Protective functions of coastal forests and trees against natural hazards

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Abstract
On the basis of field data as well as fluid and soil mechanics and structural engineering, it is argued that mangroves and coastal forests need to be restored and even created to enhance the protection of coastal areas from salt spray, wind damage, and erosion from wind-driven waves and typhoon waves. These forests also save human lives during a tsunami below a threshold level that depends on the tsunami wave height and the characteristics of the forest. Mangroves also provide important ecohydrological services such as providing self-scoured navigable channels, sheltering coastal seagrass beds and coral reefs from excess sedimentation, and enhancing fisheries; these are all resources that the human population living along tropical estuaries and coasts rely on for their livelihood and quality of life. Mangroves are very susceptible to below-root level erosion from boat wakes and shallow water wind waves near low tide.

1. Introduction

Tidal wetlands, including mangroves and salt marshes, are essential to the maintenance of biodiversity of many estuaries by trapping sediment, converting nutrients to plant biomass, trapping pollutants and serving as a habitat for fish and crustaceans (Wolanski et al., 2004). They also enhance offshore fisheries as well as biodiversity in seagrass and coral reefs offshore (Manson et al., 2005; Wolanski et al., 2003). They also protect the coast from wave erosion (Mazda et al. 1997 and 2006; Prasetya 2006). They have helped saved human lives in the 2004 Indian Ocean tsunami (Kathiresan and Rajendran 2005; Vermaat and Thampanya 2006). Nevertheless mangroves are increasingly destroyed and degraded by human activities (see the review papers in this volume by Preuss 2006; Prasetya 2006; Latief and Ladi 2006). 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 its shores, as well as to protect the coast from wind damage, salt spray, coastal erosion, and even in saving human lives during a tsunami.

3. Protection against coastal erosion by absorption of wave energy

Wind waves and typhoon waves

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. The vector of the horizontal force F is the sum of the inertial F_i and drag F_d forces (Figure 1; Milne-Thompson 1960):

$$F = F_i + F_d \qquad (1)$$

where

$$F_i = C_m \rho_w V a \qquad (2)$$

$$F_d = 0.5 \rho_w C_d (D Z) |u| u \qquad (3)$$

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,

$$u = U \cos (kx - \omega t) \qquad (4)$$

$$a= 2 \pi U \cos (kx - \omega t) / T \qquad (5)$$

where

$$U = \pi H \cosh k(z+h) / T \sinh(kh) \qquad (6)$$

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

$$\omega^2 = g k \tanh (kh) \qquad (7)$$

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. Mangroves thus protect the coast from wave erosion by absorbing wave energy through the 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 Vietnam's Thai Binh province where *Kandelia candel* trees have been planted at 1 m intervals in a strip 1.5 km wide (toward offshore) and 3 km long (along the coast; Figure 2a). There was a wave swell of period 5-8 seconds entering the forest. They measured the rate of wave reduction, r, per 100 m of mangroves in the direction of wave propagation,

$$r =(HS-HL) / HS \qquad (8)$$

where HS and HL are the wave heights at the offshore edge of the mangrove forest and 100 m inshore in the mangroves respectively. r varied between 0.2 for 5-6 year old mangroves and 0.05 for 1 year old mangroves. Within six years after planting the trees have grown sufficiently that the wave height of 1 m at the open sea was reduced to 0.05 m at the coast (Figure 2a), enabling aquaculture ponds behind a coastal levee. Without the sheltering effect of mangroves the waves would arrive at the coast with wave height of 0.75 m (Figure 2b) and the levees would have been eroded and breached. Mazda et al. (2006) repeated that study for a *Sonneratia* plantation at sea protecting the Vinh Quang coast, also in Northern Vietnam. They found (Table 1) that because of their pneumatophores, the rate of wave reduction is much higher by up to a factor 3 for *Sonneratia* forests than for *Kandelia candel* forests (Mazda et al., 2006); leaves are important in absorbing wave energy.

Table 1. Wave reduction, r (in %) per 100 m of adult mangrove plantation (Data from Mazda et al., 1997 and 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

Another quantified example of mangroves protecting the coast is that of India's Bhitarkanika mangroves following the October 1999 super cyclone with a wind speed of around 260 km h^{-1} and a storm surge of about 9 m 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 with different protection; 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 the village that was not sheltered by mangroves and had a dyke that failed, followed by the village that was neither in the shadow of mangroves or the dyke (US$ 44), and the losses were the least for the village that was protected by mangrove forests (US$ 33).

Thus mangroves are efficient in protecting the coast.

Tsunamis

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

$$u = 0.5\ (g\ H)^{1/2} \qquad (9)$$

The trees absorb some of this wave energy through energy dissipation by drag forces. Because of the long duration of the tsunami wave, the trees cannot stop the wave. They can however transform this broken wave into a flood; the shock wave effect is reduced and thus human lives can be saved and damage to property is lessened, as long as the trees survive flattening, trunk breaking or overturning as has been documented in the worst affected areas in the December 2004 Indian Ocean tsunami (Figure 3). The propagation of a 5 m tsunami at the shore over a flat terrain that was either bare ground or heavily forested with mature trees of either *Kandelia candel* or *Sonneratia* was predicted using a dam break model (Chanson, 2005). The predictions (Figure 4) suggest that at a point 500 m from the shore the water depth rises 1 m in 77 sec for a bare ground, in 343 sec for *Kandelia candel* and 727 sec for *Sonneratia*.

