4): Bangladesh, India, Pakistan, Sri Lanka.

Sub-Saharan Africa (4): Comoros Islands, Madagascar, Mozambique, Seychelles.

Our estimates indicate mangroves in developing regions with previous exposure to tropical cyclones covered an area of 79,756 sq. km during 1997-2000. (See Annex 1 for mangrove area by country.) The largest area of mangroves was in East Asia & Pacific (57 percent), followed by the Latin America & Caribbean (26 percent), South Asia (11 percent), and Sub-Saharan Africa (6 percent) (Figure 1). The top 10 of the 46 countries account for a total of 80% of mangrove area (Table 1). Indonesia has by far the single largest mangrove area (33% of the total); the remaining top-10 countries account for less than 10% each.

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



Note: Mangrove distribution is limited to the countries selected for this study as described in the text.

Source: Authors estimates described in the text.

Table 1. Countries with the largest mangrove areas, 2000 (in square kilometers)

Countries	**Area**	**Per cent of total area**
Indonesia	26,705	33%
Mexico	6,358	8%
Myanmar	4,935	6%
Papua New Guinea	4,705	6%
Bangladesh	4,290	5%
Cuba	4,241	5%
India	3,821	5%
Venezuela, RB	3,309	4%
Mozambique	2,891	4%
Philippines	2,482	3%
Remaining 36 countries	16,019	20%
Total	**79,756**	**100%**

Note: these 10 countries account for 80% of mangroves in the study area.

Source: Authors estimates described in the text.

3. Coastal Protection Service of Mangroves

Scientific literature to date emphasizes the role of mangroves in protecting adjacent coastal land from the impacts of inundation and erosion, both during natural disasters and through their longer-term influence on coastal dynamics. The flow of water through the mangrove forest 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,[6] providing "natural protection."[7] A literature review and a meta-analysis of wave and storm surge dampening by wetlands across a variety of storms and locations highlights the critical role of even narrow vegetated wetland sites in attenuating waves (Gedan et al. 2011) as vegetation can cause substantial drag (Pinsky et al. 2013).[8]

The global scientific community has developed models of the wave/storm surge attenuation processes. For example, see Brinkman et al 1997; Mazda et al 1997; Massel et al 1999; Quartel et al 2007; Barbier et al. 2008; Tuyen and Hung 2009; Gedan et al 2010. One of the main factors affecting wave height decline is cross-shore distance (Bao 2011). Other factors include tree density, stem and root diameter, shore slope, bathymetry, spectral characteristics of incident waves, and tidal stage upon entering the forest (Alongi 2008). Massel et al. (1999) presented a theoretical predication model of surface wave attenuation through mangrove forests that identifies key factors in generating drag on a wave from the density and vertical structure (i.e. height) of the mangrove canopy. The literature also has established allometric,[9] latitudinal or

[6] *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 (IPCC AR4 2007).

[7] 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 (Kerr and Baird, 2007; Chatenoux and Peduzzi, 2007). Storm surges differ from tsunamis in having shorter wavelengths and relatively more of their energy near the water surface (Cochard, 2008). Theoretical models indicate that mangroves attenuate shorter waves more than longer waves (Massel 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; Mazda et al. 1997).

[8] The paper further reports that this ecosystem service is context-dependent and exhibits nonlinear characteristics across space and time.

[9] For a review of self-thinning rules see (Berger and Hildenbrandt 2000). The overall maximum biomass, which can be produced per ha, is species-independent and limited to about $9*10^5$ kg ha^{-1}.

climate relationships in order to derive biomass (Saenger and Snedaker 1993, Berger and Hildenbrandt 2000, Simard et al 2006, and Hutchison et al. 2013); biomass then determines the mangrove density (Berger and Hildenbrandt 2000; Mazda 1997) and density finally determines the flow velocities (Horstman et al. 2013) and the wave attenuation function (e.g. Horstman et al. 2012).

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 surge[10] 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).

$$SS\_PA = SS * wave_n - SS * wave_m$$

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:

[10] It is a statistical measure of the average recurrence interval over a long period of time and is the inverse of the probability that the event will be exceeded in any one year. A 100 year storm surge has a 1% chance of occurring in any given year.

