CHAPTER 6
SYNTHESIS

Thematic paper: Synthesis of the protective functions of coastal forests and trees against natural hazards

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This paper argues that coastal forests and mangroves need to be restored and even created to enhance the capacity of estuaries and coastal waters to provide ecological services to the human population living on their shores. Further, coastal forests and mangroves protect the coast from wind damage, salt spray, coastal erosion, typhoons, and can even save human lives during a tsunami. It is stressed that these coastal bioshields cannot provide complete protection; they must be part of a regional plan to reduce the risk of loss of life, property and infrastructure to an acceptable level. A sacrificial zone within this bioshield must be incorporated in the management plan. The appropriate choice of vegetation depends on the severity of the natural hazards, bathymetry, the climate, the local land use and the available options to survive extreme events. It is stressed that the solution to protecting the coast from natural hazards is not just local; it also involves the whole river catchment. Indeed, vegetation must be used to protect the coastal population from landslides in mountainous areas and along river banks, and large dam operations must ensure that the coarse riverine sediment flow necessary to prevent coastal erosion is maintained. Bioshields, including mangroves, provide important ecohydrological services such as creating self-scoured navigable channels, sheltering coastal seagrass beds and coral reefs from excess sedimentation, and enhancing fishery capacity; these are all resources that human populations living along tropical estuaries and coasts rely on for their livelihoods and quality of life.

1 Introduction

Throughout human history, coastal plains and lowland river valleys have usually been the most populated areas throughout the world. This is due to the use of the rivers and estuaries as transport routes and to their very high biological productivity, sustaining a high level of food production (Wolanski *et al.*, 2004). Coastal waters, including those covering continental shelves, supply about 90 percent of the global fish catch. Worldwide, there is an increasing migration towards the coasts; this has resulted in a doubling of the population along many coasts over the last 20 years. At present, about 60 percent of the world's population lives near estuaries and the coast (Lindeboom, 2002). This rapid population growth near the coast is posing new and increasing challenges for humanity, through pollution, eutrophication, increased turbidity, overfishing and habitat destruction. Pollutants number not only nutrients, but also mud from eroded soil, heavy metals, radionuclides, hydrocarbons and a number of chemicals, including new synthetic products.

By aggregating near the coast, the human population is increasingly threatened by risks from natural hazards typical to the coast, which may not exist, or would generally be milder, in the hinterland. Some natural hazards in coastal areas originate from the hinterland such as floods that are of longer duration in low-relief coastal plains than in steep mountainous zones, and siltation, including mud flows; dams also contribute to coastal erosion. Other natural hazards are maritime in origin, namely typhoons and storm surges, salt spray, erosion and tsunamis. They are the focus of this synthesis paper.

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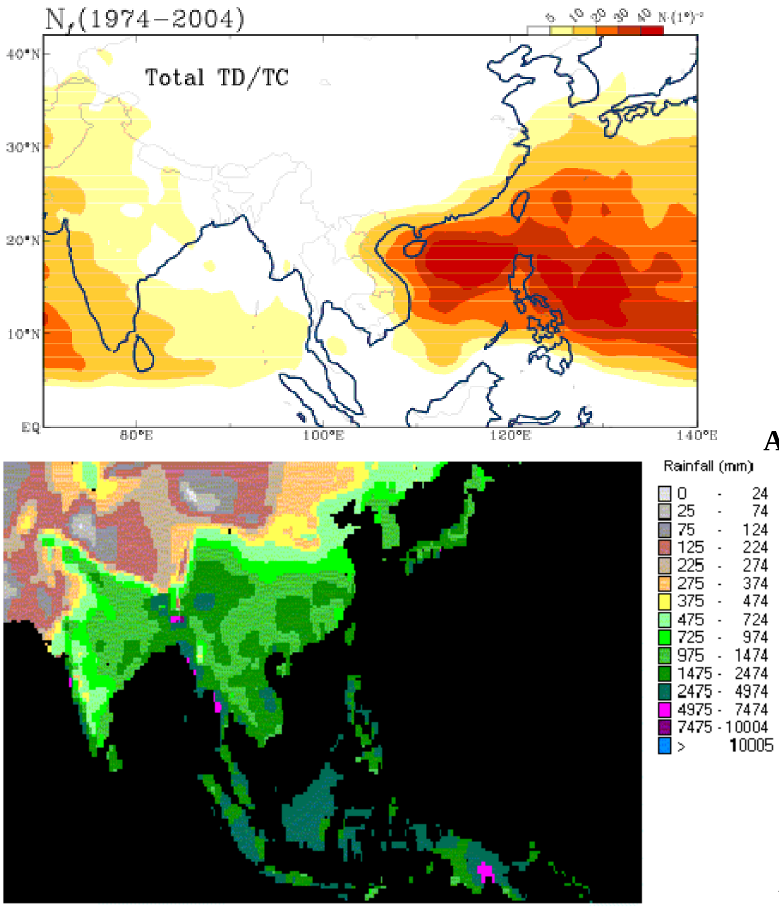
2 Natural marine hazards

Storms and typhoons generate storm surges and waves, winds and heavy rains mainly in regions at 10º to 40º latitude. Along the seaboard, the high impact area might be 30 kilometres wide, with extensive damage at lesser impact over 100 kilometres or more. The incidence of significant tropical cyclones in various regions varies spatially (Figure 6.1); Indochina, southern China, Taiwan Province of China and the Philippines experience the most tropical cyclone landfalls. Storm surges of up to eight metres can occur in the Bay of Bengal, and up to six metres throughout the "cyclone belt". Typhoons also generate extreme rainfall, adding to coastal flooding, and wind waves with periods of ten to twenty seconds and heights reaching 25 metres at sea. The highest waves break as they run into shallow water; smaller waves penetrate inland with the storm surge and attack the vegetation and structures. Storm surge inundation typically lasts for six to twenty-four hours. The mitigating effect of a coastal forest on the duration of inundation of a storm surge itself is negligible. A forest will have a major effect in attenuating water currents, waves and wind. The vegetation can protect against scour and may be more effective and less expensive than "hard" solutions of rocks and concrete, provided a sacrificial zone is planned.



A

B

Figure 6.1 (a) Frequency of typhoons in Asia (1974–2004). Southeast Asia and the Bay of Bengal are the most threatened (from Takle *et al.* [this volume]) (b) Mean annual rainfall in Asia. The areas with rainfall of less than 0.5 m/year and offshore winds are most threatened by salt spray
Source: *http://www.fao.org/ag/AGL/swlwpnr/reports/v_a/amp131.htm*

A tsunami is a solitary wave group generated by sudden tectonic movements and volcanoes, with a wavelength of many kilometres, wave height of less than one metre at sea, and traveling at speeds of several hundred kilometres per hour in the ocean. In shallow water, the tsunami shoals and its height increases to several metres or even to tens of metres. It damages the coast through inundation for typically five to twenty minutes and causes physical damage to vegetation and structures (Latief and Hadi, this volume). Loss of human lives is usually due to drowning and impact by debris.

Coastal erosion and coastal sedimentation are natural processes (Prasetya, this volume). Most coasts are naturally eroded during storms. In short time scales (years to decades), the coast can be protected from natural hazards by a sacrificial mangrove forest (Figure 6.2a), by hard engineering structures (Figure 6.2b), or by sea plantation of mangroves protecting smaller hard structures (Figure 6.2c). In the long term (decades to centuries), the movement of the coast (eroding landward or prograding seaward), and hence the success or failure of bioshields, depends on tectonics, the wind and wave regime and the coastal sediment wedge that receives sediment from the land and exports sediment (Figure 6.4). Large-scale human-induced soil erosion will increase the riverine sediment load and favour seaward progradation of the coast; large dams will trap the sediment and favour landward coastal erosion (Syvitski *et al.*, 2005).

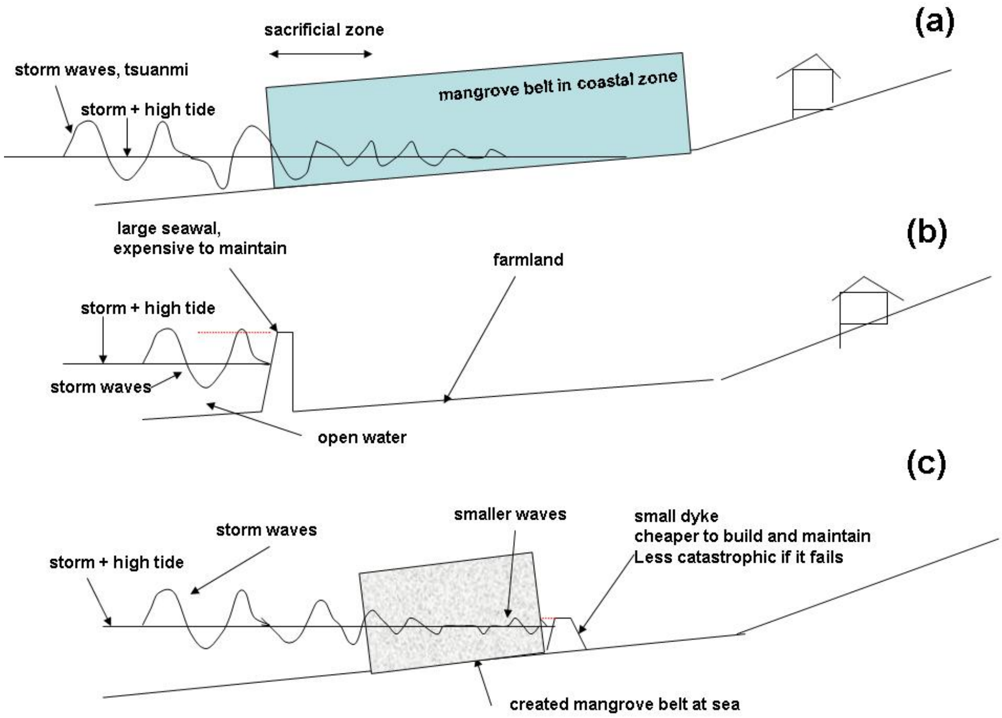


Figure 6.2 The role of coastal bioshields — (a) is the natural balance that, on a seaward prograding coast, can be mimicked by revegetating and relying on a sacrificial belt to absorb extreme waves (b) is the protection of the coast using hard engineering structures (expensive to build and maintain and when they fail, the consequences can be catastrophic) (c) is the protection of the upper coastal belt by a small dyke and creating a mangrove forest bioshield at sea, used successfully in the seaward prograding Gulf of Tonkin in Viet Nam