The empirical evidence that mangroves helped save human lives is very strong. For instance Sri Lanka data suggest that in the Yan Oya River the 7 m tsunami in December 2004 reduced to 0.5 m 3.5 km upstream (point b in Figure 5a), and in the

Mahaweli Ganga River the tsunami wave was 12 m at the cost, 4 m in the Mudduchchenal Village (point b in Figure 5b) protected by a sand dune, and only 2 m at a point a similar distance as the village from the shore but additionally protected by trees. The saving in human lives and damage to property is substantial (Figure 6) though not 100% (Danielsen et al. 2005; see also http://eqtap.edm.bosai.go.jp/useful_outputs/report/hiraishi/data/papers/greenbelt.pdf).

Trees are thus effective as long as they are not uprooted or snapped at which case they form debris that may destroy human lives and property. 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),

$$4 (F_i + F_d) / 3 \geq \pi (D/2)^2 \sigma_s \quad (10)$$

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 en 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,

$$-G/ 2 \pi (D/2)^2 + \eta (F_i + F_d) D/2 / 0.25 \pi (D/2)^4 \geq \sigma_s \quad (11)$$

or the breaking strength in compression σ_c of the tree,

$$G/ 2 \pi (D/2)^2 + \eta (F_i + F_d) D/2 / 0.25 \pi (D/2)^4 \geq \sigma_c \quad (12)$$

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

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

$$(F_i + F_d) \eta/2 > \pi R (D_1/2)^2 \quad (13)$$

where (Figure 1) R is the force of resistance of the soil to shearing at the interface between the root matrix and the soil and D_1 ($D_1 \sim 4$ D) is the width of the root system, and

$$R = c + P \tan \theta \quad (14)$$

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 ($\theta \sim 40^o$ for sand, $\theta \sim 0$ for clay). The calculations suggest that a 3 m tsunami is thus able to uproot an isolated 3 m mangrove tree. However if the trees grow close together, then R_1 can become much larger as a result of interlocking of roots from adjoining trees. Thus densely vegetated trees of a height > 6 m may be able to sustain a 6 m tsunami wave. There is some evidence for that in the observations of the 2004 Indian Ocean tsunami.

Mangroves can thus survive and attenuate tsunami waves by transforming them in a flood instead of a shock wave. Thus they can save human lives and decrease property damage (Figure 6). However if the wave exceeds a threshold level, a catastrophic failure of the mangrove ecosystem occurs whereby snapped or uprooted trees are carried by the currents as debris to destroy tress in its path and create debris that harms 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.

All those results agree qualitatively with observations of the impact on mangroves of the 2004 Indian Ocean tsunami (Figure 3 a-d).

Non-mangrove trees such as *casuarnia* and palm trees also exerted a similar impact on absorbing tsunami wave energy, though their threshold level was smaller, about 2-3 m even for fully grown trees, at which the trees were snapped or uprooted (Figures 3e; http://river.ceri.go.jp/rpt/asiantsunami/en/survey.html).

Erosion from wind waves and boat wakes

Mangroves and other trees fringing rivers, estuaries and coasts are however 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. When the erosion starts, the erosion can be swift, taking sometimes only a few weeks, until the undercut trees fall down in the water (Figure 3f).

4. Protection of the coast against wind and salt spray

In the same way that the water current through a mangrove forest is decreased by the 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 7a) is decreased throughout the height of the tree, H, particularly at leaves' height. This diminishes the momentum of the air exiting the canopy and thus shelters the area downstream by a wake effect to a distance L rarely longer than 5 H (Figure 7b), as dictated by classical fluid dynamics. Because the flow around vegetation is three-dimensional, the sheltering distance L (i.e. the length of the wake) can be significantly increased if the trees are grown in a wide shelterbelt (one or two rows of trees whose canopy touches each other) and forest belts (multiple rows); then $L \approx 20H$ if the wind blows perpendicular to the shelterbelt and $L < 5H$ if the wind blows parallel to the shelterbelt (Takle et al. 2006). A wide shelterbelt forms a long turbulent wake in its lee (Figure 7c).

This sheltering effect diminishes if the tree is partially or partially defoliated (Figure 7 d-e) and disappears if the tree is overturned (Figure 7f). Large trees are overturned more readily than small trees (Figure 6f) because they are exposed to stronger winds as a reason of the wind shear near the ground (Figure 7a). Experience with cyclones in Australia and hurricanes in the USA shows that full defoliations of fully developed mangrove mature trees happens only during super cyclones winds, and is typically restricted to a strip less than 50 m wide (M. Williams, pers. comm.).

The foliage of some non-mangrove trees such as *casuarina* is less hardy and the tree can be defoliated for severe but non-cyclonic winds. These trees often also are much more readily snapped or overturned by the wind; they thus 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 air (Figure 7b; Takle et al., 2006). Just like the water flow through mangrove forests creates less turbulent wakes behind trees where the suspended mud deposits, the air flow downwind of trees creates less turbulent zones where the suspended salt particles deposit. This effect extends to a distance ≈ 10 H downwind of a windbreak. Thus a wide shelterbelt projects a wide turbulent wake that is very efficient at capturing salt particles in suspension (Figure 7 c-d). This process traps the salt spray near the coast, facilitating its return to the sea rather and preventing the salt to pollute inland soils.

5. Ecohydrological services provided by mangroves

Mangrove provide important ecological services (Badola and Hussain 2005; Blaber 1997; Prasetya 2006; Preuss 2006). Three key ecohydrological services provided by mangroves are summarised below.

a. Enhancement of estuarine and coastal fisheries

Mangroves are an important component of tropical estuarine and coastal ecosystems. Mangroves provide for marine animals a refuge from predators, high levels of nutrients, and shelter from physical disturbance (Manson et al. 2005). Typically 1 ha of mangrove forests support 100-1000 kg yr^{-1} of marine fish and shrimp catch; for the Mekong this catch is about 450 kg yr^{-1} (de Graaf and Xuan 1998).