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

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

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

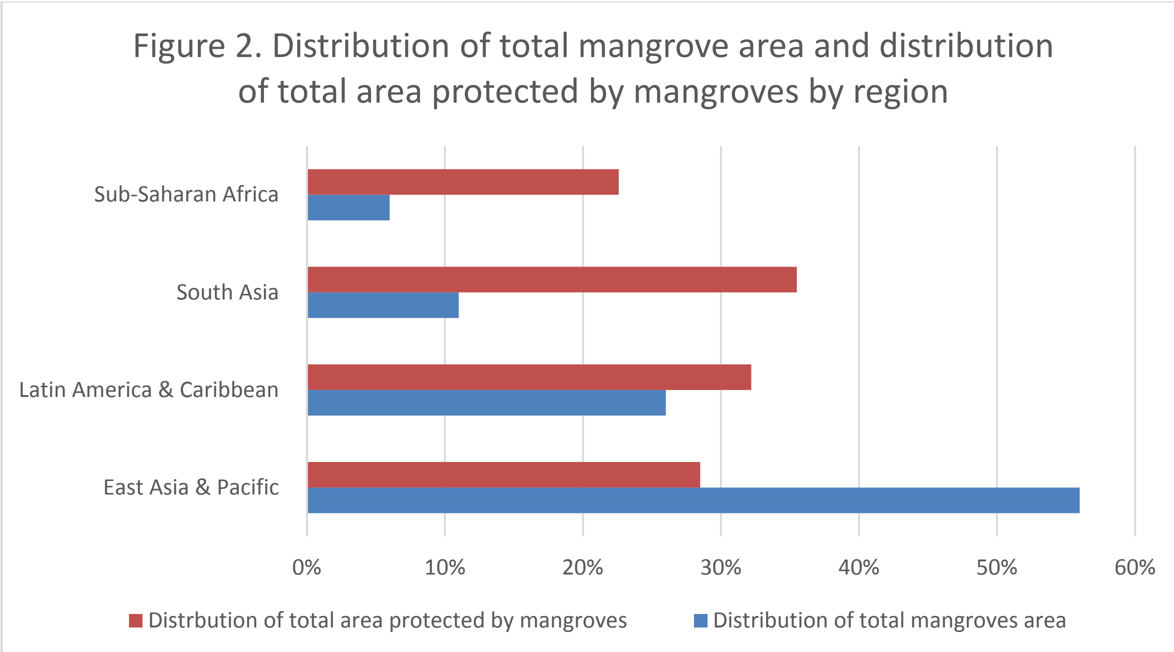
4. The total of the cumulated wave reduction in meters calculated from step 2 and step 3 above and elevation above sea level[11] was subtracted from the storm surge wave height. If the result is positive, it is marked as an area of inundation.

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 planametrically across each cell (wave height) to adjust for direction and elevation.

The resulting estimates of area benefiting from storm surge attenuation by mangroves are expected to vary among the 46 countries due to between-country variations 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 (Figure 2). For example, while East Asia has 56 percent of the mangroves in our study area, 29 percent benefit from storm surge attenuation from mangroves. On the other hand, South Asia has 11 percent of the mangroves but 36 percent benefit from surge protection.

[11] Elevation data are from SRTM, and elevation of mangroves is modified as zero meter above sea level.



Source: Figure 1 and authors estimates described in the text.

For the top 10 countries with mangroves listed in Table 1, 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. (Similar estimates for all countries are listed in Annex 2). It should be noted 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 percent. Papua-New Guinea (7 percent), Bangladesh (10 percent) and República Bolivariana de Venezuela (14 percent) are illustrative examples.

Table 2: Coastal protection from storm surges due to mangroves in the top 10 mangrove countries under current climate conditions

Country	**Mangrove area, sq km**	**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	37,904	27,865	27%
Mexico	6,358	12,819	6,478	50%
Myanmar	4,935	7,873	5,612	29%
Papua New Guinea	4,705	5,123	4,763	7%
Bangladesh	4,290	4,849	4,365	10%
Cuba	4,241	5,724	4,463	22%
India	3,821	7,875	4,159	47%
Venezuela, RB	3,309	3,928	3,398	14%
Mozambique	2,891	4,076	3,071	24%
Philippines	2,482	3,947	2,849	28%
Remaining 36 countries	16,019	23,952	16,856	30%
Total	**79,756**	**118,070**	**83,879**	**29%**

Source: Table 1 and authors estimates described in the text.

In unison, while not in the top 10 of mangrove coverage, there are a number of additional countries with significant mangrove coverage (at least 1,000 square kilometers) that benefit considerably, achieving at least a 25 percent reduction in the surge inundation. China (84 percent), Vietnam (54 percent), Pakistan (58 percent), Nicaragua (45 percent), and Honduras (35 percent) 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.

4. Assessing the Impact of Sea-Level Rise on Mangroves

Historically, mangroves have shown considerable resilience to fluctuations in sea level rise (Alongi, 2009; Erwin 2009; Gilman et al. 2006). However, their adaptation to future sea level rise (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 fresh-water inflows, and a rate of sea level rise that is not greater than the rate at which mangroves can migrate (Ellison and Stoddart 1991; Semeniuk 1994; UNEP 1994; McLeod and Salm 2006; Lange et al. 2010).[12] 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.

Understanding the impact of SLR on mangroves must take into account factors that affect the ecological balance 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 fresh water and sediment, and salinity of soil and groundwater (Belperio 1993; Semeniuk 1994; Blasco et al. 1996; Kumura et al. 2010).