Salt spray originates from seawater droplets entrained in the air from whitecaps (Takle *et al.*, this volume). The seawater evaporates and leaves salt particles moved by the ambient wind. Most salt particles reside in the lower 200 metres over the coast. Salt-laden air will encounter the bioshields and deposit salt. The seaward edge of the shelterbelt or forest will be most highly impacted and this will also enhance soil salinity. Turbulent motions above the canopy will increase salt deposition as the air traverses inland from the coast. Salt propagates further inland in drier climates. Damage to growing plants from sea-spray salt can be due to higher water stress and leaf or needle necrosis, as well as inhibition of growth depending on the species. Some species (for example pines) are particularly vulnerable to "salt-pruning" on their ocean-facing sides. Salt spray impacts significantly on farming activities in semi-arid coastal areas with onshore winds and rainfall of less than 0.5 metre per year, such as in Pakistan (Figure 6.1b). It is less of a problem in wet areas (rainfall greatly in excess of 0.5 metre per year), such as in most of Southeast Asia (Figure 6.1b), where rainfall reduces salt accumulation problems by washing salt from the vegetation and leaching salt from the soil (Takle *et al.*, this volume).

3 Bioshields

The effect of coastal forests, including mangroves, is to slow the progress of water from storm surges and tsunamis by reducing the height and speed of the wave and reducing water currents as seawater propagates inland. They also protect the coast from wave erosion (Mazda *et al.*, 1997, 2006; Prasetya, this volume) and helped to save human lives in the 2004 Indian Ocean tsunami. This latter finding was first suggested by Kathiresan and Rajendran (2005); it was criticized by Kerr *et al.* (2006) on statistical grounds but its validity was finally confirmed by Vermaat and Thampanya (2006).

Coastal forests also protect the hinterland from salt spray, and this effect is particularly important in arid and semi-arid areas (rainfall less than 0.5 metre/year; Takle *et al.*, this volume).

These coastal forests also provide essential ecological services to the environment and the human population by trapping sediment, converting nutrients to plant biomass, trapping pollutants, providing wood, fodder and medicine and enhancing estuarine and coastal fisheries (de Graaf and Xuan, 1998; Wolanski *et al.*, 2003, 2004; Manson *et al.*, 2005). However, these services are diminishing because mangroves and coastal forests are increasingly being destroyed and degraded by human activities (see review papers by Preuss; Prasetya; and Latief and Ladi, this volume).

4 Hazards from the hinterland — the role of vegetation and dams

In wet river catchments, intense rainfall coupled with deforestation, overgrazing and other poor farming practices, as well as roadworks and mining activities, have increased soil erosion and sediment loads in rivers typically by a factor of 10 (Table 6.1; Wolanski and Spagnol, 2000). Land clearing also increases peak flood flows by up to 30 percent and decreases dry season flows, thus exacerbating flooding in the wet season and droughts in the dry season.

The effect of deforestation on estuaries is much more rapid in the tropics than in temperate zones because of intense rainfall. The catchments of the Cimanuk and La Sa Fua rivers are small and profoundly modified by human activities. The Ngerdoch River drains a hilly, forested area. The sediment yield is largely determined by the climate, the topography and human activities, and is weakly dependent on the catchment size (Table 6.1, data from Wolanski and Spagnol 2000; Syvitski *et al.* 2005; Victor *et al.* 2005).

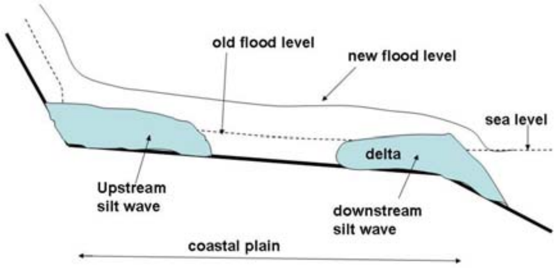
Table 6.1 Comparison of drainage areas, sediment load and yield for various rivers

River	Area (106 km^2)	Yield (tonne/km^2/year)
Minimal land use		
Ngerdoch (Palau)	39×10^{-6}	2
King Sound (Australia)	0.12	50
Moderate land use		
Yangtze (China)	1.9	252
Amazon (Brazil)	6.1	190
Mississippi (USA)	3.3	120
Mekong	0.79	215
Extensive land use		
La Sa Fua (Guam)	5×10^{-6}	480
Ganges/Brahmaputra (India)	1.48	1 670
Cimanuk (Java)	0.0036	6 350

In some cases the effects are catastrophic in coastal areas (for example, mud slides, Figure 6.3). Even without such catastrophes, and except where dams capture the sediment, the future for tropical estuaries and coasts is increased muddiness and increased flooding. This in turn reduces primary productivity and impacts the tourism industry with the inherent loss of aesthetics.

Increased water turbidity also leads to environmental degradation from the smothering of coral reefs and seagrass beds (Duke and Wolanski, 2001; Wolanski *et al.*, 2003). The mud also affects the biological properties of the water and the benthic food chains in river deltas, which economic planners have generally chosen to ignore. The impact can be dramatic and is sketched in Figure 6.3b for the case of the Cimanuk River in Java, Indonesia (Wolanski and Spagnol, 2000). Deforestation of the mountainous upper catchment in the Second World War resulted in two silt waves, one at the base of the coastal strip and the other in the river delta; these two silt waves are progressing towards each other and have raised the bed and flood levels by up to four metres in the past 40 years. In the coastal area, the bed level is higher than the surrounding coastal plains that are heavily populated. To prevent flooding of the coastal plains, 3–4-metre-high levees have been constructed along the lower 30 kilometres of the river; when they break, which they do occasionally, catastrophic floods result.


a



b

Figure 6.3 Hazards to the coastal zone from erosion in the hinterland (a) Mud slide originating from the hinterland that devastated a coastal area in the Philippines (b) Changes in the Cimanuk River, Java, over 40 years following deforestation of the mountains. The river has silted by up to 4 m vertically, increasing flood levels in the coastal belt also by 4 m, and the delta has grown seaward by 5 km

This situation contrasts with that in the presence of large dams, where estuaries are generally suffering from sediment starvation. The dams trap much of the coarse sediment, such as sand; this creates coastal erosion by starving the coastal sediment wedge (Figure 6.4). Such examples abound (Wolanski *et al.,* 2004; Syvitski *et al.*, 2005). For instance, about 90 percent of Nile River sediment is trapped by the Aswan High Dam; as a result, coastal erosion is intense — the Rosetta and Damietta promontories are eroding at rates of 106 and 10 metres/year respectively. The Ribarroja–Mequinenza Dam on the Ebro River in Spain traps about 96 percent of the riverine sediment; this has led to coastal recession at the river mouth area, reversing the previous seaward progradation of the delta. Water diversion from China's Luanhe River has decreased the riverine sediment load by 95 percent and resulted in the delta receding at a rate of approximately 17.4 metres/year. The Mississippi River's suspended sediment load decreased by about 40 percent between 1963 and 1989; this may be the major cause for the recession of the Mississippi deltaic coast. It is also likely that the Three Gorges Dam in China, under construction, will generate coastal erosion and recession. The ongoing rapid shoreline retreat in several segments of the Atlantic coast of Portugal is mainly caused by dams.

Therefore, to protect the human population living near the coast from excess sedimentation and erosion, a governance system needs to be established to regulate human activities in the whole river catchment as the fundamental planning unit. The aim is to decrease soil erosion, largely by the use of vegetation, as well as to maintain sediment fluxes when rivers are dammed.

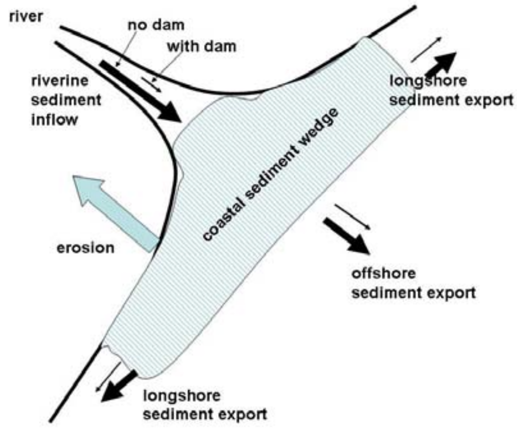


Figure 6.4 In the long term, the net movement of the coast as seaward progradation or landward erosion is determined by the balance between riverine sediment outflow to the coastal sediment wedge and the outflow of sediment from that wedge as longshore and offshore exports. Large dams will trap sediment and cause coastal erosion; deforestation and poor land use in the river catchment will increase the riverine sediment load and increase seaward coastal progradation.