Mangroves are also important in supporting fish. An ecohydrology model was applied to Darwin Harbour, Australia, and calibrated against field data. Darwin Harbour covers 3227 km^2. The land drainage area is 2417 km^2, about 10% of which is mangrove. The harbour is a macro-tidal estuary with three arms, each of which drains a seasonal river with negligible flow in the dry season. During that time, Darwin Harbour is an inverse estuary. Seawater enters the estuary as a result of evapotranspiration. In the dry season the flushing time of water is about 20 days. This period of time for is sufficient for the biology to become important. The model reveals that the mangroves are essential for the fisheries, because if they were destroyed the carnivorous fish would decrease by 70% and the detritivores by 50%, in the mangrove-fringed reaches where they are presently abundant (Wolanski et al., 2006).

b. Trapping of fine sediment

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 it comes in and what goes out is the sediment trapping (Figure 8). As a rule of thumb, as sketched in Figure 9a, a mangrove that covers 3.8% of the river drainage area traps about 40% of the riverine mud inflow; of the remaining 60%, 20% contributes to estuarine siltation and 40% is exported to coastal waters. This relationship is independent of land use in the catchment, holding true for catchment sediment yield in the range 1.5 to > 150 tons km^{-2} $year^{-1}$ (Victor et al. 2004 and 2006).

Mangroves fringing muddy open waters trap large amounts of mud from coastal waters (e.g. Figure 9b).

Thus mangroves also can shelter coastal seagrass and corals from excessive sedimentation.

c. Maintaining navigable channels

Mangrove creeks are self-scouring (Wolanski et al., 2001). During spring tides there exists a marked tidal asymmetry of the currents in the channel or estuary that drains the mangroves, the peak ebb tidal currents at the mouth of the creek being measurably larger than the peak flood tidal currents (Figure 10). If the mangrove area decreases from mangrove land reclamation, the creek silts. Examples of that abound in areas where developers, such as prawn farmers in Thailand, have reclaimed mangrove land. In the case of the Klong Ngao estuary in Thailand where half of the mangrove land was reclaimed, the tidal creek has been observed to silt within 5-10 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). This sedimentation can be even more rapid when the sediment inflow has increased in the river catchment as a result of poor land use (Wolanski and Spagnol 2000).

6. Discussions

Bioshields

Mangroves and coastal forests provide important ecological services that provide a livelihood for the local population and help improve their quality of life. They help protect the coast from wave erosion from wind-driven waves and typhoon waves. Mangroves and coastal forests can save human lives and property in a tsunami, by transforming a shock wave into a flood, at least up to a threshold level. They also shelter the inland from salt spray and wind damage up to a threshold level. These findings are observed in the field and 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 against natural hazards, as well as to improve the quality of life of the human population, are numerous. Where possible thus it is necessary to conserve and even create mangroves and coastal forests and this is compatible with economic and social development (Wolanski 2006).

Creating these bioshields is very much soft technology that involves tree plantations on land as well as restoring former mangrove areas or even planting over coastal areas.

Restoring mangroves

Recreating mangroves from abandoned shrimp ponds is the ‘easiest’ option; it has the additional benefit to enable some parallel commercial activities. For instance fish and crab ponds in the mangrove-fringed tidal creeks can be successful. However planting mangroves in shallow shrimp ponds as is tried in Vietnam largely fails (B.Clough, pers. comm.). Planting seedlings in reclaimed shrimp ponds fails if the natural drainage pattern is not properly restored and the seedlings rot in stagnant water (Figure 11a). This is not always successful. The degree of success depends on local expertise in finding and selecting seedlings, growing seedlings in nurseries, local soil conditions, the choice of locations, the elevation of the substrate and frequency of tidal inundation, the acidity and salinity of the degraded soils, and on water currents, tides and storms (see a review of the technology by Prasetya 2006). Soil preparation is needed for former mangrove soils that have turned acidic when used as shrimp ponds.

Mangroves at sea

There have even been mangrove forests created at sea by planting seedlings over a wide, intertidal area above mean sea level; this was done successfully over a muddy substrate in Vietnam (Mazda et al. 1997 and 2006), with moderate success over a muddy sand substrate in Thailand (e.g. in Eritrea, see Figure 11b; in Thailand’s Chumphon Bay; Brown and Limpshaichol, 2000), and has somewhat failed in the upper Gulf of Thailand due to persistent wave erosion (Figure 11c). Where waves dominate, attempts have been made, with mixed success, to protect the young trees until it can survive the waves. Some techniques include (1) to let the seedling grow much longer in a nursery until it becomes a small tree that can better resists waves, (2) to plant the seedlings in hollows within solid structures such as tyres or hollows in a concrete structure, (3) to plant the seedlings in transparent PVC tubes (Figure 11d), and (4) to protect the seedlings behind temporary structures such as bamboo walls. Mixed success is achieved, because in this case people try to plant mangroves in wave-dominated areas where they would not occur naturally.

Sacrificial bioshields
The seaward edge of the forest (mangrove or non-mangrove) is the sacrificial zone (Takle et al., 2006).; it takes the brunt of the damage due to "flagging" by wind, high salt impaction, and occasionally total defoliation in typhoons, and the destruction of the tree in typhoons and tsunami. It must be managed as such, by accepting that this zone is unsteady and unstable and thus not allowing human settlements, and by allowing for natural regeneration, replanting of destroyed trees, and possibly even building artificial fences to better protect the first line of trees from lethal salt and wind damage in high impact zones.