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-meter rise in sea level. 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

[12] Mangroves have adapted special aerial roots, support roots, and buttresses to live in muddy, shifting, and saline conditions. Mangroves produce peat from decaying litter fall and root growth and by trapping sediment in water. The process of building peat helps mangroves keep up with sea level rise. Mangroves can expand their range despite sea level rise if the rate of sediment accretion is sufficient to keep up with the sea level rise.

associated with an island or mainland coast), as described in Hoozemans et al. (1993).[13] Five possible responses to SLR, or categories of wetland migratory potential (WMP), were defined for the DIVA database:

WMP1:	No, or hardly any change
WMP2:	A retreat of the coastline, combined with inland migration of coastal ecosystems
WMP3:	A retreat of the coastline without the possibility of inland migration due to topography (e.g., coastlines with relatively high relief)
WMP4:	A possible retreat of the coastline but increase of flooding area behind the coastline ("ponding")
WMP5:	Total loss of the coastal ecosystem (Hoozmans et al. 1993).

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). If mangroves can migrate, category WMP 2, then they may survive in their current location to the extent that natural migration or sediment accretion keeps pace with sea level rise (Alongi 2008). Mangroves in the category WMP 3 cannot migrate, and the human resources associated with them will lose their protection. Mangroves in category WMP 4 are at great risk, but may survive, depending on the effect of flooding behind the coastline. If the flooding is severe enough and persists long enough to seriously disrupt the flow of freshwater and nutrients to mangroves, the mangroves will be severely degraded and may die, putting at risk the population currently protected by them.

Geographic overlays of mangroves with the WMP characteristics of the coastlines from the DIVA database[14] indicates across our study area, 68 percent of the mangroves fall under WMP 2

[13] 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.

(57,003 square kilometers), where there is a potential for mangroves to migrate inland with a 1-meter SLR (Table 3). Another 28 percent of mangroves fall into categories WMP3 and WMP4 (22,753 square kilometers), in which climate change will seriously compromise the existence of mangroves. Category 4 mangroves account for the 18 percent of mangrove area where survival of mangroves is possible, but at risk depending on local conditions. Category 3 mangroves account for the remaining 9 percent; these mangroves are the most vulnerable to SLR and are likely to be lost.[15]

Table 3. Mangrove area and wetland migratory potential by region

	Total mangrove area (sq km)	Mangrove area by Wetland Migratory Potential (Percent of total mangrove area)		
		WMP2	WMP3	WMP4
East Asia & Pacific	45,119 (57%)	34,770 (77%)	8,795 (19%)	1,554 (3%)
Latin America & Caribbean	20,636 (26%)	8,830 (43%)	6,053 (29%)	5,703 (28%)
South Asia	8,803 (11%)	8,181 (93%)	333 (4%)	290 (3%)
Sub-Saharan Africa	5,197 (7%)	5,172 (~100%)	20 (<1%)	5 (<1%)
Total	**79,756 (100%)**	**57,003 (71%)**	**15,201 (19%)**	**7,552 (9%)**

Notes: Mangroves in WMP 2 are potentially capable of migration; those in WMP 3 & 4 are not able to migrate. Totals may not sum to 100% due to rounding

Source: Authors' estimates as described in the text.

Once again, the vulnerability of mangroves varies a great deal by region and by country. In South Asia and Sub-Saharan Africa, more than 90 percent of mangroves respectively are in

[14] For this computation, the following adjustments were made: (i) The coastline in DIVA is not the same as the SRTM coastline. Therefore, 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 90m 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 0m above sea level.

[15] 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)

WMP category 2, with great potential for migration. In East Asia & Pacific, most mangroves (77 percent) have the potential to migrate and survive. But in Latin America & Caribbean only 43 percent of mangroves have the potential to migrate; most are extremely vulnerable, with 29 percent in WMP3 and 28 percent in WMP4, and likely to be lost.

Table 4 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 percent of coastal mangroves. Other countries where climate change will severely threaten the existence of mangroves include Philippines (85 percent), República Bolivariana de Venezuela (59 percent), Papua New Guinea (31 percent) and Myanmar (27 percent).

Table 4: Mangrove area and wetland migratory potential in top-10 mangrove countries

Rank in global total	Country	Area of Mangroves in sq. km	Percent of mangrove in WMP 2 category	Percent of mangroves in WMP 3 & 4 categories
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	Venezuela, RB	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.

Source: Authors' estimates as described in the text.

5. Coastal Protection Services of Mangroves at Risk in a Changing Climate

As the climate changes during the 21st century, larger storm surges are expected in cyclone-prone coastal areas. 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.[16] Second, the current scientific consensus, summarized by IPCC (2011), holds that a warmer ocean is likely to intensify cyclone activity and heighten storm surges.[17] As storm surges increase, they will create more damaging flood conditions in coastal zones and adjoining low-lying areas. Investment in coastal protection will be essential for disaster prevention and mangroves can play a critical role as 'natural infrastructure' in many countries (e.g., Waite et al. 2014).

If mangroves can migrate inland with a possible retreat of the coastline, WMP category 2, 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, WMP categories 3 and 4, then they may not continue to provide coastal protection services in a changing climate.

