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MANGROVES AS A SUSTAINABLE COASTAL DEFENCE

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ABSTRACT: Mangroves effectively reduce the height of wind and swell waves over short distances (less than 500 m), and can reduce storm surge water levels over greater distances (several kilometres of mangroves). Thus mangroves can contribute to coastal defence strategies. However, their appropriate use depends on a thorough understanding of the conditions under which they can provide these coastal defence services. Here we present a literature review of this topic. Small wind and swell waves can be reduced in height by between 50 and 100% over 500 m of mangroves. Wave reduction largely depends on water depth and vegetation structure and density. However, few measurements are available for the reduction of bigger waves (> 70 cm in height) in deeper water (> 2 m). Storm surge water levels may be reduced by between 5 cm and 50 cm per kilometre of mangrove, based on field measurements and validated numerical models; water level reduction rates depend on the distance from the edge of the mangrove and the forward speed of the cyclone, amongst other factors. Extreme events may severely damage or destroy mangroves, reducing their effectiveness as a coastal defence. The use of mangroves in hybrid engineering can reduce flood risk: for example, a mangrove foreshore in front of a sea wall/dyke will reduce wave impacts on the wall/dyke. The likelihood of waves overtopping the sea wall or walls being breached is thus reduced, with an associated reduction in sea defence maintenance costs. Therefore mangroves can contribute to coastal risk reduction, alongside other risk reduction measures such as sea walls/dykes, early warning systems and evacuation plans. Additionally, mangroves can respond dynamically to rising sea levels, in some cases maintaining their surface elevation with respect to local sea level; thus they may act as a sustainable coastal defence in the face of rising sea levels and changing climatic patterns.

Keywords: Mangroves, coastal defence, wind and swell waves, storm surges, coastal risk reduction.

INTRODUCTION

Mangroves are coastal forests found in tropical and sub-tropical regions, many of them in areas subject to cyclones, hurricanes and typhoons and the waves and storm surges they create. Many local people believe that mangroves provide protection from these coastal hazards (e.g. Farnsworth and Ellison 1997; Walters 2003; Badola and Hussain 2005; Walton et al. 2006; Walters et al. 2008; Warren-Rhodes et al. 2011). The coastal defence functions of mangroves also provide the motivation for several mangrove restoration projects, for example in Vietnam and The Philippines (Tri et al. 1998; Jegillos et al. 2005; Primavera and Esteban 2008).

However, relatively few studies have quantified the level of coastal defence service provided, or provided information on how the level of service varies with local conditions and hazard characteristics. An understanding of how such factors affect service provision is needed by coastal communities, planners, managers and engineers to aid them in making appropriate use of mangroves in coastal defence strategies. In particular, they need to know when they can rely on mangroves to reduce risk from coastal hazards, what level of risk reduction will be provided (and hence whether this will be adequate), and what limits there are on the provision of this service (i.e. if the provision of the service will fail beyond certain thresholds, such as a critical storm surge height). Through understanding how ecosystem characteristics influence service provision, ecosystems can be managed to maintain or increase the level of service provided.

This paper summarizes the findings of a review of available English-language literature on the coastal defence functions of mangroves, particularly with respect to wind and swell waves and storm surges (McIvor et al. 2012a & b). It aims to bring this information together in order to allow coastal defence practitioners to make informed decisions about the most appropriate uses of mangroves in coastal defence. The role of mangroves in coastal risk reduction is then discussed using three case studies from Vietnam, India and Australia. Finally, this paper considers the longer term provision of these services in the face of sea level rise (reviewed in McIvor et al. 2013).

COASTAL DEFENCE SERVICES

Reduction of wind and swell waves

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Wind and swell waves are rapidly reduced as they pass through mangrove forests. The studies in Table 1 found that wave height was reduced by 13 to 67% over 100 m of forest, equivalent to wave height reductions of 50 to 99.6% over 500 m of forest.

