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Vegetation bioshields for tsunami mitigation: review of the effectiveness, limitations, construction, and sustainable management

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Abstract

Coastal vegetation has been widely recognized as a natural method to reduce the energy of tsunami waves. However, a vegetation barrier cannot completely stop a tsunami, and its effectiveness depends on the magnitude of the tsunami as well as the structure of the vegetation. For coastal rehabilitation, optimal planning of natural coastal systems and their maintenance, we need to quantitatively elucidate the capacity of vegetation to reduce the energy of tsunami waves. The limitations of coastal forests in relation to the magnitude of a tsunami and the maintenance of forests as natural disaster buffer zones have to be understood correctly for effective coastal vegetation planning. Demerits of coastal forests have also been revealed: for example, an open gap in a forest (i.e., a road, river, difference in elevation, etc.) can channel and amplify a strong current by forcing it into the gap. Floating debris from broken trees also can damage surrounding buildings and hurt people. However, many studies have revealed that these demerits can be overcome with proper planning and management of mangroves and coastal forests, and that coastal vegetation has a significant potential to mitigate damage in constructed areas and save human lives by acting as buffer zones during extreme natural events. However, the mangrove forests have been damaged by anthropogenic activities (i.e., tourism, shrimp farming, and industrial development), making coastal areas increasingly vulnerable to tsunamis and other natural disasters. The effectiveness of vegetation also changes with the age and structure of the forest. This highlights the fact that proper planning and management of vegetation are required to maintain the tsunami buffering function of coastal forests. Although many government and non-government organizations have implemented coastal vegetation projects, many of them have been unsuccessful due to a lack of proper maintenance. A pilot project in Matara City, Sri Lanka, revealed that participation and support from local authorities and communities is essential to make the planting projects successful. An integrated coastal vegetation management system that includes utilization of the materials produced by the forest and a community participation and awareness program are proposed to achieve a sustainable and long-lasting vegetation bioshield.

Key words: tsunami protection, buffer zone, forest structures, participation and support of local authorities, integrated management system

Introduction

Tsunamis, along with earthquakes, volcano eruptions, and cyclones, are one of the most dreadful natural disasters that can cause catastrophic damage to both human life and socioeconomic property. Tsunamis are defined as a series of waves of extremely long wave length and long period generated in a body of water by an impulsive disturbance such as an underwater earthquake, submarine landslide, volcanic activity, or bolide impact and that vertically displaces the water (Clague et al., 2003). When a tsunami reaches a coast, it may appear as a rapidly rising or falling tide or a series of breaking waves. When a tsunami reaches the shore, part of the tsunami wave is reflected offshore, but most of it slows, increases in height, runs up towards the land with tremendous energy, and causes massive destruction on the coast and in the hinterlands.

Preparedness, escape, and mitigation are representative countermeasures to protect humans and infrastructure facilities from natural hazards. Mitigation techniques are broadly categorized in two ways. These are artificial methods (hard solutions) and natural methods (soft solutions utilizing a natural buffer zone of coastal vegetation, sand dunes, or coral reefs). Artificial methods are mainly kinds of sea walls (tsunami gates, huge embankments) that can be constructed on the coastal area for any predicted tsunami height. However, the construction costs of the artificial methods can be very high, which restricts development in many cases. Some developed countries like Japan, which has frequent tsunamis or storm surge threats, have employed such techniques. On the other hand, the use of costal vegetation as a natural method for disaster mitigation was also discussed in Japan more than 100 years ago (Honda, 1898). Recently, natural methods have been widely understood to reduce the tsunami energy remarkably, although they cannot completely stop the tsunami itself, and their effectiveness depends on the magnitude of the tsunami and the type of vegetation structure. Shuto (1987) analyzed the effects and limitations of coastal vegetation from historical records of tsunamis that occurred in Japan. Since the 1998 Papua New Guinea tsunami especially (Dengler and Preuss, 2003), many researchers have begun investigating the effects of coastal vegetation on tsunami mitigation using field investigations (Hiraishi and Harada, 2003), water flume experiments (Harada and Imamura, 2000), and numerical simulations (Hiraishi and Harada, 2003; Hamzah et al., 1999). After the Indian Ocean tsunami on 26 December 2004 (Rossetto et al., 2007), further research was carried out to elucidate the effectiveness of coastal vegetation (Danielsen et al., 2005; Kathiresan and Rajendran, 2005, 2006; Dahdouh-Guebas et al., 2005; Harada and Kawata, 2005, Harada and Imamura, 2006; Tanaka and Sasaki, 2007; Tanaka et al., 2006a, 2006b, 2007; Sasaki et al., 2007; Nandasena et al., 2007) and coral reefs (Fernando at al., 2005) in order to minimize infrastructure damage and protect human lives. Danielsen et al. (2005) pointed out that the deterioration and clearing of mangroves and other types of coastal vegetation along many coastlines has increased their vulnerability to storm and tsunami damage. This suggests that establishing or strengthening greenbelts of mangroves and other coastal forests may play a key role in reducing the effect of future extreme events.