Limitations and constraints
In practice the level of applicability of these science-based principles depends on the local climate, hydrology, drainage patterns, meteorology, oceanography, soil types, waves, storm patterns, and socio-economic drivers. Climate change may complicate the situation. There is no unique recipe; nevertheless the failure to recognize these science-based principles will always result in environmental and socio-economic degradation. The applicability of these principles to various sites is more to do thus with the willingness and the capacity of individual countries to adopt mangroves and coastal forests as bioshields, on a case-to-case basis. The level of adoption will depend on socio-economic imperatives. Where the coast has been totally urbanized, by planned developments or slums, that 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 livelihood and quality of life. The protection that bioshields offer is far from total, it involves risks because the usefulness of bioshields has limits in extreme events. The bioshield solution has the advantage that it is often practical, inexpensive by comparison with pure engineering solutions such as the Dutch solution of dyking the coast, relatively low technology, and it protects and enhances the environmental services provided by estuaries and coastal waters on which the population often depends for their livelihood. It is thus a matter of living within accepted risks.
The level of risk will vary from site to site with details of the bathymetry of the coastal waters and the topography of the coastal areas, the geology, the meteorology, and the oceanography. Judging from typhoon statistics alone, no two sites are alike in Asia, suggesting that the relevance and use of bioshields will vary spatially just as much (Takle et al. 2006).

What science needs to provide now is a synthesis of all this physical and biological knowledge so that the risk can be quantified for individual sites for various choices of bioshields' characteristics, size and location. This is very much a new science;

unfortunately at present the risk can be qualified from basic science processes and empirical evidence, but it cannot be quantified yet for predictive purposes for specific applications of bioshields at individual sites.

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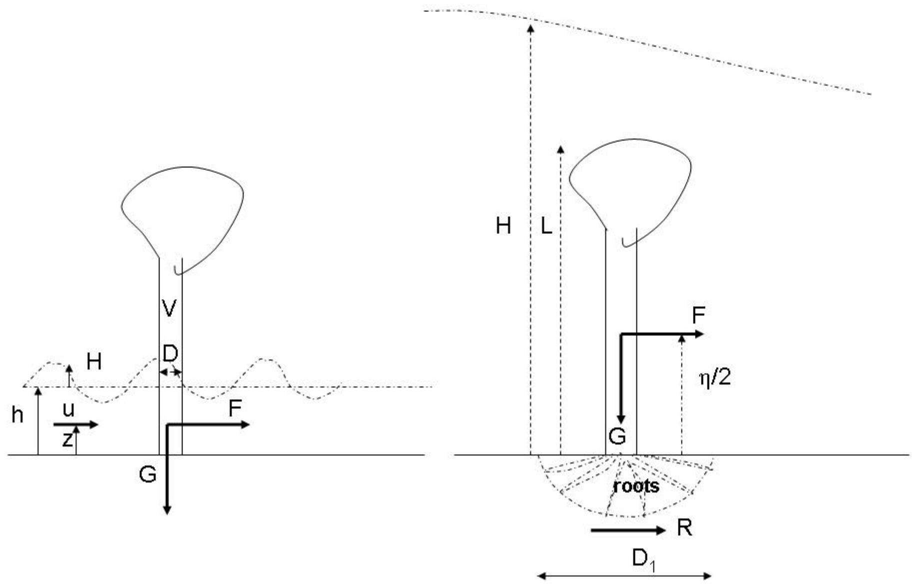

Figure 1. Idealised wind and typhoon waves (left) and a tsunami wave (right) through trees showing terms used in text.

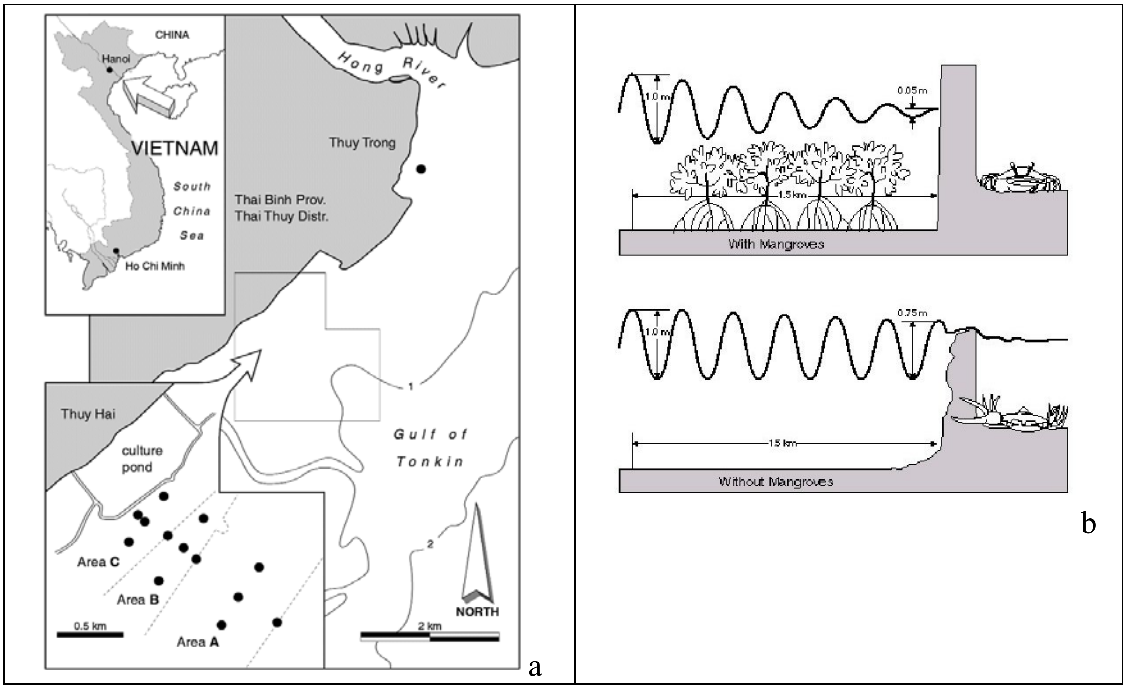

Figure 2. (a) A map of the mangrove-fringed Thuy Hai coast in the Thai Binh Province, Vietnam. Groups A, B and C are mangrove plantations comprising respectively 0.5 year-old trees, 2-3 year-old trees and 5-6 year-old trees. The symbols • indicate the field measurements sites of tides, waves and currents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