In sum, climate change is likely to expand the storm surge inundation areas due to a combination of three effects: i) sea level rise, ii) heightened surges from more powerful storms,

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[16] The most recent evidence suggests that sea level rise could reach 1 meter or more during this century (Hansen and Sato 2011; Vermeer and Rahmstorf 2009; Pfeffer et al. 2008: Hansen 2007; Rahmstorf 2007; Overpeck et al. 2006; Hansen 2006). The more recent research cited above has focused on the dynamic implications of ice sheet instability. For a review of scientific literature on sea level rise, see Dasgupta and Meisner (2010).

[17] 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 (Emmanuel et al 2008). A sea-surface temperature of 28^{o} C is considered an important threshold for the development of major hurricanes of categories 3, 4 and 5 (Michaels et al., 2005, Knutson and Tuleya, 2004).

and (iii) loss of protection (wave attenuation) from mangroves. Hence, in this section the mangroves in WMP categories 3 and 4 were combined with the inundation zone for storm surges and 1 meter SLR to estimate the land area and human resources that will be at risk in a changing climate.

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. First in step 1, we estimated the impacts of 1-meter SLR and a 10 percent increase in storm intensity (assuming no loss of existing mangroves) on the surge inundation area. This was calculated using data and methods described in Nicholls et al. (2007), Dasgupta et al. (2011) and Brecht et al. (2012) and is summarized in Box 2. Thereafter in step 2, we estimated the additional impact on inundation area due to loss of mangroves.

Box 2. Estimating storm-surge zones and human resources at risk

Storm surge zones are 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 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:

Future storm surge = S100 + SLR + (UPLIFT * 100 year) / 1000 + SUB + S100 * x

where:

S100 = 1-in-100-year surge height (m)

SLR = sea level rise (1 m)

UPLIFT = continental uplift/subsidence in mm/year

SUB = 0.5 m (applies to deltas only)

In the absence of a scientific consensus on where tropical storms will or will not intensify, and by how much; we follow Hanson, et al. (2011) and Nicholls (2010), with a baseline assumption of a 10% increase in storm surges/extreme water levels for the 100 year event. This assumption of 10% increment is conservative, as a review of the regional studies of storm surges reveals predictions of storm surge height in 100-year events that are generally above 10% (Hardy et al. 2004; McInnes et al. 2005; Karima & Mimura 2008).

x = 0.1 (increase of 10%) applied only in coastal areas currently prone to cyclone/hurricane.

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 (see Section 3).

Source: Based on Nicholls et al. (2007), Dasgupta et al. (2011) and Brecht at al. (2012)

The joint impacts of SLR and increased storm intensity in a changing climate as described in Step 1 are summarized in Table 5, column 2. Estimates indicate relatively modest increase in the inundation area from 84,222 to 86,257 sq. kilometers, or by 2 percent globally (Table 5, column 2). 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 percent.

However, the vulnerability from SLR and the increased storm intensity increases 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 5, column 3). For the 46 countries considered in this study, the total storm surge inundation area is expected to increase by 31 percent from 84,222 sq. km to 110,218 sq. km and all the regions will be adversely affected. Among the regions, Latin America and Caribbean is the most affected: the inundation area is expected to increase by 61 percent. Among the countries, once again a wide variation of impacts is observed: increase ranging from Cuba (2 percent), Bangladesh and Mozambique (4 percent), Papua New Guinea (6 percent) to India (71 percent) and Mexico (173 percent). 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.

Table 5: Impact of climate change on storm surge area: increase due to sea level rise, storm intensification and loss of mangroves

	Area exposed to storm surge, Sq km			
Regions	Area exposed under current climate and mangrove cover (1)	Area exposed due only to sea level rise plus storm intensification (2)	Area exposed due to all climate change effects: sea level rise, 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)
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%
Venezuela, RB	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 sea level rise and storm intensification but it does not include the likely loss of mangroves due to the lack of migratory potential described in Section 4. Column 3 is the full impact of climate change on inundation area taking into account sea level rise 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.
Source: Column 1 from Table 2; other figures from authors' calculations described in the text.

In order 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 Landscan 2005 (Bright et al. 2006) and GDP for 2005 from the World Bank/UNEP databases (World Bank/UNEP Global Assessment Report on Disaster Risk Reduction 2011) with the geographic area vulnerable to storm surges due to the loss of mangroves (Table 6). 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 in Table 6 also do not include the additional areas and resources at risk that are not upstream of any mangroves.

Our estimates further indicate that under current climate and mangrove coverage, 3.5 million people and GDP worth roughly $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 three-fold and population at risk more than doubles (Table 6, Figure 3). These risks are especially acute in Latin America and Caribbean and East Asia. Densely populated South Asia has an increase of 60 percent and 70 percent 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 climate change for the remaining countries increases nearly four-fold 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.