There is considerable variation in measured rates of wave height reduction, and a number of factors influence this.

Wave reduction varies non-linearly with distance into the mangrove, and the greatest reduction occurs as the wave begins its passage through the mangrove (Quynh 2010; Bao 2011).

Water depth (and hence tidal phase) influences wave reduction: Mazda et al. (2006) showed that wave reduction per unit distance decreased with increasing water level in a *Sonneratia* mangrove forest, as waves were reduced less once the water level reached above the aerial roots of this mangrove species. Conversely, wave reduction increased with increasing water levels in a *Kandelia* forest (Quartel et al. 2007), when the water depth reached the branches and leaves (*Kandelia* does not have aerial roots). Quartel et al. (2007) found that the drag coefficient (a measure of the resistance to water flow) increased with the projected area of mangrove vegetation (where projected area refers to the silhouette of the vegetation as seen from the direction of incoming waves, and is related to the structure and density of vegetation). The projected area of the vegetation varies with water depth and mangrove species, depending on the morphology of trees and the density of aerial roots and branches.

Modelling and prediction of wind wave reduction

Two numerical models have been used to represent wave reduction within mangroves: the WAPROMAN model, developed by Vo-Luong and Massel (2008), and the SWAN model (Booij and Holthuijsen 1999), adapted to include mangroves by Suzuki et al. (2011). Both models are based on a simplified representation of mangroves as a series of cylindrical elements with different densities per unit area at different heights above the ground. The two models have been validated using a wave height reduction dataset through mangroves on the Red River Delta, Vietnam (Vo-Luong and Massel 2006, 2008); the results of both models show a reasonable fit with the observed data (however the observed data show a high level of variation between measurements).

Narayan et al. (2010) used Suzuki et al.'s (2011) modified SWAN model to explore the effect of a mangrove island (Kanika Sands mangrove island, Orissa, India) on waves reaching Dhamra port, which lies behind the island. They found that for cyclone induced wind and swell waves with a return period of 25 years approaching the port at a 90º angle, wave height at the

Table 1. The rates of attenuation or transmission of wind and swell waves through mangroves.

Location	Species	Wave attenuation / transmission	**Source**
Cocoa Creek, Australia	*Rhizophora stylosa*	Wave energy transmission factor: 0.45 to 0.8 (1 = no loss of wave energy) over 150 m (from Figure 4 of Brinkman et al. 1997)	Brinkman et al. 1997
Tong King Delta, Vietnam	*Kandelia candel*	Wave height reduction up to 20% per 100 m	Mazda et al. 1997
Vinh Quang coast, northern Vietnam	*Sonneratia* sp.	Wave height reduction between 0.0014 and 0.0058 per m (equivalent to 13 to 44% per 100 m)	Mazda et al. 2006
Red River Delta, Vietnam	*Kandelia candel*	Wave height reduction: 0.002 to 0.011/m (equivalent to 18 to 67% per 100 m) (from Figure 5a in Quartel et al. 2007)	Quartel et al. 2007
Nang Hai, Can Gio Mangrove Forest, Vietnam	*Avicennia* sp. *and Rhizophora* sp.	Wave energy reduction: 50 to 70% in first 20 m (coinciding with a 2 m change in surface elevation)	Vo-Luong & Massel 2006, 2008
Red River Delta and Can Gio forest, Vietnam	as above	Wave height reduction: mean 0.0043/m over 80 m of forest (equivalent to 35% per 100 m) (calculated from data from Figures 4 and 5 in Bao 2011)	Bao 2011
Andaman Coast, Trang Province, southern Thailand	*Avicennia, Sonneratia, Rhizophora*	Wave energy reduction: 63% over 246 m along Kantang transect and 72% over 98 m along Palian transect.	Horstman et al. 2012

port was reduced by nearly 50%. They also estimated that 2.5 m high waves have a return period of 60 years at the port, compared with a return period of 20 years if the mangrove island were not present. They found that an extension of the island to the north would further decrease wave height at the port. This example demonstrates the use of a numerical model to predict mangrove wave reduction and to determine which forms of mangrove management will optimise risk reduction from wind and swell waves.