Figure 3. (a-d) photographs of mangroves damaged by the Indian Ocean 2004 tsunami. (a-b) mangroves snapped. Note in (a) that 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 with its roots. (d) the catastrophic failure of mangroves occurs when large trees break and are carried as debris destroying smaller trees, property and human lives. (e) Other trees beside mangroves, such as this palm tree, were also uprooted or snapped, by this tsunami. (f) Mangroves destroyed by small wind-driven waves undercutting the banks at low tide on the Daly Estuary, Australia. A similar effect results from boat wakes. Sources: Muntadhar et al., V. Selvam, the Internet, the author.

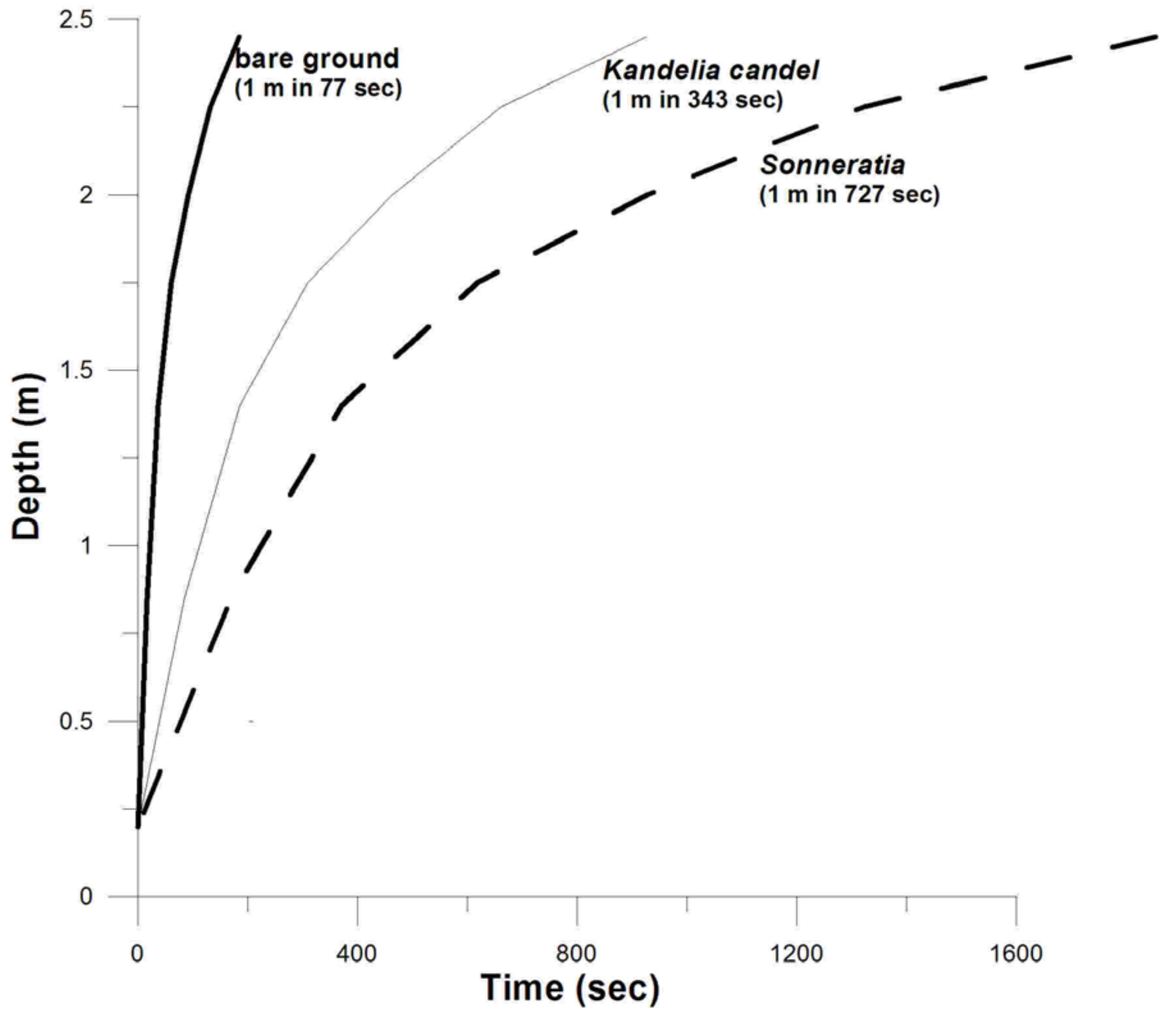

Figure 4. Model predictions of the rise of water level at a point 500 m from the shore for a flat terrain following a 5 m tsunami at the shore, for three scenarios, namely a bare ground, mature *Kandelia candel* forest and mature *Sonneratia* forest. The trees are assumed not to be destroyed by the wave. Time starts when the tsunami arrives at that point.