5 Protection against coastal erosion by absorption of wave energy

5.1 Wind waves and typhoon waves

Typhoons are a natural hazard because they produce large waves, swift currents, strong winds and a storm surge. Storm surge effects are exacerbated by flooding due to the heavy rain accompanying the typhoon. Storm surges up to eight metres in depth can occur in the Bay of Bengal. Water currents reach 1–2 metres/second.

Mangroves and other trees can provide some flow reduction and significant mitigation of wave action. They have the potential to provide better protection than "hard" solutions of rocks and concrete. Mangroves are blunt bodies that can absorb water wave energy as a result of wave-induced reversing and unsteady flows around the vegetation. The reduction of wave energy can be estimated from fluid mechanics' principles (see Appendix A). Mangroves thus protect the coast from wave erosion by absorbing wave energy through drag and inertial forces (Massel *et al.*, 1999). Probably the best data set on this process is that of Mazda *et al.* (1997) at the muddy coast of Viet Nam where *Kandelia candel* mangrove trees have been planted at one-metre intervals in a strip 1.5 kilometres wide (towards offshore) and three kilometres long (along the coast) (Figure 6.5a). A typhoon-driven swell lasting 5–8 seconds entered the forest. Measurements were taken of the rate of wave reduction, r, per 100 metres of mangroves in the direction of wave propagation,

$$r = (HS - HL) / HS \quad (1)$$

where HS and HL are the wave heights at the offshore edge of the mangrove forest and 100 metres inshore in the mangroves respectively; r varied between 20 percent per 100 metres for 5–6-year-old mangroves and five percent for one-year-old mangroves. Within six years after planting, the trees have grown sufficiently so that a wave height of one metre in the open sea has been reduced to 0.05 metre at the coast (Figure 6.5a), enabling aquaculture ponds to function behind a coastal levee. Without the sheltering effect of mangroves, the waves would have arrived at the coast with wave heights of 0.75 metres (Figure 6.5b) and the levees would have been eroded and breached.

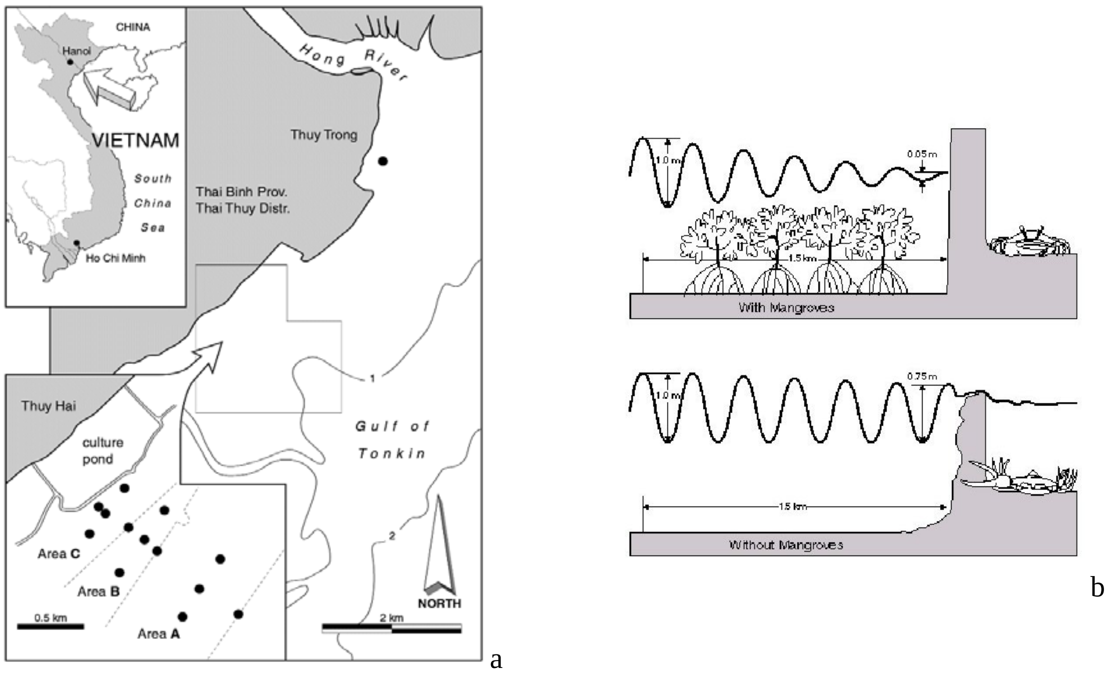


Figure 6.5 (a) Mangrove-fringed Thuy Hai coast in Thai Binh Province, Viet Nam. Groups A, B and C are mangrove plantations comprising, respectively, 0.5-year-old trees, 2–3-year-old trees and 5–6-year-old trees. The symbols • indicate the field measurement sites of tides, waves and currents of Mazda *et al.* (1997a). (b) The wave field at that site with (top) and without (bottom) mangroves. Adapted from Mazda *et al.* (1997)

Mazda *et al.* (2006) repeated the study for a *Sonneratia* plantation at the sea protecting the Vinh Quang coast, also in northern Viet Nam. They found that (Table 6.2) because of their pneumatophores, the rate of wave reduction is much higher by up to a factor of 3 for *Sonneratia* forests than for *Kandelia candel* forests (Mazda *et al.*, 2006); leaves are also important in absorbing wave energy. The typhoon created a storm surge that flooded the coastal dykes. These dykes survived and protected the coast because there were negligible swell/waves in the shadow of the mangroves.

Table 6.2 Wave reduction, r (in %) per 100 m of adult mangrove plantation (data from Mazda *et al.* 1997, 2006). The value of r without mangroves was about 5% next to the *Kandelia candel* site and 10% next to the *Sonneratia* site

Mangrove species	Water depth (m)			
	0.2	**0.4**	**0.6**	**0.8**
Kandelia candel	20	20	18	17
Sonneratia	60	40	30	15–40

The use of mangrove plantation at sea is successful in Viet Nam's Gulf of Tonkin because the coast has extensive shallow water areas that absorb some of the typhoon wave energy, so the waves do not exceed one metre.

Mangroves only slightly diminish peak flood levels, but their drainage systems can accelerate the draining of storm surge water back to the ocean; thus, they reduce the duration of a storm surge on land (Fritz, this volume). Mangroves also protect the human population on the coast from swift water currents when an area is inundated by a storm surge. An example comes from India's Bhitarkanika mangroves following the October 1999 super cyclone with a windspeed of circa 260 kilometres/hour and a storm surge of about nine metres that hit the Orissa coast. The economic impact of this cyclone was evaluated by Badola and Hussain (2005) for three villages equidistant from the seashore and with similar aspects but with different protection; village A was not sheltered by mangroves and had a dyke that failed; village B was not protected by mangroves or by a dyke; village C was in the shadow of mangroves. The damage included household damage by the wind, inundation of crops, loss of fingerlings and salt intrusion. The losses incurred per household were greatest (US$154) in village A, followed by village B (US$44) and were least for village C (US$33). The high cost for village A is attributed to the swift currents after the dyke breached. Thus, mangroves are efficient in measurably, but not totally, protecting the coast against typhoon swell and in reducing the duration of a storm surge flooding the land.

5.2 Tsunamis

When a tsunami encounters shallow water, the wave steepens and the wave height increases severalfold. It breaks and sends a surge of water landwards, destroying vegetation and human assets, which in turn become debris that increases the destructive power of the tsunami. Such damage to vegetation was documented in the worst-affected areas in the 2004 Indian Ocean tsunami (Plate 6.1; also the photographic evidence of Latief and Hadi, 2006).

During the Indian Ocean tsunami, trees along some coasts did not break and offered frictional resistance. This reduced the depth and velocity of flow overland. Because of the long duration of the tsunami wave, trees cannot stop it. They can, however, transform the broken wave into a flood; the shock wave effect is reduced, human lives can be saved and damage to property is reduced, as long as the trees survive flattening, trunk breaking or overturning.

There are two bodies of evidence for the beneficial role of mangroves: (1) fluid dynamics modelling; and (2) empirical evidence.

The propagation of a five-metre tsunami at the shore over flat terrain that was either bare ground or heavily forested with mature trees of either *Kandelia candel* or *Sonneratia* was calculated using fluid dynamics. The prediction used a dam break model (Chanson, 2005). The predictions (Figure 6.6) suggest that at a point 500 metres from the shore, water depth rises one metre in 77 seconds for bare ground, in 343 seconds for *Kandelia candel* and 727 seconds for *Sonneratia*.