Knowledge gaps / directions for future research

While mangroves are clearly able to efficiently reduce wave energy, most mangroves are found in sheltered environments where large waves rarely occur except during storms. Currently, no data are available relating to reduction of larger wind and swell waves greater than 70 cm in height, or to reduction of wind and swell waves by mangroves in deeper water (greater than 2 m depth); such data are needed to understand the effectiveness of mangroves in reducing these large waves that may occur during storms.

Storm surge water level reduction

Limited data are available on storm surge water level reductions within mangrove areas; available studies are shown in Table 2. All measurements are from Florida, USA. Water level reduction rates per unit distance through mangroves vary from 4.2 to 15.8 cm/km based on water level observations (Krauss et al. 2009), and from 23 to 48 cm/km based on well-validated numerical models of storm surge water levels (Zhang et al. 2012) (Table 2). These data suggest that mangroves can reduce storm surge water levels; however, large mangrove areas, several kilometres wide, are needed to achieve significant water level reductions.

Because it is impossible to control for the presence of mangroves (i.e. it is impossible to measure water levels over similar areas under similar storm surge conditions but without mangroves present), validated numerical models, such as that described by Zhang et al. (2012), are essential to increasing our understanding of the role played by mangroves in storm surge reduction, and the factors affecting rates of reduction.

Numerical models that have been used to explore the effect of mangroves on storm surge water levels include the Eulerian-Lagrangian Circulation (ELCIRC) model (Xu et al. 2010) and the Coastal and Estuarine Storm Tide (CEST) model (Zhang et al. 2012). Both these models represent the area using a spatial grid, with mangroves being incorporated into the model by increasing the surface roughness of grid cells containing mangroves. Manning's roughness coefficient n is used as the measure of surface roughness.

Xu et al. (2010) explored storm surge inundation from Hurricane Andrew (1992, a category 5 hurricane) in Biscayne Bay, Florida. They found that the model's prediction of storm surge inundation extent best matched observed debris lines when cells containing mangroves were assigned a Manning's roughness coefficient of 0.15 in the model.

Zhang et al. (2012) explored storm surge flooding in South Florida during Hurricane Wilma (2005, a category 3 hurricane, characteristics given in Table 2). They chose to use a Manning's roughness value of 0.14 (slightly lower than that used by Xu et al. (2010) because of the large number of lakes, rivers and creeks inside this mangrove area). They compared simulations for the case

Table 2. Peak water level reduction during storm surges passing through mangrove wetlands in Florida, based on observations (Krauss et al. 2009) and validated numerical models (Zhang et al. 2012).

Location and Source	Storm surge	Wetland type and width	Water level height reduction
Ten Thousand Islands National Wildlife Refuge, Florida, USA (Krauss et al. 2009)	Hurricane Charley, 13 August 2004, max winds 240 km/hr, peak water level travelled at 0.4 km/hr.	Mangrove/interior marsh community; dominant species *Rhizophora mangle.* Mangrove width 3.2 km.	9.4 cm/km across whole area (15.8 cm/km in mangrove area)
Along Shark River (Everglades National Park) in Florida, USA (Krauss et al. 2009)	Hurricane Wilma, 24 October 2005, with max winds of 195 km/hr, peak water travelled at 1.4 km/hr.	Riverine mangrove, dominant species *R. mangle* (Chen and Twilley 1999). Distance through mangroves: 14.1 km measured along the Shark River.	4.2 cm/km (lower stretch: -0.2 cm/km; upper stretch: 6.9 cm/km)
Gulf Coast, Florida, from Sanibel West to Key West, USA (Zhang et al. 2012)	Hurricane Wilma 24 October 2005, with max winds of 195 km/hr.	Dominant species *R. mangle, Laguncularia racemosa, A. germinans.* Mangrove width 20 - 45 km.	Models suggest 23 to 48 cm/km (well-validated with recorded water levels)