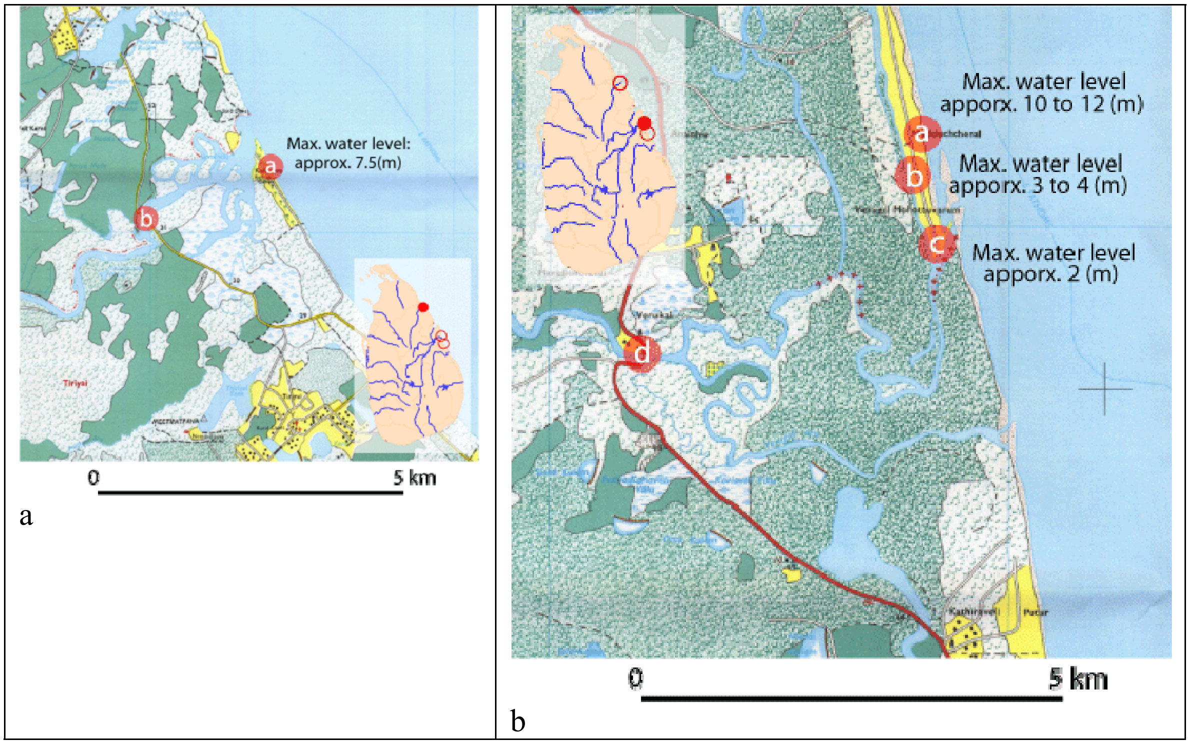

Figure 5. Maps of the mouths of the (a) Yan Oya River and (b) the Mahaweli Ganga River, together with estimate of maximum water level during the Indian Ocean 2004 tsunami. Source: http://river.ceri.go.jp/rpt/asiantsunami/en/survey.html

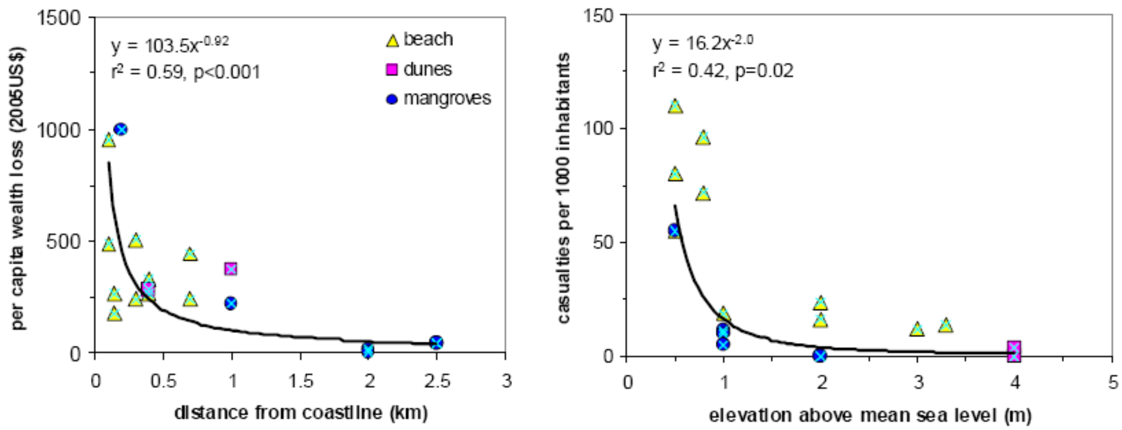

Figure 6. For the December 2004 Indian Ocean tsunami, plot of property loss (per capita 2005US$, left) and mortality (lives lost per 1000, right) in 18 hamlets on the coast of Tamil Nadu against distance from the shore (km) and elevation above mean sea level (m), respectively. Different symbols depict different coastal types. The fitted curve is to the pooled data set of 18 hamlets. Reproduced from Vermaat and Thampanya (2006).