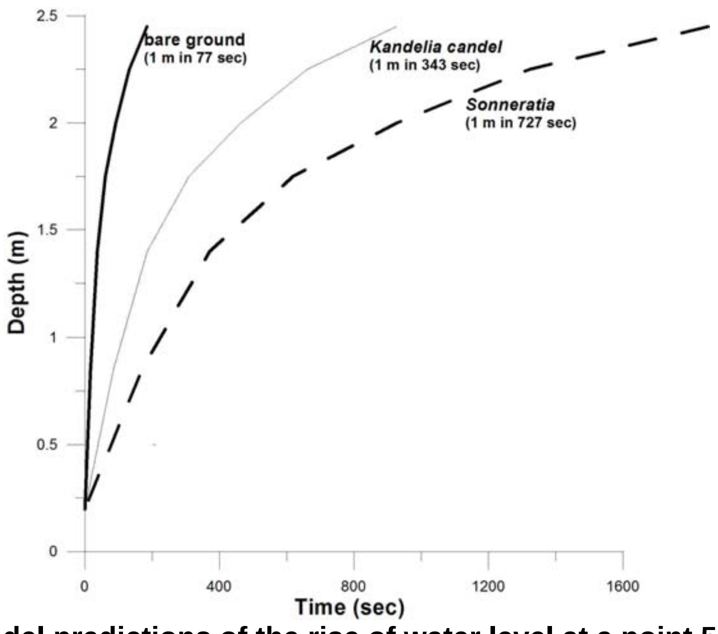


Figure 6.6 Model predictions of the rise of water level at a point 500 m from the shore for flat terrain following a 5-m tsunami at the shore. Three scenarios: Bare ground, mature *Kandelia candel* forest and mature *Sonneratia* forest. The trees are assumed not to be destroyed by the wave. Time starts when the tsunami arrives at that point.

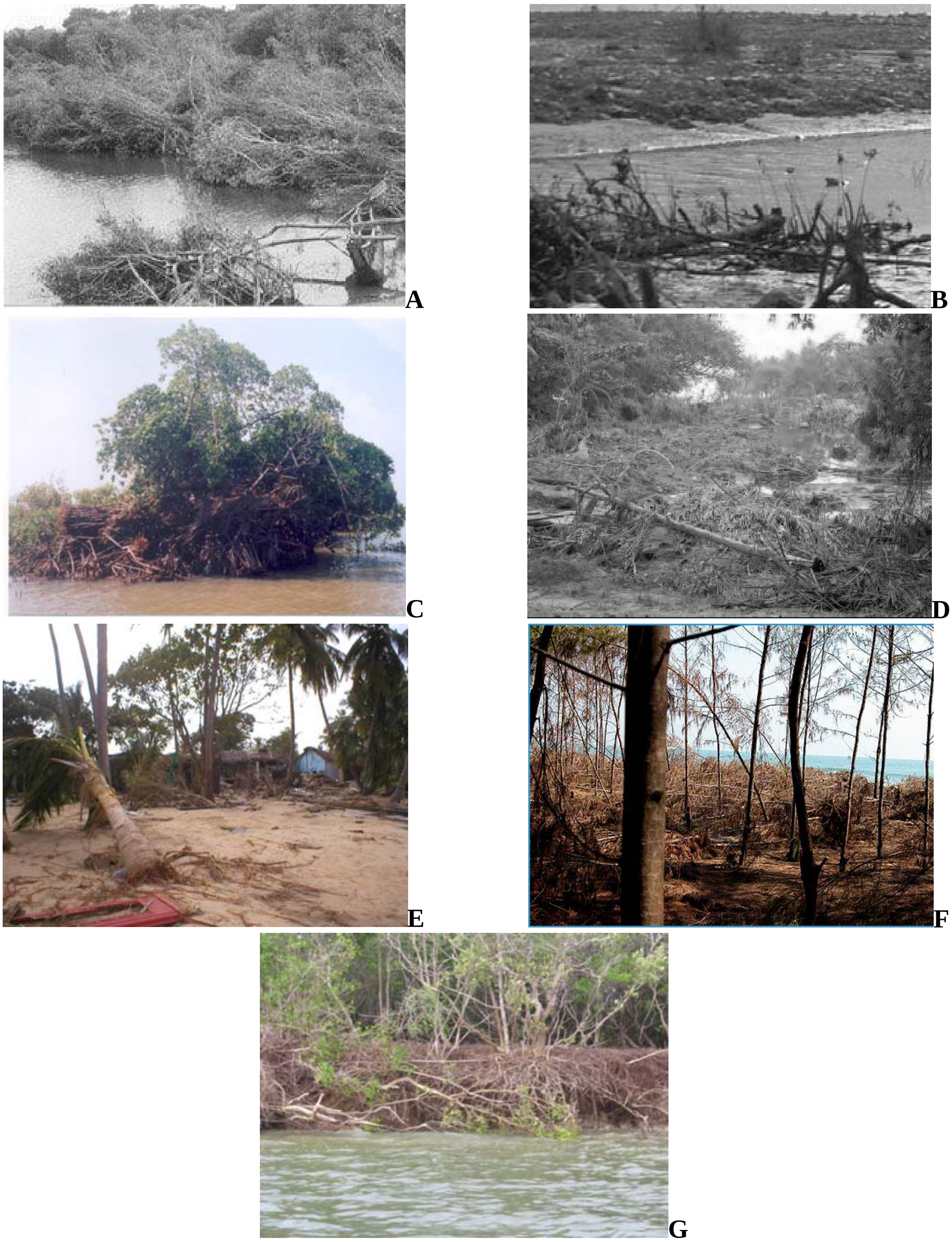


Plate 6.1 A–D: Mangroves damaged by the Indian Ocean tsunami. A–B: Mangroves that snapped; in A the mangroves in the background were sheltered by the 20-m-wide coastal strip of mangroves that were flattened by the tsunami. C: Mangrove tree uprooted exposing roots. D: Catastrophic failure of mangroves — large trees broke and formed destructive debris. E: Other trees were also uprooted or snapped by the 2004 event. F: Flattening of plantation trees in Sri Lanka was limited to a coastal strip for a small (3-m) tsunami in 2004. G: Mangroves destroyed by small wind-driven waves in shallow water undercutting the banks at low tide on Daly Estuary, Australia; boat wakes have the same effect. Sources: Muntadhar *et al.*; V. Selvam; the Internet; the author

The empirical evidence that mangroves attenuated the tsunami as it propagated landward, and in the process saved human lives, is very strong. For instance, Sri Lanka data suggest that in the Yan Oya River the seven-metre tsunami in December 2004 was reduced to 0.5 metre, 3.5 kilometres upstream in the mangroves (point b in Figure 6.7a). In the Mahaweli Ganga River, the tsunami wave was 12 metres at the coast, four metres in Mudduchchenal Village (point b in Figure 6.7b) protected by a sand dune and only two metres at a point a similar distance as the village from the shore but additionally protected by trees. Another body of evidence is the statistical analysis of the saving of human lives; this evidence is shown in Figure 6.8. Similar findings were also suggested by Danielsen *et al.* (2005).
See also http://eqtap.edm.bosai.go.jp/useful_outputs/report/hiraishi/data/papers/greenbelt.pdf).

Clearly, mangroves helped to save some human lives, but not all (see Figure 6.8). Thus, their protection is beneficial but not perfect.

There is considerable spatial variability on the impact of a tsunami wave (Siripong, 2006) and this is largely due to the local bathymetry, the angle of attack and the presence of headlands and bioshields that can deflect the tsunami wave towards high impact zones.

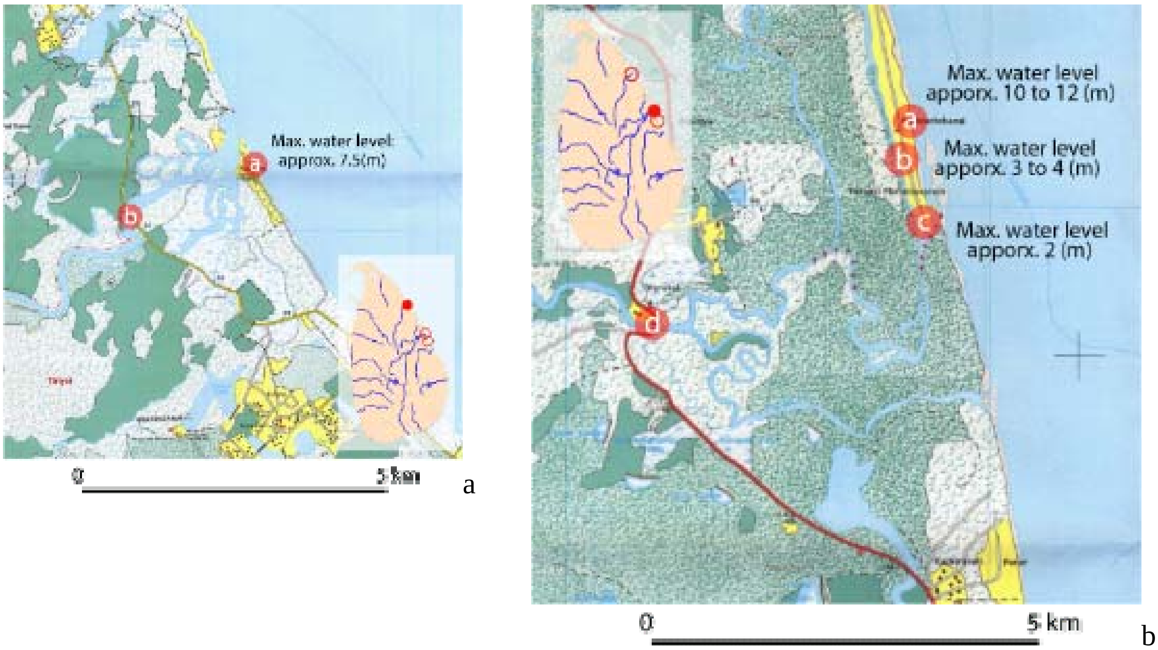


Figure 6.7 Mouths of the (a) Yan Oya River and (b) the Mahaweli Ganga River, together with an estimate of maximum water level during the Indian Ocean 2004 tsunami. Source: *http://river.ceri.go.jp/rpt/asiantsunami/en/survey.html*