Table 6: GDP and population exposed to storm surges under current climate and future climate change effects (GDP in thousand US$ in 2005; Population in number of persons)

	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	
Region	GDP	Population	GDP	Population	GDP	Population
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%
Venezuela, RB	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%

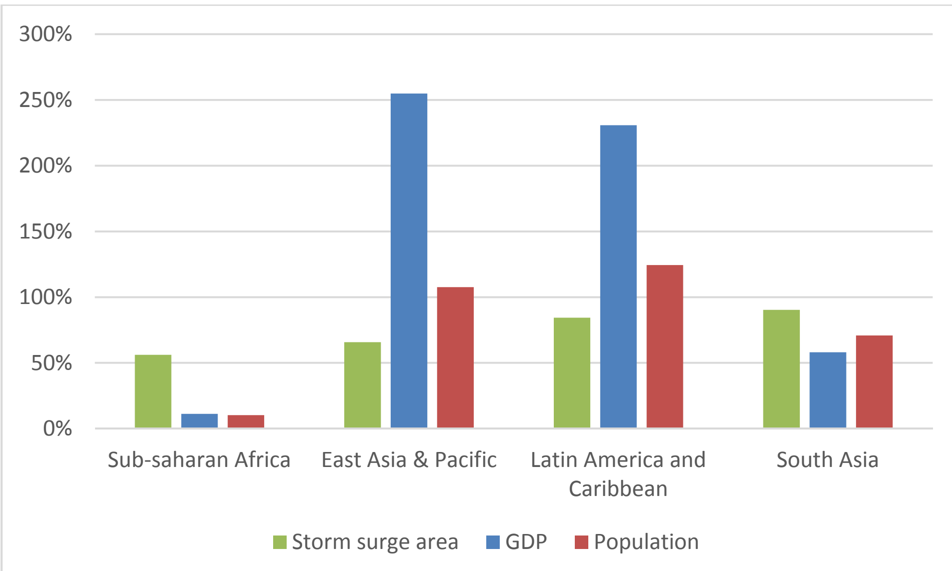
*GDP estimates value of production in constant US dollar for the year 2005; population estimates are for 2005

Source: authors' estimates as described in the text.

The change in vulnerability of GDP and population to storm surge across countries depends on many local factors, especially on the extent of coastal development. Although the increase in the storm surge area in a changing climate is relatively similar for all regions – between 50 and

100 percent (Table 5); the increase in GDP affected ranges from 11 percent in Africa to more than 250 percent in East Asia, and vulnerable population increases by 10 percent in Africa and by 124 percent in Latin America (Table 6).

Figure 3. Increase in storm surge area, GDP and population at risk under climate change by region



Sources: Tables 5 and 6

6. Limitations of the Approach

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 and the lack of local characteristics in the mangrove presence and absence database. The mangrove database used in this analysis is from the NASA GLS data for 2000 supplemented by Landsat imagery from the USGS archives from 1997 to 2000. In some countries there has been significant loss of mangroves since 2000, so the use of 2000 data may tend to overestimate the current levels of coastal defense. FAO (2007) indicates that globally only 3 percent of mangroves were lost between 2000 and 2005, so the 2000 data may be reasonably accurate at the regional level, but the loss of mangroves may be much larger in some countries. Furthermore, the mangrove database shows the extent and shape of the mangrove area, but does not indicate the status of the mangroves; for example, patchiness, health, size of trees, etc. Studies have shown that specific characteristics of mangroves are important for protection from storm surge. For example, if stands are not dense enough, they provide insufficient resistance to wave energy, but if the stand is too dense, waves may simply pass over.

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 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; and 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 a to the 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 towards 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 report.

7. Concluding Remarks

There has been an increased recognition that mangroves can be successfully used either alone or in combination with built infrastructure to provide coastal protection (Narayan et al., 2016).[18] Greater awareness of the role of mangroves in coastal protection as part of a multi-dimensional strategy for climate change adaptation 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 (Beck et al., 2015). Mangroves may be particularly effective in rural areas where populations are widely dispersed and the construction of hard infrastructures like seawalls may not be economically feasible over long coastlines. A review of 53 nature-based defense projects (including 12 mangrove projects), found that mangroves could be 2 to 6 times less expensive than the commonly used alternative, submerged breakwaters, for relatively low waves (Narayan et al, 2016).

[18] For example, mangroves planted in front of an embankment can provide additional protection and reduce the necessary height of the embankment as well as its maintenance costs (Tri et al. 1998).

However, SLR may threaten the survival of mangroves with climate change. Earlier 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. But these previous studies did not quantify the geographic area and human resources at risk from the loss of mangroves' cyclone protection function in a changing climate. Our analysis is a step forward in that direction.

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 one meter SLR, approximately 29 percent of mangroves are likely to be lost but 71 percent 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,[19] 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

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

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 (Forbes and Broadhead 2007). [20] See Box 3 for an example.

Box 3. Mangrove afforestation and coastal protection in Bangladesh: the importance of siting

A study to design the optimal combination of mangrove forest size and polder height was conducted by the Institute of Water Modeling for protecting *Hatia Island* from cyclones in Bangladesh. The study used simulation modeling to (a) identify the relationship between storm-surge height and forest parameters such as species, density, tree girth and forest width; and (b) based on this information, determined the necessary forest area for a given height of embankment.