where all grid cells were assumed to have low surface roughness (Manning's n = 0.02, equivalent to the sea bed) and the case where Manning's n varies in each grid cell, based on the National Land Cover Dataset classification of the cell (i.e. cells were allocated surface roughness values based on the type of vegetation within the cell, with n = 0.14 in mangrove areas). This latter case produced the best match between the simulation output and observed water depths and flooding extent: the root mean square error of computed peak surge heights versus observed ones decreased from 0.60 m (mangroves not included in simulation) to 0.39 m (with mangroves).

Factors affecting storm surge reduction

Zhang et al. (2012) showed that storm surge reduction rates were highest near the seaward edge of mangroves, declining further into the mangrove forest (i.e. storm surge reduction was non-linear with distance through the mangrove). This contrasts with the linear reduction rates (e.g. 15 cm/km) that are often quoted for wetlands, which nevertheless may still serve as good 'rules of thumb' (discussed in Wamsley et al. 2010).

Mangrove vegetation characteristics are also expected to influence storm surge reduction rates: inundation extent was highly sensitive to the Manning's n value assigned to mangrove cells in the simulations by Xu et al. (2010), and Manning's n is known to vary with vegetation density as measured in river floodplains (Arcement and Schneider 1989). However, such variation cannot yet be included in models because of a lack of data on spatial variation in mangrove density. Remote sensing data, such as airborne Light Detection and Ranging (LiDAR) measurements, may provide such information in the future, allowing a more realistic representation of mangroves within models (Medeiros et al. 2012).

Channels and pools are expected to affect rates of reduction as they present less resistance to the flow of water. Krauss et al. (2009) suggest that this may explain the low storm surge reduction rates seen in mangroves bordering the Shark River (Table 2).

Cyclone and storm surge characteristics are also expected to affect storm surge reduction rates: storm surges with slow forward speeds are expected to be reduced less than faster moving surges (Zhang et al. 2012). Additionally, extreme events with very high winds and very large surges may damage or destroy mangroves, resulting in reduced surge reduction rates (discussed in the "Surviving storm damage" section below).

Wind waves riding on storm surges

Through attenuating wind waves riding on top of storm surges, mangroves may significantly reduce flooding and damage. Wind waves may result in large wave set-up, which can contribute a substantial proportion of storm surge height in some areas (Dean and Bender 2006). Dean and Bender (2006) used a numerical modelling approach to explore the effect of vegetation on wave set-up; they found that vegetation could reduce wave set-up by two thirds, and in some cases a set-down occurred. Their results are as yet unvalidated, but suggest that vegetation such as mangroves could have a large effect on storm surge water levels in areas where wave set-up makes a large contribution to the raised water levels.

Tanaka (2008) developed a different approach to numerically model the storm surge from Cyclone Sidr (2007, a category 5 cyclone that made landfall in Bangladesh) passing through a 150 m belt of *Casuarina equisetifolia* trees (a non-mangrove species whose vegetative structure is usually less dense that that of mangroves). He used a one-dimensional non-linear long wave differential equation to explore the effect of vegetation on the short wave (wind and swell waves) and long wave (storm surge) component of the raised water levels. He found that the trees had no effect on the long wave component, but when short waves with a period of 1 or 2 minutes were included, water depth was reduced by the vegetation by 12 or 28 cm respectively (compared to no vegetation being present). This suggests that the largest effect of vegetation on storm surge water levels may be through their effect on the short-period wind waves riding on top of the surge.