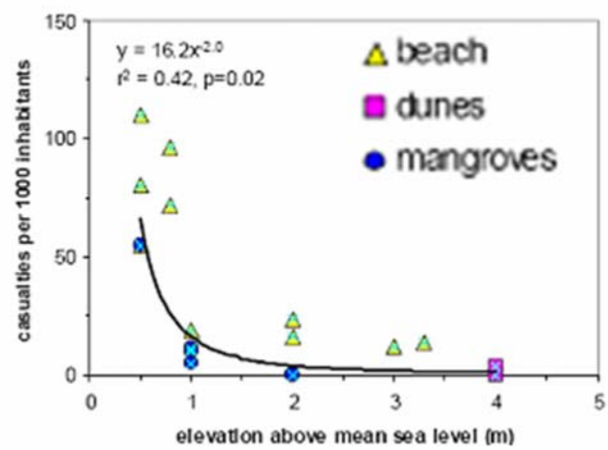


Figure 6.8 For the 2004 Indian Ocean tsunami, plot of mortality (lives lost/1 000, right) in 18 hamlets on the coast of Tamil Nadu against distance from the shore (km) and elevation above mean sea level (m), respectively. The symbols depict different coastal types (Δ = beach; □ = dune; O = mangroves). The curve is fitted to the pooled data set of 18 hamlets. Data from Vermaat and Thampanya (2006)

Trees are thus effective as long as they are not uprooted or snapped, in which case they form debris that may destroy human lives and property. The survival of the trees depends on the size of the trees, their density and the size of the tsunami. The calculations (Appendix B) suggest that a three-metre tsunami is thus able to uproot an isolated three-metre mangrove tree. However, if the trees grow close together, then, as a result of interlocking of roots from adjoining trees, densely vegetated trees of a height greater than six metres may be able to withstand a six-metre tsunami wave. There is some evidence of this from observations of the Indian Ocean tsunami. Mangroves cannot survive a larger tsunami. Thus, mangroves probably cannot protect the coast against a tsunami greater than six metres. All of these results agree qualitatively with observations of the impact on mangroves of the Indian Ocean tsunami (Plate 6.1A–D; Latief and Hadi, this volume).

Mangroves can thus save human lives in a small to moderate tsunami (Figure 6.8). However, if the wave exceeds the threshold level, catastrophic failure of the mangrove ecosystem occurs, whereby snapped or uprooted trees are carried by the currents as debris to destroy other trees in its path and harm people and property. From models, this threshold can be determined by the size and the density of the mangrove vegetation, the root and soil structure, and the size of the tsunami.

Non-mangrove trees such as *Casuarina* and palm trees also exerted a similar impact on absorbing tsunami wave energy. However, the tsunami threshold level was smaller, about two to three metres even for fully grown trees, where trees snapped or were uprooted (Figure 6.9e,f; http://river.ceri.go.jp/rpt/asiantsunami/en/survey.html). Thus, plantations of these trees offer protection against only small tsunamis.

5.3 Erosion from shallow water wind waves and boat wakes

Mangroves are not efficient at absorbing small water waves from boat wakes and shallow-water wind waves at low tide when the wave erodes the soil below the root level. Once the erosion starts, it swiftly progresses, sometimes taking only a few weeks until the undercut trees fall down in the water (Plate 6.1G).

6 Protection of the coast against wind and salt spray

In the same way that the water current through a mangrove forest is decreased by vegetation that exerts a drag force on the water, the vegetation also exerts a drag force on the air flow through the canopy. The wind through a tree canopy (Figure 6.9a) is decreased throughout the height of the tree, particularly at the height of the leaves. This shelters the area downstream through a wake effect to a distance rarely greater than five times the height of the tree (Figure 6.9b), as dictated by classical fluid dynamics.

Because the flow around vegetation is three-dimensional, this sheltering distance can be significantly increased if the trees are grown in a wide shelterbelt (one or two rows of trees whose canopies touch each other) and forest belts (multiple rows). A wide shelterbelt forms a long turbulent wake in its lee (Figure 6.9c). Then the sheltering distance can be as much as 20 times the height of the trees if the wind blows perpendicular to the shelterbelt. The sheltering distance is only twice the height of the trees if the wind blows parallel to the shelterbelt (Takle *et al.*, this volume).

This sheltering effect diminishes in a typhoon if the tree is wholly or partially defoliated (Figure 6.9d–e), and disappears if the tree is overturned (Figure 6.9f). Large trees are overturned more readily than small trees (Figure 6.9f) because they are exposed to stronger winds as a result of the wind shear near the ground (Figure 6.9a). Experience with cyclones in Australia and hurricanes in the United States shows that total defoliation of fully developed mature mangrove trees happens only during super cyclones, and is typically restricted to a strip less than 50-metres wide (M. Williams, personal communication).

The foliage of some non-mangrove trees such as *Casuarina* is less hardy and the tree can be defoliated by severe, but non-cyclonic, winds. Often these trees are also much more readily snapped or overturned by the wind; thus, they constitute an unreliable wind bioshield during a typhoon.

Trees also offer significant protection against salt spray, i.e. fine salt particles carried in suspension in the air (Takle *et al.*, this volume). Just as water flow through mangrove forests creates less turbulent wakes behind trees where the suspended mud is deposited, the air flow downwind of trees creates less turbulent zones where the suspended salt particles are deposited (Figure 6.9b). This effect extends downwind of a windbreak to a distance equal to about ten times the height of the tree.

Thus, a wide shelterbelt projects a wide turbulent wake that is very efficient at capturing salt particles in suspension (Figure 6.9c). This process traps the salt spray near the coast, facilitating its return to the sea and preventing the salt from polluting inland soils.

7 Discussions

7.1 Services to the coastal community

Mangroves provide important services to the human population by providing ingredients for traditional medicine, housing prawns and fish, and supplying wood and fodder (Badola and Hussain, 2005; Blaber, 1997; Prasetya, this volume; Preuss, this volume; Manson *et al.*, 2005). In addition, mangroves provide two hydrodynamic services of importance to the coastal population that are described hereunder.

<u>Maintaining navigable channels:</u> Mangrove creeks are self-scouring (Wolanski, 1992; Wolanski *et al.*, 2001). During spring tides there is a marked tidal asymmetry of the currents in the channel or estuary that drain the mangroves, the peak ebb tidal currents at the mouth of the creek being measurably larger than the peak flood tidal currents. If the mangrove area decreases from mangrove clearing, the creek silts up. Examples of this abound in areas where developers, such as prawn farmers, have reclaimed mangrove land. In the case of Klong Ngao Estuary in Thailand, where half of the mangrove land was reclaimed, the tidal creek silted within five to ten years so that it now dries up completely at low tide. In its natural state it was navigable even at low tide (Wattayakorn *et al.*, 1990). Thus, mangrove vegetation is essential to maintain navigable channels.

<u>Trapping of fine sediment:</u> Muddy waters enter the mangroves at rising tide, deposit some of the suspended sediment in quiet zones near slack high tide in the mangroves, and return to the estuary with less sediment. The difference between the mud that enters and leaves is sediment trapping. Field studies (Victor *et al.*, 2004, 2006) have shown that a mangrove that covers 3.8 percent of the river drainage area traps 40 percent of the riverine mud inflow; the rest contributes to estuarine

siltation (20 percent) and is exported to coastal waters (40 percent). This relationship is independent of land use in the catchment, holding true for developed and undeveloped catchments.

Mangroves fringing muddy open waters are also effective in trapping large amounts of mud from coastal waters – up to 1 000 tonnes/km^2/year (Wolanski *et al.*, 1998).