Therefore, natural methods that employ coastal vegetation together with other natural features such as sand dunes and submerged reefs have been studied because they require relatively little capital investment compared to artificial measures, provide human-friendly beach fronts, and enhance inter-relationships with other ecological systems.

For coastal rehabilitation, that is, optimal planning of the natural systems and their maintenance, we need to quantitatively elucidate the effects of vegetation on the reduction of tsunami potential. This requires knowledge of the limitations of coastal forests in tsunami mitigation and consideration of how to maintain the forest as a natural disaster buffer zone. The objectives of this article are to review the important points about the 1) effectiveness and vulnerability of coastal forests against tsunami revealed by field investigations and numerical simulations, 2) breaking conditions of coastal tree species and forests, 3) implications of results obtained from flume experiments and numerical simulations, and 4) future establishment and management of coastal vegetation.

Effectiveness and vulnerability of coastal forests against tsunami revealed by field investigations and numerical simulations

Effectiveness of coastal forests in tsunami mitigation

Dengler and Preuss (2003) investigated the disaster caused by the 1998 Papua New Guinea tsunami and found that *Casuarina* trees presented relatively greater resistance than palm trees. However, they pointed out the need to conduct further research in understanding the interaction of trees, roots, and high-flow water regimes in order to utilize vegetation as a tsunami abatement measure because significant scouring occurred in the areas where the root systems were undermined, and in some cases, trees caused additional damage to their surroundings in the fast-moving water. This demerit was also pointed out by Shuto (1987).

Kathiresan and Rajendran (2005) concluded that the presence of mangroves reduced the human death toll along the Tamil Nadu coast of southeast India, although Kerr et al. (2006) argued that this is an oversimplification of a complex scenario. All mechanistically important factors should be addressed in considering the issue. However, the buffering behavior of mangroves has been examined in many other post-tsunami investigations. Dahdouh-Guebas et al. (2005) showed by cluster analysis that the man-made structures located directly behind the most extensive mangroves were less damaged, while Danielsen et al. (2005) reported that a dense mangrove of *Rhizophora* spp. and *Avicennia* spp. (density = 14-26 tree trunks per 100 m^2) contributed to low damage in 96% of surveyed cases in India. Exposed villages suffered the highest levels of damage, and those behind mangroves experienced intermediate levels of damage.

Effects of forest density, tree diameter, and stand structure of trees

Field surveys in Sri Lanka and Thailand after the Indian Ocean tsunami showed that older *Casuarina equisetifolia* belts on the coast withstood the tsunami but failed to provide good protection (Tanaka et al., 2006a, 2006b, 2007). Tanaka et al. (2007) showed that tree growth and forest density can have a significant effect on tsunami mitigation because trees with larger trunk diameters require more space (lower tree density) between them to grow. It suggests that trunk diameter and density effect, important parameters for estimating vegetation drag, cannot be discussed independently. Tanaka et al. (2007) reported that the relationship between the crown height and tsunami height is also important in terms of the drag characteristics of broad-leaved trees because they have branches with large diameters. The United Nations Food and Agriculture Organization (FAO) (2007) stated that active forest management is required to produce variously-aged stands of trees with a range of sizes and with branches at all levels to enhance the potential for mitigation, particularly in smaller tsunamis, because the mitigation potential of *Pinus* spp. and *Casuarina* spp. declines with age due to self-thinning (density is decreased) and because tree crown height exceeds the tsunami water depth, etc.