ROLE OF MANGROVES IN RISK REDUCTION

By reducing wave height and storm surge depth, mangroves can reduce flood risk to coastal communities and properties. In practice, where human resources are in close proximity to mangrove coastlines, mangroves are often seen as part of a wider risk reduction strategy, which may also include measures such as sea walls, dykes or levees, and early warning systems, evacuation plans and refuges. The examples below demonstrate some of the ways that mangroves have been incorporated into coastal defence planning.

Mangrove restoration in Vietnam

As part of a large-scale Disaster Preparedness Programme in Vietnam, the Vietnam Red Cross (working with the Danish Red Cross and the Japanese Red Cross) restored 8,961 hectares of mangroves between 1994 and 2010, in order to protect 100 km of dyke (Jegillos et al. 2005; IFRC 2011). The mangroves were planted in front of the dykes to reduce the energy of wind waves acting on the dykes. This reduces the risk of overtopping by waves, and also reduces maintenance costs of dykes (Jegillos et al. 2005).

Additionally, 324,700 students, teachers, volunteers and commune wards were trained in disaster preparedness. Two million people are estimated to be better protected from typhoons and associated flooding through this project (IFRC 2011).

When the level of damage from similar typhoons was compared before and after the tree planting programme, it was found that avoided dyke damage after tree planting amounted to between US$ 80,000 and US$ 295,000, while avoided losses to public infrastructure and private property were calculated to be US$ 5 million and US$ 15 million in two communes (IFRC 2011).

The mangrove replanting also provided substantial co-benefits in the form of honey production from bees and other products from the mangrove area (IFRC 2011).

This project exemplifies the use of mangroves in hybrid structures, where the mangroves help to protect dykes, which then protect landward areas from flooding. It also exemplifies the use of several risk reduction measures in combination: alongside mangrove planting, large numbers of people were trained in disaster preparedness.

Mangroves reduced the death toll and economic damage from a cyclone in Orissa, India

Two studies have explored the role of mangroves in reducing the death toll and economic damage from a 9 m storm surge in Orissa, India, in 1999. This storm surge was associated with Cyclone 05B (also called Odisha Cyclone) which resulted in the loss of 10,000 lives.

Despite the massive loss of life, many lives were saved by the early warning system, evacuation centres, and the presence of mangroves in front of some villages. Das and Vincent (2009) estimated that the early warning issued by the government saved 5.84 lives per village, while the presence of mangroves in some villages prevented 1.72 additional deaths per village. This was based on a statistical study of the death toll in 409 villages, all of which had been fronted by mangroves in 1944, but only some of which still had mangroves at the time of the 1999 cyclone (see also Baird *et al* (2009) and Vincent and Das (2009) for further discussion of this study).

While the early warning system was clearly more effective at saving lives, mangroves helped to save the lives of those people who did not evacuate. Again, this demonstrates the importance of a range of risk reduction measures, of which mangroves can form a part.

In a separate study, Badola and Hussain (2005) investigated the level of damage in three villages caused by the same cyclone. They noted that the village protected by mangroves suffered the smallest economic losses. The village protected by an embankment experienced greater crop damage, because after the embankment was breached, the sea water took longer to flow back out of the breaches, exposing crops to salt water for a longer period. In the village protected by mangroves, the water was able to drain away rapidly, resulting in reduced crop damage.

Boats protected during Cyclone Larry in Australia

Another example of mangroves providing coastal defence services comes from Cairns, Australia, which was affected by cyclone Larry in 2006. Based on an early warning system, and following detailed evacuation plans and procedures, the various commercial, recreational and naval vessels that were present in Cairns Port moved deep into the mangrove creeks to wait out the storm (Williams et al. 2007). All vessels rode out the storm safely with no loss of life. Again, the combination of an early warning system, evacuation plans and the presence of mangrove forests all contributed to this positive outcome.

Recommendations for the use of mangroves in coastal defence strategies

These examples demonstrate that mangroves can help to reduce risk from coastal hazards, ideally alongside other risk reduction measures. Neither mangroves nor engineered defences can ever completely eliminate risk, and there will always be a level of residual risk, for example if a sea wall fails, or due to human error in assessing when to issue or act on an early warning message. Nevertheless, these examples show that mangroves can significantly reduce risk when used appropriately alongside other risk reduction measures.