The authors derived the function showing the relationship between surge height and forest width up to 600 meters wide for different parts of the island. The study found that storm-surge attenuation varied not only by forest width, but also by location on the island. At the southern end of *Hatia* island, a mangrove forest 600m wide reduced the surge height by 0.45m, from about 6.20 m to 5.75m. For a forest width of 133 m, the reduction in surge height was 0.18m. However, no appreciable (>0.1 m) reduction in surge height from mangroves was observed at the southeastern or southwestern sides of the island. The results 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.

Source: Coast, Port and Estuary Division, Institute of Water Modeling, Bangladesh 2000

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

[20] For a list of mangrove resilience factors that inform site selection, see McLeod and Salm 2006, pp 20-21.

$500/hectare 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 (Herr et al. 2012, Murray et al., 2011). 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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Table 1: Mangrove area by country

Regions	Country	Mangrove area (Km2)
EAP	Indonesia	26,705
LCR	Mexico	6,358
EAP	Myanmar	4,935
EAP	Papua New Guinea	4,705
SAR	Bangladesh	4,290
LCR	Cuba	4,241
SAR	India	3,821
LCR	Venezuela, RB	3,309
AFR	Mozambique	2,891
EAP	Philippines	2,482
EAP	Thailand	2,371
AFR	Madagascar	2,295
EAP	Vietnam	2,093
LCR	Colombia	2,050
LCR	Panama	1,522
EAP	Fiji	1,066
LCR	Nicaragua	727
LCR	Honduras	662
LCR	Belize	563
SAR	Pakistan	491
EAP	Solomon Islands	446
LCR	Costa Rica	369
LCR	Guatemala	343
SAR	Sri Lanka	202
LCR	Dominican Republic	179
EAP	China	147
LCR	Haiti	145
LCR	Jamaica	93
EAP	Micronesia, Fed. Sts.	75
LCR	Trinidad and Tobago	63
EAP	Palau	56
EAP	Vanuatu	13
AFR	Seychelles	10
EAP	Timor-Leste	10
LCR	Antigua and Barbuda	9
EAP	Tonga	7
EAP	Hong Kong SAR, China	4
EAP	Samoa	3

LCR	Grenada	2
LCR	Saint Lucia	1
AFR	Comoros Islands	1
EAP	Taiwan, China	1
LCR	Saint Kitts and Nevis	<1
LCR	Saint Vincent and the Grenadines	<1
EAP	Macao SAR, China	<1
LCR	Dominica	<1

Table 2: Storm surge area change due to mangrove by country

Regions	Country	Storm surge area without mangroves (sq km)	Storm surge area with mangroves (sq km)	Change due to mangroves
LCR	Dominica	<1	0	100.0%
EAP	China	2,212	343	84.5%
EAP	Macao SAR, China	<1	<1	81.0%
EAP	Taiwan, China	9	2	79.4%
LCR	Saint Vincent and the Grenadines	1	<1	70.3%
EAP	Hong Kong SAR, China	26	8	69.3%
SAR	Pakistan	1,627	675	58.5%
EAP	Timor-Leste	28	12	57.8%
EAP	Vanuatu	34	15	55.4%
EAP	Vietnam	5,313	2,461	53.7%
LCR	Mexico	12,819	6,478	49.5%
SAR	India	7,875	4,159	47.2%
LCR	Jamaica	189	102	46.1%
LCR	Nicaragua	1,350	743	44.9%
LCR	Saint Kitts and Nevis	1	1	41.7%
LCR	Honduras	1,030	672	34.8%
AFR	Comoros Islands	2	1	33.0%
LCR	Antigua and Barbuda	14	9	31.6%
EAP	Samoa	5	4	31.5%
LCR	Saint Lucia	2	1	30.9%
EAP	Myanmar	7,873	5,612	28.7%
EAP	Philippines	3,947	2,849	27.8%
EAP	Indonesia	37,904	27,865	26.5%
AFR	Mozambique	4,076	3,071	24.7%
AFR	Seychelles	14	10	23.7%
EAP	Solomon Islands	604	466	22.9%
LCR	Cuba	5,724	4,463	22.0%
LCR	Belize	705	565	19.8%
AFR	Madagascar	2,991	2,401	19.7%
LCR	Dominican Republic	232	187	19.4%
LCR	Colombia	2,590	2,131	17.7%
SAR	Sri Lanka	253	213	15.8%
EAP	Thailand	2,931	2,466	15.8%
LCR	Grenada	2	2	15.4%
LCR	Venezuela, RB	3,928	3,398	13.5%
EAP	Tonga	8	7	13.3%

LCR	Panama	1,740	1,554	10.7%
SAR	Bangladesh	4,849	4,365	10.0%
LCR	Costa Rica	415	376	9.4%
LCR	Trinidad and Tobago	69	63	7.9%
EAP	Palau	61	57	7.7%
EAP	Papua New Guinea	5,123	4,763	7.0%
EAP	Micronesia, Fed. Sts.	81	76	5.8%
LCR	Haiti	158	149	5.7%
EAP	Fiji	1,123	1,084	3.4%
LCR	Guatemala	344	343	0.3%