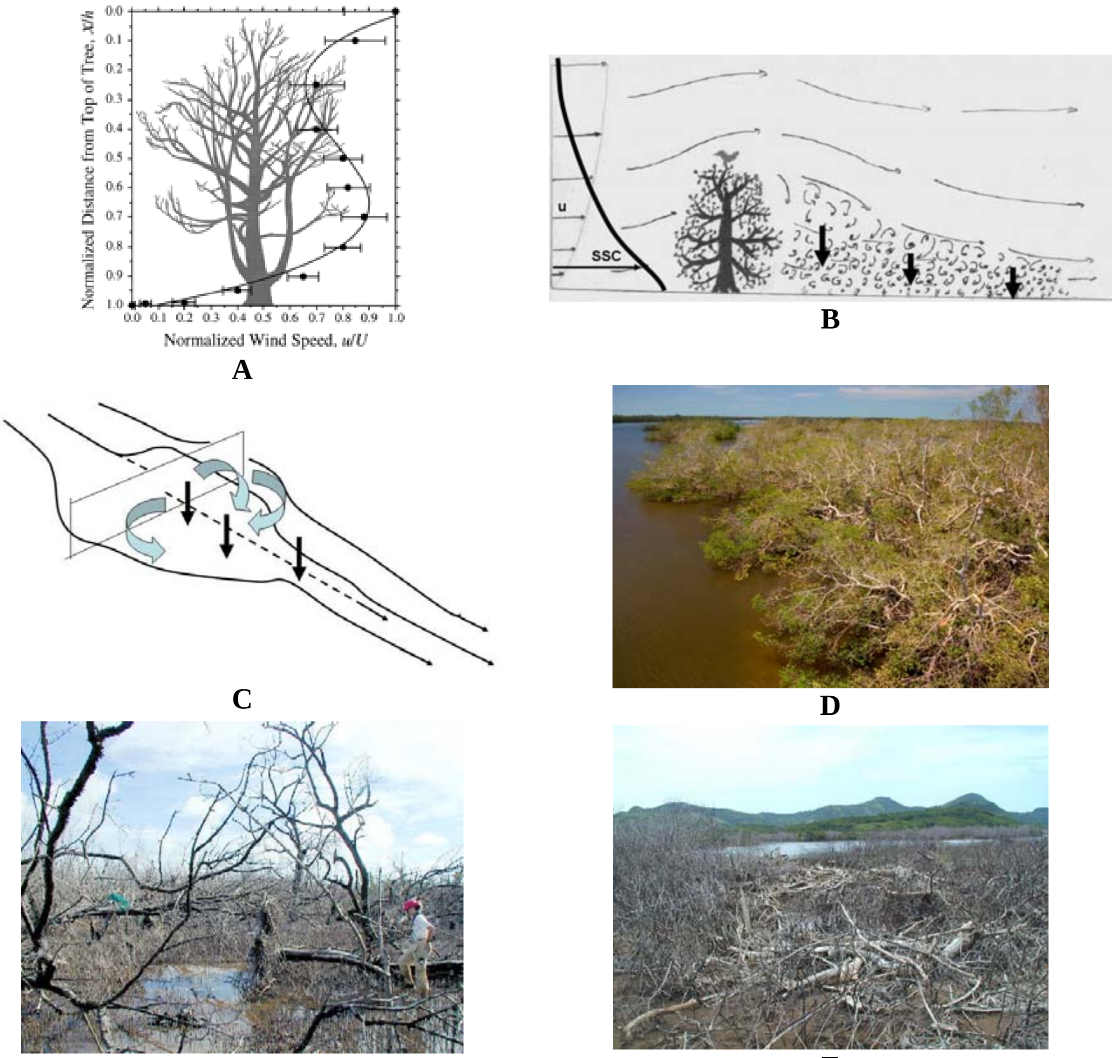


Figure 6.9 A: Vertical profile of windspeed u through a 13.1-m-high wild cherry tree, 0.4 m in diameter at 0.5 m from ground level, growing in an open site. The velocity is normalized by the maximum windspeed u measured at the top of the canopy. The silhouette of the tree shows all branches for which d >5 mm (from Niklas *et al.* [2000]). B: Sketch of the air flow around, over and through: (a) a single tree; and (b) a shelterbelt — the wind accelerates over and around the vegetation and a turbulent wake forms behind the tree. SSC = suspended salt concentration; down arrows = deposition of salt particles in the wake. C: A wide shelterbelt forms a long turbulent wake in its lee. D–F: Mangroves in Florida: (D) partially defoliated; (E), totally defoliated by a hurricane; and (F) overturned by the hurricane. (Note: Large trees are overturned more readily than small trees.) Source: USGS Florida

7.2 The relevance of bioshields against natural hazards

Mangroves help to protect the coast from wave erosion by wind-driven waves and typhoon waves. Coastal forests and mangroves can save human lives and property in a tsunami by transforming a shock wave into a flood, at least up to threshold level. They also shelter the hinterland from salt spray and wind damage up to threshold level.

All these findings have been observed in the field; they are science-based because they result from well-known principles of fluid and soil mechanics, structural engineering and ecology. Thus, the benefits of mangroves and coastal forests for protection against natural hazards and enhancing the quality of life of human populations are numerous.

7.3 Creating bioshields

Creating bioshields is a highly soft technology that involves tree plantations on land, as well as restoring former mangrove areas and even planting mangroves at sea.

7.3.1 Restoring mangroves in sheltered areas

Recreating mangroves from abandoned shrimp ponds is the easiest option and has the additional benefit of fostering commercial activities. For instance, fish and crab ponds in mangrove-fringed tidal creeks can be successful. However, planting mangroves in shallow shrimp ponds, as attempted in Viet Nam, has largely failed (B. Clough, personal communication).

Soil preparation is needed because former mangrove soils turn acidic when used as shrimp ponds. Planting seedlings in reclaimed shrimp ponds fails if the natural drainage pattern is not properly restored; otherwise, the seedlings rot and die in stagnant water (Plate 6.2a).

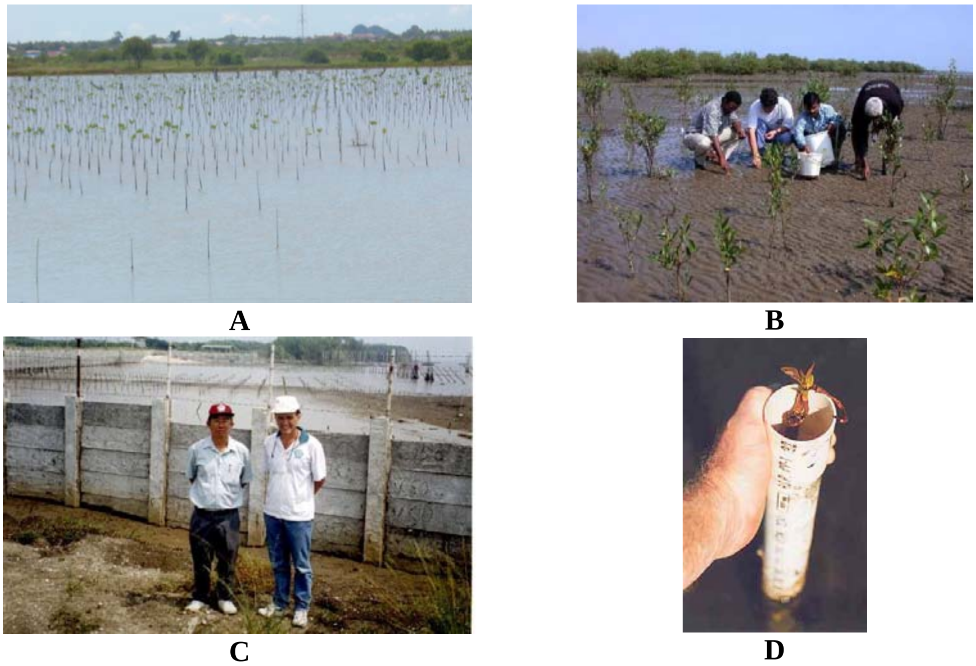


Plate 6.2 A: Mangrove plantation in a reclaimed shrimp pond near Surat Thani, Thailand. About half of the mangrove seedlings died where the water was ponded. B: Planting mangrove seedlings in Eritrea where mangroves did not formerly exist (http://www.ramsar.org/wwd/3/wwd2003_rpt_eritrea1.htm). C: Planting mangroves along the north coast of the Inner Gulf of Thailand has been unsuccessful due to accelerated wave erosion; hard structures are necessary to protect the coast against wave erosion. D: Protection of mangrove seedlings using the Riley encased method (Riley and Kent, 1999; http://mangrove.org/video/rem.html) is suitable for sheltered estuaries where ocean swell is absent and the only waves are shallow wind waves and boat wakes

7.3.2 Creating mangrove forests along estuaries and at sea

Mangroves are highly susceptible to below-root level erosion from boat wakes and shallow water wind waves near low tide. This limits the areas where mangroves can be planted.

Mangrove forests can even be created at sea by planting seedlings over an intertidal area above mean sea level, provided that the shallow coastal water strip is very wide (typically a 2–3-kilometre-wide area above mean sea level). This was done successfully over a muddy substrate in Viet Nam (Mazda *et al.*, 1997, 2006). It was done with moderate success over a muddy sand substrate in Eritrea (Plate 6.2b) and in Thailand's Chumphon Bay (Brown and Limpsaichol, 2000). It has failed somewhat along the north coast of the Inner Gulf of Thailand due to persistent wave erosion; the shallow coastal water strip is too narrow and this allows frequent wave attacks along the coast (Plate 6.2c). Planting mangroves at sea fails in areas where large waves occur, even if only occasionally, because in this case mangroves are planted in areas where they would not occur naturally. For successful mangrove planting, the maximum wave height appears to be one metre according to the experiences in Viet Nam, Thailand and Eritrea.

In estuaries and channels where boat wakes and small wind waves occur, successful attempts have been made, but at great cost, to protect the young trees until they can survive the waves. Techniques include: (1) allowing the seedlings to grow much longer in a nursery until they become small trees that can better resist waves; (2) planting the seedlings in hollows within solid structures such as tyres or a concrete structure; (3) planting the seedlings in transparent PVC tubes (Plate 6.2d); and (4) protecting the seedlings behind temporary structures such as bamboo walls.

7.3.3 Sacrificial bioshields

A belt of forest might be sacrificed to give protection against extreme natural hazards; it should be managed accordingly. The seaward edge of the forest (mangrove or non-mangrove) is the sacrificial zone (Takle *et al.,* this volume). It takes the brunt of the damage due to "flagging" by wind, high salt impaction and occasionally suffers total defoliation (in typhoons) and destruction of the trees by typhoons or tsunamis, as well as from coastal erosion events that can occur even when the coast is generally prograding seaward in the long term. Management has to accept that this zone is unsteady and unstable and precludes human settlement; also, it should allow for natural regeneration, replanting of destroyed trees and possibly construction of artificial fences to better protect the first line of trees from lethal salt and wind damage in high impact zones.