A combination of different tree species is recommended in a buffer forest (Tanaka et al., 2007, 2008b). *Pandanus odoratissimus* was observed to grow under the shade of the taller *Cocos nucifera* and *C. equisetifolia*. In field observations, two layers of vegetation, *P. odoratissimus* and C. *equisetifolia*, in the vertical direction exhibited a strong potential to decrease the damage behind the vegetation cover (Tanaka et al., 2007), but a combination of *P. odoratissimus* and *C. nucifera* had little effect because they leave wide gaps vertically. *C. equisetifolia* is recommended as an appropriate tree species for a mixed forest. If it does not break, it traps debris. Considering the other roles, i.e. trapping debris and providing something to climb to escape or a soft-landing place for people, that coastal vegetation plays (Shuto, 1987; Tanaka et al. 2006b, 2007), a two-layer forest of *P. odoratissimus* and dense *C. equisetifolia* should be planted and preserved near the coast, and other broad-leaved trees should be grown behind this buffer forest (towards inland), as shown in Fig. 1 (Tanaka et al., 2007).

Importance of forest undergrowth

The characteristics of the undergrowth and soil resistance are also understood to be important factors in the case of plantations or fringe areas of *P. odoratissimus* or *C. equisetifolia* vegetation (Tanaka et al., 2007). Poor soil resistance allows scouring by the high flow velocities and shear stresses of the tsunami current, and this can uproot trees and reduce the mitigation effect (Shuto 1987, Tanaka et al. 2007, Dengler and Preuss 2003). Sasaki et al. (2007) also indicated the importance of coastal grasses (*Ipomoea pes-caprae*, *Spinifex littoreus*) in front of a coastal forest to decrease the depth of sand dune erosion when the tsunami water depth is not large, whereas Mascarenhas and Jayakumar (2008) reported that most of the *Ipomoea* creepers and *Spinifex* were uprooted and removed by a tsunami, often leaving no trace of frontal dune vegetation. The removal condition of undergrowth in forests and creepers in front of the forest zone should be analyzed because it affects the removal condition of the frontal trees.

Vulnerability of sand dunes, coastal vegetation, and coral reefs: Open gap problem

A gap in the coastal zone is reported to increase risks and potential damage. Gaps in sand dune vegetation are due to natural or artificial causes, such as construction of access roads to a beach or for sand mining, the mouths of rivers, mangrove channels opening onto the sea (FAO, 2007), and coral reefs for constructing headlands or embayments (Fernando et al., 2005). The water flow through the gaps is accelerated as it moves into the constriction (FAO, 2007; Fernando et al., 2005, 2008; Mascarenhas and Jayakumar, 2008; Tanimoto et al., 2008a, 2008b). When the gap is narrow, it increases the velocity immediately behind the gap, although the water depth will actually decrease in most cases (Struve et al., 2003, Nandasena et al., 2008). The areas behind a coastal forest can still be protected from the tsunami (FAO, 2007; Thuy et al., 2008), but gaps increase the hazards in the gap line (Fernando et al., 2005, 2008; Tanimoto et al., 2008a; Cochard et al., 2008). Because it is not realistic to consider a coastal forest without any gap in the barrier, careful planning is required in the design of an actual coastal forest to incline the gap direction away from the tsunami current direction or to stagger it to reduce the water velocity through the gap.

Breaking conditions of coastal tree species and forest due to tsunami force

Damage to single tree

Tanaka et al. (2006b, 2008b) conducted tree breaking tests in situ using small diameter trunks or branches and showed that the breaking moment curve of representative tree species can be classified into three parts by elasticity and habitat as

1) the curve for coastal vegetation (ex. *P. odoratissimus*),

2) the curve for elastic trees

3) the curve for trees with hard trunks (ex. *C. equisetifolia*).