Table 3: Mangrove area at risk (WMP3 and WMP4) by country

Region	Country	Mangrove area (km2)	Ratio of WMP 2 in Total	Ratio of WMP 3 & 4 in Total
EAP	Indonesia	26,705	0.16	0.80
LCR	Mexico	6,358	0.98	0.00
EAP	Myanmar	4,935	0.27	0.73
EAP	Papua New Guinea	4,705	0.31	0.69
SAR	Bangladesh	4,290	0.01	0.99
LCR	Cuba	4,241	0.01	0.85
SAR	India	3,821	0.09	0.88
LCR	Venezuela, RB	3,309	0.59	0.41
AFR	Mozambique	2,891	0.00	0.95
EAP	Philippines	2,482	0.80	0.15
EAP	Thailand	2,371	0.16	0.84
AFR	Madagascar	2,295	0.01	0.93
EAP	Vietnam	2,093	0.24	0.76
LCR	Colombia	2,050	0.05	0.75
LCR	Panama	1,522	0.99	0.01
EAP	Fiji	1,066	0.00	0.40
LCR	Nicaragua	727	0.42	0.58
LCR	Honduras	662	0.43	0.57
LCR	Belize	563	0.85	0.11
SAR	Pakistan	491	0.08	0.92
EAP	Solomon Islands	446	0.00	0.61
LCR	Costa Rica	369	0.96	0.00
LCR	Guatemala	343	0.61	0.39
SAR	Sri Lanka	202	0.87	0.13
LCR	Dominican Republic	179	0.20	0.80
EAP	China	147	0.15	0.85
LCR	Haiti	145	0.19	0.81
LCR	Jamaica	93	0.00	0.99
EAP	Micronesia, Fed. Sts.	75	0.00	0.63
LCR	Trinidad and Tobago	63	0.79	0.21
EAP	Palau	56	0.00	0.61
EAP	Vanuatu	13	0.00	0.31
AFR	Seychelles	10	0.00	0.55

EAP	Timor-Leste	10	1.00	0.00
LCR	Antigua and Barbuda	9	0.00	0.82
EAP	Tonga	7	0.00	0.65
EAP	Hong Kong SAR, China	4	1.00	0.00
EAP	Samoa	3	0.00	0.93
LCR	Grenada	2	0.00	1.00
LCR	Saint Lucia	1	0.00	1.00
AFR	Comoros Islands	1	0.00	1.00
EAP	Taiwan, China	1	1.00	0.00
LCR	Saint Kitts and Nevis	<1	0.00	0.19
LCR	Saint Vincent and the Grenadines	<1	0.00	1.00
EAP	Macao SAR, China	<1	0.00	1.00
LCR	Dominica	<1	0.00	0.00

Table 4: Storm surge area in the current climate and in a changing climate with mangrove protection by country

Region	Country	Current storm surge area (sq km)	Storm surge area due to sea level rise and storm intensification (sq km) (no loss of mangroves)	Change (sq. Km.)
EAP	Indonesia	27,865	28,177	312
LCR	Mexico	6,478	7,115	637
EAP	Myanmar	5,612	5,722	110
EAP	Papua New Guinea	4,763	4,774	11
LCR	Cuba	4,463	4,572	108
SAR	Bangladesh	4,365	4,411	46
SAR	India	4,159	4,303	143
LCR	Venezuela, RB	3,398	3,423	24
AFR	Mozambique	3,071	3,181	110
EAP	Philippines	2,849	2,978	130
EAP	Thailand	2,466	2,504	38
EAP	Vietnam	2,461	2,564	103
AFR	Madagascar	2,401	2,412	11
LCR	Colombia	2,131	2,153	22
LCR	Panama	1,554	1,563	9
EAP	Fiji	1,084	1,092	7
LCR	Nicaragua	743	755	11
SAR	Pakistan	675	788	112
LCR	Honduras	672	683	12
LCR	Belize	565	568	3
EAP	Solomon Islands	466	472	7
LCR	Costa Rica	376	378	3
EAP	China	343	380	37
LCR	Guatemala	343	343	0
SAR	Sri Lanka	213	225	12
LCR	Dominican Republic	187	190	3
LCR	Haiti	149	152	3
LCR	Jamaica	102	105	3
EAP	Micronesia, Fed. Sts.	76	76	0
LCR	Trinidad and Tobago	63	64	0
EAP	Palau	57	57	0