7.3.4 The width of bioshields

In terms of protection against typhoon winds, mangroves constitute excellent wind bioshields and a zone of 100 metres may be sufficient against a typhoon (Dutton, 1986). Empirical evidence (for example, Cyclone Winifred in Queensland in 1986) (Dutton, 1986) suggests that coastal forests need to be much wider (up to one or two kilometres?) to measurably protect the hinterland from cyclone winds; however, the science is unavailable to better quantify this theory.

In terms of protection against coastal erosion from typhoon waves, field evidence suggests that when the coastal waters are shallow, a coastal belt of 500 to 1 000 metres of adult mangroves seems to be necessary to protect small coastal dykes that halt further coastal erosion. Thus, the protection is twofold: it consists of mangroves absorbing the brunt of the wave energy and a small coastal dyke absorbing the rest (Figure 6.2). This will fail if the coastal waters are deep because the waves are large and will uproot the mangroves. Nature is a good guide to where this technique can be used. If there are no mangroves growing in such areas, this is probably because the coast is naturally eroding; thus, attempts to plant mangroves at sea will fail in the long term (Hanley, 2006). In arid areas of Eritrea, the lack of natural mangroves is due to extreme temperatures that affect the seedlings.

In terms of protection against tsunamis, the science remains qualitative rather than quantitative; as a rule of thumb, field data suggest that a belt of at least 500 metres of adult, densely forested, mangroves will measurably save human lives from a tsunami not exceeding four metres in height. A width of 2 000 metres will reduce the tsunami to a small wave of less than one metre. In all probability, mangroves will not be helpful against a larger tsunami. As pointed out by Latief and Ladi (this volume), the size of the tsunami wave cannot be predicted because it varies spatially as a result of tectonics and interacts with the local bathymetry. Thus, the decision to create a bioshield is based on a calculated risk, i.e. knowing that the bioshield will be ineffective for extremely large tsunamis, at which times other measures (such as advance warning systems, evacuation plans and shelters) are necessary.

8 Limitations and constraints

8.1 Diagnostic tools

For a sheltered estuary (Figure 6.10a), a muddy or degraded coast can be restored and better protected by the use of mangroves. The sediment capture rate of the mangroves depends on the riverine sediment inflow and can be calculated. This enables one to calculate how fast land can be reclaimed for agriculture. The data required are oceanography, mud dynamics and riverine sediment inflow, and mangrove forestry in order to select the appropriate species of trees, the eventual use of a mangrove nursery and the forestry exploitation rate.

For protection against erosion on an open coast (Figure 6.10b), historical data can be used to determine if a coast is eroding or prograding in the long term. However, the past is not an indication of the future if a large structure has been built, or is planned, because this may reverse the coast from prograding to eroding. If the coast is eroding, planting mangroves at sea is likely to fail. If the coast is prograding, planting mangroves over intertidal areas above mean sea level in coastal waters may succeed in protecting the coast if combined with a hard structure such as a small levee or dyke, as practised in the Gulf of Tonkin. If the intertidal area is too short to reduce the wave height to below one metre, a bioshield may be successful if combined with an offshore structure as well as a hard structure on the coast.

For protection against typhoons and their associated river floods, winds and storm surges (Figure 6.10c), bioshields have minimal impact on peak flood levels, but have a large impact on reducing waves, currents and wind. If the drainage pattern is well-planned, they can significantly reduce the flooding duration. A bioshield of two kilometres may be needed, together with a sacrificial bioshield, possibly accompanied by a sand dune nearest the coast. Data required include hydrology (river floods), oceanography and meteorology, to determine the width of the sacrificial bioshield based on acceptable loss of economic returns. The drainage patterns must be carefully designed so as to allow the water to readily return to sea. In the case of a super cyclone, bioshields will not help measurably and other measures need to be planned to save human lives, including storm surge barriers, an evacuation strategy and shelters.

For protection against tsunamis (Figure 6.10d) the first defence has to be an early warning system combined with an evacuation strategy, shelters, community awareness and engineering structures to reduce damage to infrastructure and loss of life. The level to which a bioshield can protect against a small tsunami (< 5–6 metres) varies locally according to the bathymetry (areas near headlands are most at risk), the angle of attack and the distribution of the bioshield. A mangrove forest may block the tsunami wave — and protect people and property as close as 500 metres from the beach — while at the same time it can redirect the wave towards an estuary where the damage may be amplified. The wave can be largely attenuated within 2.5 kilometres. A large tsunami (> 6 m) may be unstoppable by a bioshield.

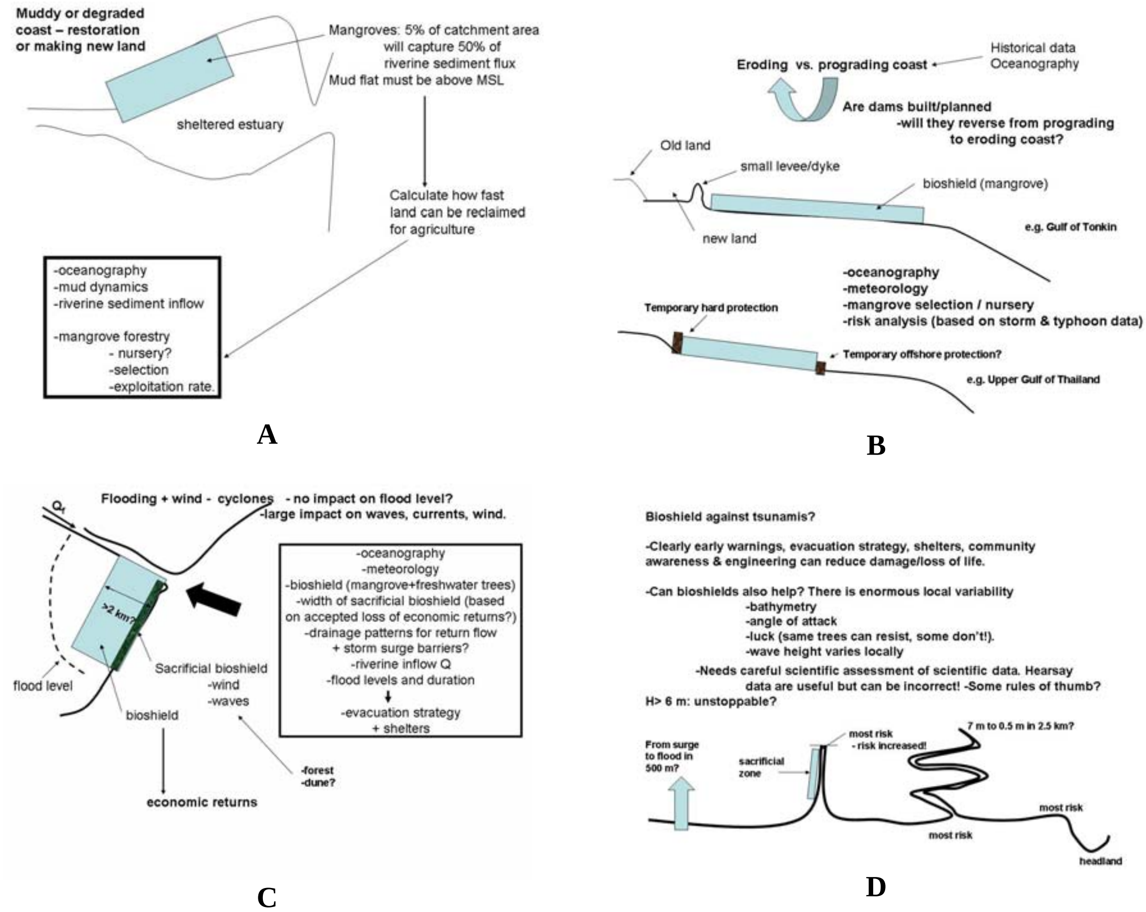


Figure 6.10 Diagnostic tools for the use of bioshields in: (A) a sheltered estuary (B) protection against erosion of an open coast (C) protection of a coast from a typhoon (D) protection against a tsunami

9. Conclusion and discussion

To protect the human population living near the coast from excess sedimentation and erosion, a governance system needs to be established to regulate human activities in the whole river catchment as the fundamental planning unit; the aim is to decrease soil erosion and to stop mud flows, largely by the use of vegetation, especially on steep slopes and on the river banks, as well as to maintain sediment fluxes when rivers are dammed so as to prevent human-induced coastal erosion.

The cost of bioshields is high, but it is balanced by the ecological and socio-economic services that they provide. This cost is much lower than that of a hard structure that fully protects the coast. However, when hard structures fail, the cost can be catastrophic because of the accumulation of human assets in its shadow.

As a rule of thumb, a mangrove area covering about five percent of the catchment area can halve the impact on coastal sedimentation, seagrass and corals. It can considerably lessen the impact of increased riverine sediment on fisheries (see Table 6.1) owing to poor land use in the river catchment. Thus, mangroves protect fisheries by sheltering the seagrass and coral reefs from excess sedimentation.

The efficacy of bioshields for protection against natural hazards as well as to provide socio-economic and ecological services has been proven. In practice, the level of applicability depends on the local climate, hydrology, drainage pattern, meteorology, oceanography, soil type, wave, storm pattern and socio-economic drivers. Climate change may complicate the situation. There is no unique recipe. Applicability to various sites thus depends more on the willingness and the capacity of individual countries to adopt mangroves and coastal forests as bioshields, on a case-by-case basis. The level of adoption will depend on socio-economic imperatives (Preuss, 2006). Where the coast has been totally urbanized by planned developments or slums, this solution is then in practice impossible to implement. In other cases the practical use of coastal forests and mangroves is feasible to protect people and property and enhance their livelihoods and quality of life. The protection that bioshields offer is far from total; it also involves risks because the usefulness of bioshields has limits in extreme events. The bioshield solution is advantageous because it is often practical and inexpensive in comparison with pure engineering solutions (such as the Dutch solution of building dykes along the coast), requires relatively low technology and it protects and enhances the environmental services provided by estuaries and coastal waters on which populations often depend for their livelihoods. It is thus a matter of living within accepted risks.