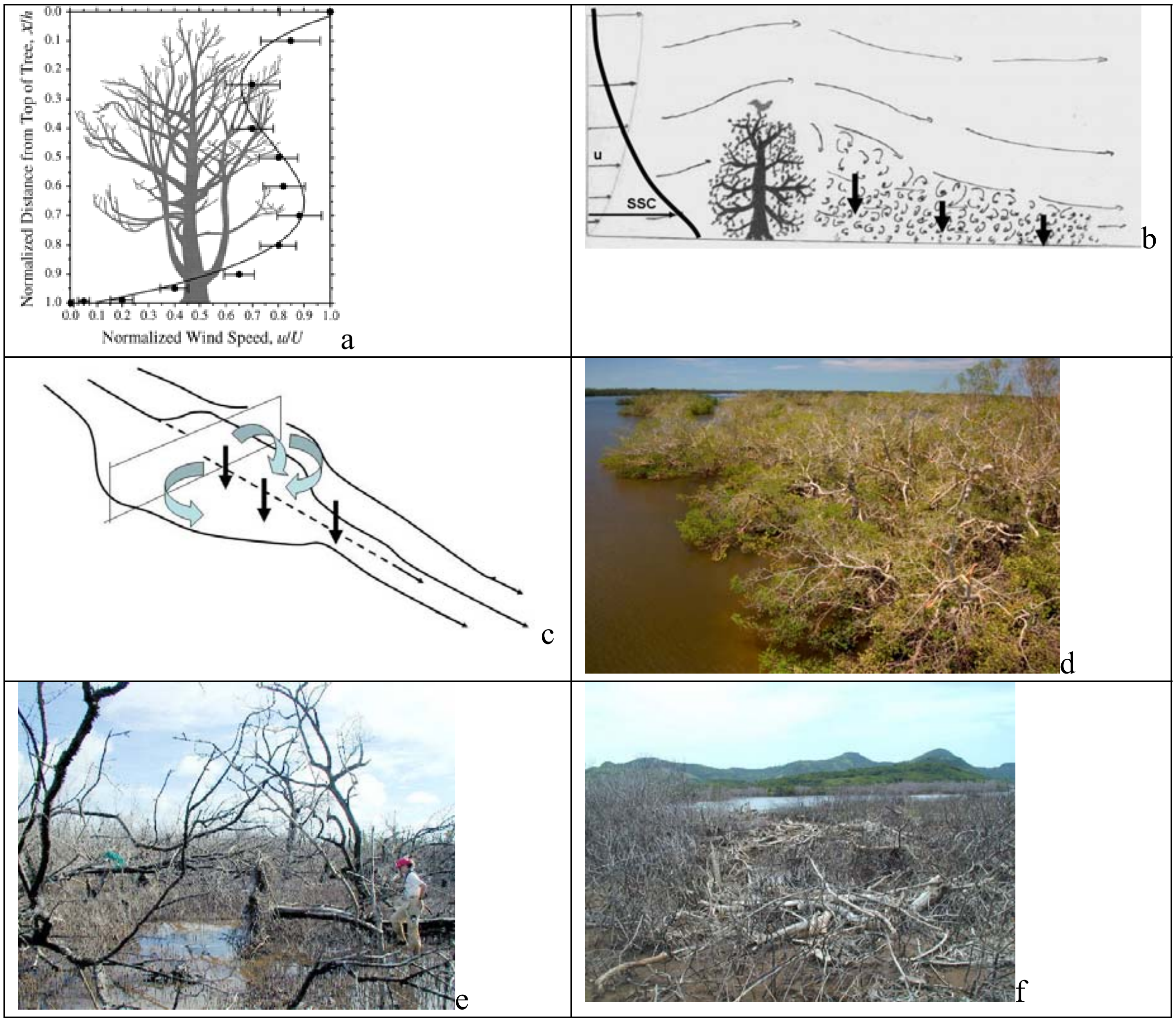

Figure 7. (a) Vertical profile of wind speed *u* through a 13.1 m high wild cherry tree, 0.4 m in diameter at 0.5 m from ground level, growing in an open site. The velocity is normalised by the maximum wind speed *U* measured at the top of the canopy Silhouette of tree shows all branches for which *d* >5 mm. Reproduced from Niklas et al. (2000). Sketch of the air flow around, over and through (a) a single tree and (b) a shelterbelt, showing that that the wind accelerates over and around the vegetation, and a turbulent wake forms behind the tree; SSC = suspended salt concentration. Down arrows = deposition of the salt particles in the wake. Mangroves in Florida defoliated (d) partially and (e) totally by the wind in a hurricane, and (f) overturned by the hurricane wind; large trees are overturned more readily than small trees. Source: USGS Florida.

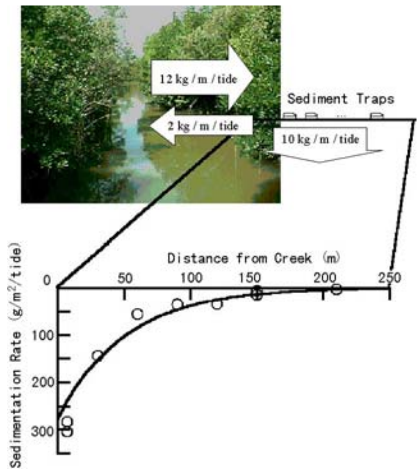

Figure 8: Composite diagram illustrating the net fluxes of suspended sediment in the mangrove swamp originating from the tidal creek. About 80% of the sediment entering the swamp at rising tide remained trapped in the swamp and was not exported back into the creek at falling tide. The sediment traps reveal that the bulk of the suspended sediment deposited within 50 m from the edge of the creek. Reproduced from Wolanski et al. (2001).