LONG TERM SUSTAINABILITY

An important consideration relating to the use of mangroves in coastal defence is their long-term sustainability in the face of sea level rise and possible changes in storm frequency and intensity. Mangroves must be able to survive and adapt if they are to continue to provide coastal defence services into the future. The dynamic nature of mangrove forests may allow them to withstand such changes, for example by increasing in soil surface elevation in response to sea level rise.

Sea level rise

In response to sea level rise, mangrove soil surfaces can increase in elevation and mangroves can migrate landwards (Woodroffe 1990; Cahoon et al. 2006; McKee et al. 2007; Gilman et al. 2008; Soares 2009). Various factors influence these processes.

The rate of increase of soil surface elevation depends on sediment inputs (Woodroffe 1990) and on sub-surface root growth (McKee et al. 2007). Sediment inputs depend on nearby sediment sources and currents which transport these sediments, while sub-surface root growth may be nutrient limited (McKee et al. 2007).

These factors influence the rate of sea level rise that mangrove surfaces can keep pace with. Critical rates of sea level rise will therefore be location-specific. Recent evidence suggests that in most areas, some parts of the mangrove forest are keeping pace with sea level rise, while other parts are lagging behind (reviewed in McIvor et al. 2013).

The potential for landward migration of mangroves will depend on topography (coastal slope) and the presence or absence of coastal defences and landward development (Woodroffe 1990). If mangroves are in front of a steep rise such as a cliff, they will not be able to migrate. Similarly, engineered coastal defences and landward development may prevent mangroves colonising areas further inland (Gilman et al. 2008).

Where such constraints are not present, mangroves are expected to survive rises in sea level, either in their current locations or in more landward locations.

Surviving storm damage

While mangroves can play a role in reducing storm surge water levels, they can also suffer damage from cyclones and storm surges. Smaller cyclones and storm surges may result in some tree morality and defoliation, but in most cases the structural complexity of the forest is maintained and the forest is able to recover given sufficient time.

The types of damage that occur include defoliation, breakage of branches and trunks, uprooting, erosion of sediment around and under trees, or massive sedimentation covering over aerial roots (Jimenez et al. 1985; Lacambra et al. 2008; Tanaka 2008). Larger trees are more likely to be damaged, and the level of damage also depends on species (McCoy et al. 1996). Tree death may result in a lowering of the surface elevation below the level required for mangrove recolonisation (Cahoon et al. 2003).

The rate of regeneration after storms will depend on the severity of the damage and the species composition. New growth may occur via sprouting from surviving trees (more likely for *Avicennia* and *Laguncularia* species) or via establishment of new seedlings (for *Rhizophora* species) (Baldwin et al. 2001).

Cyclones causing widespread damage to mangroves are relatively infrequent, allowing the mangrove forests to recover their structural integrity over years or decades. The required recovery time is likely to depend on the type and magnitude of the disturbance causing the damage, as well as characteristics of the mangrove forest. While mangrove forests are regenerating, the level of coastal defence service may be reduced.

Future monitoring and research

Long-term monitoring and research into the dynamics controlling mangrove growth and survival under environmental and anthropogenic pressures is critical to increase our understanding of mangrove survival in the face of sea level rise and changing climatic conditions.

CONCLUSIONS

Mangroves can reduce wind and swell waves over relatively short distances (500 m) and can reduce storm surge water levels over much greater distances (several kilometres) although this depends on storm surge characteristics (slow moving surges are reduced less). Mangroves can contribute to coastal risk reduction strategies alongside other measures, such as dykes and evacuation plans. The ability of mangroves to respond dynamically to rising sea levels may ensure the continued provision of coastal defence services into the future.

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