EAP	Vanuatu	15	17	2
EAP	Timor-Leste	12	13	1
AFR	Seychelles	10	11	0
LCR	Antigua and Barbuda	9	10	0
EAP	Hong Kong SAR, China	8	9	1
EAP	Tonga	7	8	1
EAP	Samoa	4	4	0
LCR	Grenada	2	2	0
EAP	Taiwan, China	2	2	0
LCR	Saint Lucia	1	1	0
AFR	Comoros Islands	1	1	0
LCR	Saint Kitts and Nevis	1	1	0
LCR	Saint Vincent and the Grenadines	0	0	0
EAP	Macao SAR, China	0	0	0
LCR	Dominica	0	0	0

Table 5: Storm surge area at risk due to likely loss of mangroves in a changing climate by country

		1m SLR and 10 percent storm intensification and loss of mangroves	
Regions	Country	Area exposed to storm surges (sq km)	Percentage of storm surge area at risk due to expected loss of mangroves
AFR	Comoros Islands	3	0.0%
AFR	Madagascar	3,553	1.9%
AFR	Mozambique	4,984	0.0%
AFR	Seychelles	19	0.0%
EAP	China	3,110	18.4%
EAP	Fiji	1,154	0.0%
EAP	Hong Kong SAR, China	38	100.0%
EAP	Indonesia	44,670	15.1%
EAP	Macao SAR, China	0	0.0%
EAP	Micronesia, Fed. Sts.	82	0.0%
EAP	Myanmar	8,954	35.0%
EAP	Palau	62	0.0%
EAP	Papua New Guinea	5,246	33.3%
EAP	Philippines	5,146	84.9%
EAP	Samoa	5	0.0%
EAP	Solomon Islands	629	0.0%
EAP	Taiwan, China	17	100.0%
EAP	Thailand	3,319	13.5%
EAP	Timor-Leste	38	100.0%
EAP	Tonga	10	0.0%
EAP	Vanuatu	45	0.0%
EAP	Vietnam	7,214	41.1%
LCR	Antigua and Barbuda	18	0.0%
LCR	Belize	832	87.1%
LCR	Colombia	2,886	13.5%
LCR	Costa Rica	451	96.8%
LCR	Cuba	6,727	0.4%
LCR	Dominica	0	0.0%
LCR	Dominican	263	30.0%

	Republic		
LCR	Grenada	3	0.0%
LCR	Guatemala	542	55.0%
LCR	Haiti	173	18.5%
LCR	Honduras	1,273	39.2%
LCR	Jamaica	250	0.0%
LCR	Mexico	17,676	98.4%
LCR	Nicaragua	1,823	25.3%
LCR	Panama	1,857	98.7%
LCR	Saint Kitts and Nevis	1	0.0%
LCR	Saint Lucia	2	0.0%
LCR	Saint Vincent and the Grenadines	2	0.0%
LCR	Trinidad and Tobago	75	74.3%
LCR	Venezuela, RB	4,309	49.5%
SAR	Bangladesh	5,270	3.4%
SAR	India	9,884	33.3%
SAR	Pakistan	2,423	9.9%
SAR	Sri Lanka	332	88.0%

Table 6: Exposed population and GDP to storm surges in a changing climate due to expected loss of mangroves

		1m SLR and 10 percent Surge intensification	
Region	Country	Population exposed	GDP* exposed ('000 USD)
AFR	Comoros Islands	0	0
AFR	Madagascar	1,717	39
AFR	Mozambique	0	0
AFR	Seychelles	0	0
EAP	China	401,561	178,591
EAP	Fiji	0	0
EAP	Hong Kong SAR, China	147,617	448,118
EAP	Indonesia	1,296,572	67,046
EAP	Macao SAR, China	0	0
EAP	Micronesia, Fed. Sts.	0	0
EAP	Myanmar	231,629	4,817
EAP	Palau	0	0
EAP	Papua New Guinea	16,828	789
EAP	Philippines	1,286,082	104,148
EAP	Samoa	0	0
EAP	Solomon Islands	0	0
EAP	Taiwan, China	8,686	10,425
EAP	Thailand	24,780	4,448
EAP	Timor-Leste	3,749	179
EAP	Tonga	0	0
EAP	Vanuatu	0	0
EAP	Vietnam	1,048,399	24,637
LCR	Antigua and Barbuda	0	0
LCR	Belize	9,481	3,636
LCR	Colombia	6,496	1,580
LCR	Costa Rica	4,577	1,767

LCR	Cuba	1,793	591
LCR	Dominica	0	0
LCR	Dominican Republic	13,441	3,331
LCR	Grenada	0	0
LCR	Guatemala	10,934	1,381
LCR	Haiti	5,788	212
LCR	Honduras	6,168	485
LCR	Jamaica	0	0
LCR	Mexico	320,163	196,838
LCR	Nicaragua	4,623	226
LCR	Panama	24,025	8,470
LCR	Saint Kitts and Nevis	0	0
LCR	Saint Lucia	0	0
LCR	Saint Vincent and the Grenadines	0	0
LCR	Trinidad and Tobago	2,657	2,373
LCR	Venezuela, RB	63,094	26,865
SAR	Bangladesh	28,935	728
SAR	India	267,659	14,662
SAR	Pakistan	2,289	102
SAR	Sri Lanka	97,460	7,176