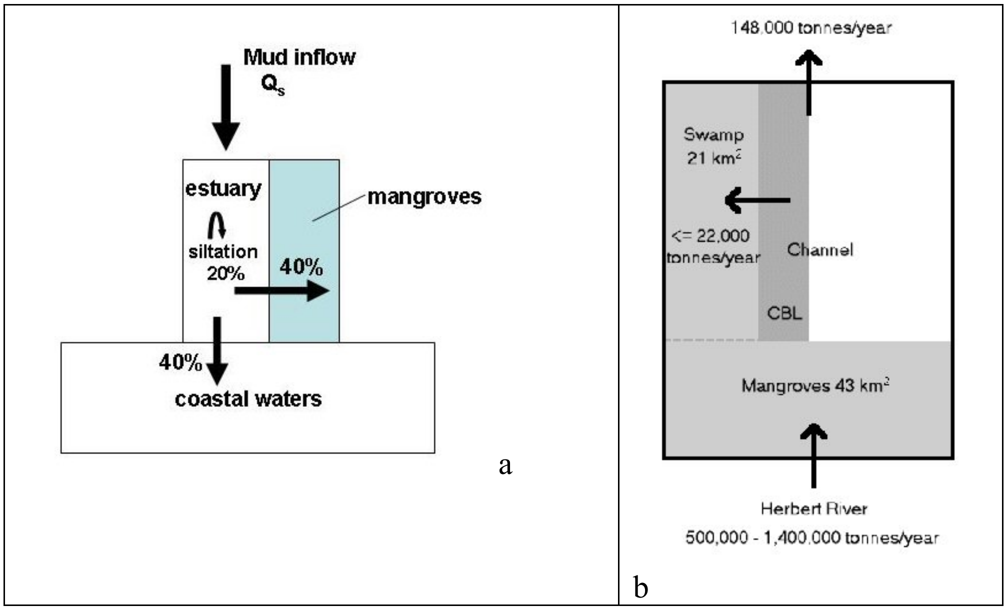

Figure 9. (a) Sketch of the fate of riverine mud in tropical, muddy, estuaries fringed by a mangrove that covers 3.8% of the river catchment area. (b) Sketch of the fate of riverine mud in the mangrove-fringed open waters of Hinchinbrook Channel, Australia (Adapted from Wolanski et al., 1998).

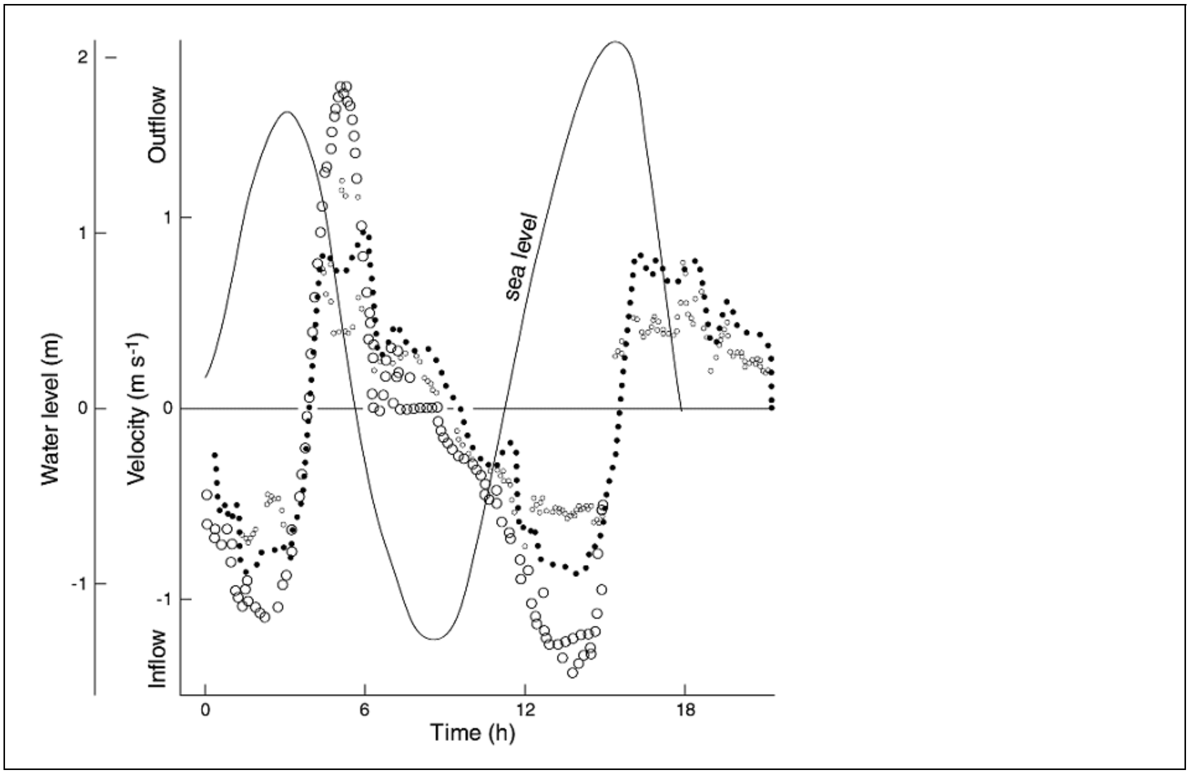

Figure 10. Time series plot over one tidal cycle of the observed currents at the mouth of a 5km long mangrove creek in Missionary Bay, tropical Australia, at different depths from near the surface (O), in mid-water (•), to near the bottom (o), during a spring tidal cycle when the mangroves were fully inundated at high tide. The creek receives no freshwater except direct rainfall. The thin line is the sea level at the mouth. Note that the peak currents are larger at ebb tide than at flood tide. Reproduced from Wolanski (1992).

Figure 11. (a) In this mangrove plantation in a reclaimed shrimp pond near Surat Thani in Thailand, mangrove seedlings died in an area where water ponded. (b) Planting of mangrove seedlings in Eritrea where mangroves did not exist (http://www.ramsar.org/wwd/3/wwd2003_rpt_eritrea1.htm). (c) Efforts to plant mangroves along the north coast of the Inner Gulf of Thailand are somewhat unsuccessful due to accelerated wave erosion since the natural mangroves were destroyed and replaced by shrimp ponds; hard structures are necessary to combat wave erosion. (d) Protection of mangrove seedlings in the Riley encased method (Riley and Kent 1999; http://mangrove.org/video/rem.html).