The level of risk will vary from site to site apropos the bathymetry and topography of the coastal areas, geology, meteorology and oceanography. Judging from typhoon statistics alone, no two sites are alike in Asia, suggesting that the relevance and use of bioshields will also vary spatially (Takle *et al.,* this volume).

The science of bioshields is well-established; however, the technology of bioshields is still developing. It is a mixture of many socio-economic and ecological considerations that include the following (see details in Saenger, 2002; Prasetya, this volume; Hanley, 2006; Preuss, this volume):

- Site selection based on existing land use and infrastructure, as well as the intensity and frequency of natural hazards, largely avoiding naturally eroding areas and selecting species based on rainfall, wind tolerance and salt spray for coastal forests and suitable sheltered coastal sites with suitable rainfall and appropriate tidal inundation for mangroves.
- Selection of species for mangrove and coastal forests that have the correct ecological requirements for the physical characteristics at the site.
- Selection of available species from the wild (some mangrove species may have become locally extinct, e.g. in Aceh — see Hanley, 2006) or from nurseries.
- Soil preparation.
- Restoring tidal flows in shrimp ponds.
- Planned economic utility (e.g. providing societal benefits such as fisheries and coastal protection in the case of mangroves, or direct benefits such as wood, fibre and fodder for mangroves and coastal forests).
- Community aspirations.
- Community involvement.
- Plantation techniques and planting pattern.
- A maintenance programme for the seedlings and the plantation.

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Appendix A

The vector of the horizontal force F is the sum of the inertial F_i and drag F_d forces (Figure 6A1; Milne-Thompson, 1960):

$$F = F_i + F_d \qquad \text{(A1)}$$

where

$$F_i = C_m \rho_w V a \qquad \text{(A2)}$$

$$F_d = 0.5 \rho_w C_d (D Z) |u| u \qquad \text{(A3)}$$

where C_m (≈ 1.5 for fully turbulent flows) and C_d (≈ 0.45) are the inertia and drag coefficients, u is the water velocity, V is the displaced volume of the body, ρ_w is the density of water, a is the acceleration, D the diameter of the vegetation assumed cylindrical, Z is the depth to which the vegetation is submerged. It is readily possible to extend the theory for a tapered stem where D diminishes with elevation (Niklas, 2000).

For an unbroken wave of period T,

$$u = U \cos(kx - \omega t) \qquad \text{(A4)}$$

$$a = 2 \pi U \cos(kx - \omega t)/T \qquad \text{(A5)}$$

where

$$U = \pi H \cosh k(z+h) / T \sinh(kh) \qquad \text{(A6)}$$

where h is the water depth, H the wave height, k is the wave number defined from the dispersion relation

$$\omega^2 = g k \tanh(kh) \qquad \text{(A7)}$$

where g is the acceleration due to gravity.

For tidal inundation and wind or typhoon waves, the vegetation is only partially submerged; therefore Z = h.

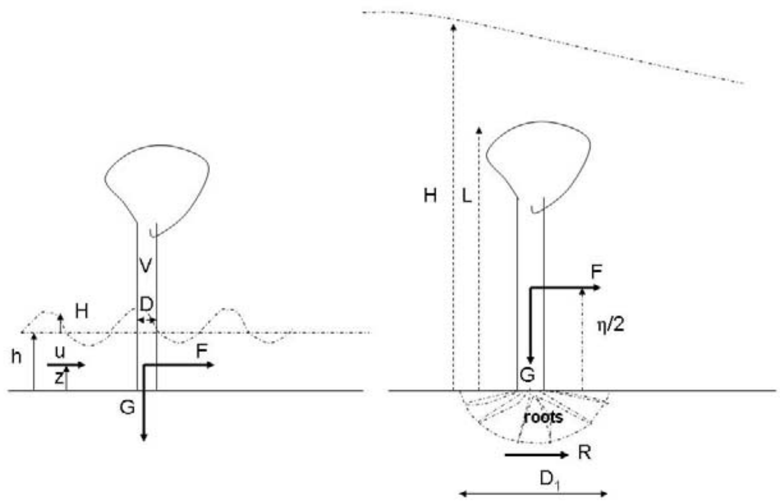

Figure 6A1 Idealized wind and typhoon waves (left) and a tsunami wave (right) through trees showing terms used in the text

Appendix B

The tsunami propagating in a mangrove is initially a broken wave. The horizontal velocity u is (Hedges and Kirkgoz, 1981)

$$u = 0.5\ (g\ H)^{1/2} \qquad \text{(A8)}$$

Trunk breaking occurs if the horizontal breaking strength σ_s ($\approx 185 \pm 35$ MN/m^2) of the tree at the base is exceeded by inertial and drag forces (Niklas, 2000),

$$4\ (F_i + F_d)\ /\ 3 \geq \pi\ (D/2)^2\ \sigma_s \qquad \text{(A9)}$$

For typical values of σ_s of healthy trees, this mode of trunk breaking is unlikely. Breaking instead seems to result from the overturning moment of forces F_i and F_i that act at an elevation η (η = H/2 or L/2, whichever is the smallest, where L is the height of the vegetation). The overturning moment lifts the upstream edge of the basal area and forces down the downstream edge, creating tension at the upstream edge and compression at the downstream edge. Trunk breaking occurs if tension exceeds the breaking strength in tension σ_t of the tree,

$$-G/\ 2\ \pi\ (D/2)^2 + \eta\ (F_i + F_d)\ D/2\ /\ 0.25\ \pi\ (D/2)^4 \geq \sigma_s\ ` \qquad \text{(A10)}$$

or the breaking strength in compression σ_c of the tree,

$$G/\ 2\ \pi\ (D/2)^2 + \eta\ (F_i + F_d)\ D/2\ /\ 0.25\ \pi\ (D/2)^4 \geq \sigma_c \qquad \text{(A11)}$$

where G is the weight of the tree. The calculations suggest that, for typical material shear strength of timber, for a 3-metre tsunami wave in the mangroves, 3-metre tall trees will snap and for a 6-metre tsunami wave, 8-metre tall trees will snap.

Trees overturn with their roots if the overturning moment exceeds the soil-resisting moment (Peck *et al.*, 1973; Bowles, 1988),

$$(F_i + F_d)\ \eta/2 > \pi\ R\ (D_1/2)^2 \qquad \text{(A12)}$$

where (Figure 6A1) R is the force of resistance of the soil to shearing at the interface between the root matrix and the soil and D_1 (D_1 ~4 D) is the width of the root system, and

$$R = c + P \tan\theta \qquad \text{(A13)}$$

where c is the cohesion (c ~ 75 kg m^{-2} for compacted clay, c = 0 for pure sand), P is the normal stress, and θ is the angle of internal friction (θ ~ 40^o for sand, θ ~ 0 for clay).

Key points and observations emphasized in the discussions

During the past 20 years, population pressure on coastal zones has nearly doubled — they house approximately 60 percent of the world's population. In Asia, several coastal localities are under threat from natural hazards, which can be divided into two main areas:

1. Hazards from land. Some examples are soil erosion caused by river deposition of silt from steep areas which occur in flat river valleys and can result in higher flood levels, or by large dams which can trap coarse sediments that normally sustain sediment wedges in coastal estuaries, and may lead to exacerbated coastal erosion.

2. Hazards from the sea, for example storms/typhoons, tsunami, coastal erosion or prograding (accretion) and salt spray (worst in arid areas where annual precipitation is less than one metre.

Mitigation measures have been discussed in Chapters 1 to 5; however, the synthesis presentation and relative discussions have highlighted that:

1. Human mortality from a tsunami is higher in coastal areas where people live along exposed beaches as opposed to areas protected by mangroves.
2. Coastal forests can provide some protection against a tsunami, in addition to all the other kinds of services and benefits such as food, wood and medicinal benefits for local communities, enhancing estuarine fisheries, trapping land-borne sediments and protecting reefs, providing self-scoured deep navigable channels, etc.
3. Mangrove trees may offer a higher protection than *Casuarina* or coconut trees.
4. It is important to note that mangroves, as well as other kinds of coastal forests, cannot stop big waves (for example, waves of three to six metres in height can snap mangrove trees three to eight metres in height respectively).
5. Indicative widths of mangrove bioshields could be:
   - typhoon: 100–300 metres
   - typhoon waves: 500–1 000 metres
   - storm surge: 200 metres
   - tsunami: 500–2 000 metres

In conclusion:

1. Coastal bioshields can provide some kind of protection, but cannot provide complete protection and should include an accepted "sacrificial zone" (i.e. the first lines of trees which could be damaged by the hazard).

2. As a consequence of this, natural hazard-prone localities should have well-developed and effective warning systems and evacuation plans, which should work in conjunction with the mitigation measures in order to save lives during the impact of natural hazards.

3. In the case of plantations, tree species should be chosen with care and based on the type and severity of hazards.

4. Mitigation solutions should involve entire watershed areas, not just coastal zones.

5. Where possible, relevant infrastructures (e.g. hospitals, schools, roads) in tsunami-prone areas should be located on high ground.