Although the breaking test was conducted in Sri Lanka before the 2006 Java tsunami (Tanaka and Sasaki, 2007), the breaking condition coincided well with the actual damage observed at the sites of the Java tsunami, except for *C. equisetifolia*. *C. equisetifolia* does not have aerial roots, but its diameter becomes greater at ground level than at breast height as the tree grows. Thus, its trunk was rarely broken. Most of the damage to *C. equisetifolia* was due to uprooting. This indicates that the breaking condition is not well expressed by the breaking test using *C. equisetifolia* with small trunk diameters. Further study of the breaking or uprooting conditions for *C. equisetifolia* is recommended with real-scale breaking or uprooting tests like those of Peltola et al. (2000) because *C. equisetifolia* is expected to be an effective species for dissipating tsunami energy in Sri Lanka, Thailand (Tanaka et al., 2006a, 2006b, 2007; FAO, 2007), and India (Mascarenhas and Jayakumar, 2008).

Tanaka and Sasaki (2007) examined the height at which *P. odoratissimus* and *C. nucifera* trees were broken in two tsunamis (the 2004 Indian Ocean and 2006 Java tsunamis) and found that the threshold of tsunami water depth at which a tree trunk broke was about 80% of the tree height for *P. odoratissimus*. *C. nucifera* was seldom damaged except for small trees, but when it was toppled, the critical tsunami height was about 80%, the same as *P. odoratissimus*. Because the breaking point of *P. odoratissimus* is 1-2 m high, the moment by drag at that point is smaller than that of a tree without aerial roots. Although the threshold tsunami water depth for breaking *P. odoratissimus* is similar to that for *C. nucifera*, the trunk strength of *P. odoratissimus* is not as great and it receives a large drag force from the tsunami current when the tsunami water depth is greater than the height of its aerial roots.

The studies by Tanaka and Sasaki (2007) and Tanaka et al. (2008b) elucidated the breaking condition for a single tree when the scouring around the tree is not severe. However, the breaking condition is not applicable for critical tree damage in the fringe area of a forest, especially the frontal vegetation on sand dunes where the substrate is not hard and severe scouring occurs.

Parameters of effects and limitation of coastal forest for tsunami mitigation

Shuto (1987) discussed the effectiveness and limitations of a forest on the reduction of tsunami energy. He classified the degrees of damage to a forest due to tsunamis, i.e., no damage, tilting or turnover due to large scouring, and trunk breakage or uprooting. The classification was based on the characteristics of a forest from the records of five previous huge tsunamis (in 1896, 1933, 1944, 1960, and 1983) that had occurred in Japan and the forest damage at the tsunami events. The relationships between the tsunami inundation depth and tree diameter at breast height and the extent of the forest were statistically analyzed considering the physical aspects of tsunamis. The length of a forest in the streamwise direction, the size and density of the trees, and the undergrowth are important parameters of tsunami energy reduction. In particular, he derived a simple but important parameter for discussing the degree of the forest damage, the ‘dn’, where d is the tree trunk diameter at breast height (cm), n is the number of trees in a forest in the streamwise direction and in unit widths in the cross-stream direction (trees within the area of the forest length in the streamwise direction (m) × 1 m in the cross-stream direction) as a major measure of resistance by a forest, assuming that the drag coefficient is constant with the changing tree density.

After the Indian Ocean tsunami, Tanaka et al. (2007) investigated the effectiveness of Shuto’s classification (1987). The damage to *C. equisetifolia* almost satisfied the criteria using the *dn*. However, the *dn* of *Anacardium occidentale* and *Avicennia alba*, broad-leaved trees, and *P. odoratissimus* and *Rhizophora apiculata*, which have aerial roots, were not well classified because the large diameter branches or aerial roots add additional drag that Shuto (1987) did not consider. Thus, to distinguish the effects of tree species, Tanaka et al. (2007) recommended calculating the effective cumulative tree diameter in the stream-wise direction, dN_{all} (cm/(vegetation width (m) ×1 m)), as:

$$dN_{all} = dn \times \frac{1}{h}\int_0^h \alpha(z)\cdot\beta(z)dz$$

where, h is the tsunami water depth, $\alpha(z)$ is an additional coefficient that expresses the effect of the cumulative width of a tree at each height on the drag, and $\beta(z)$ is an additional coefficient representing the effect of leaves or aerial roots on the drag.

Mascarenhas and Jayakumar (2008) also reported the length of vegetation damage in the streamwise direction. *Casuarina* plantations remained intact except for the frontal strips, a few trees that faced the ocean, when tsunami run-up levels ranged from 0.7–6.5 m and the length of flooding area from the coast varied from 31–862 m. Although the threshold breaking condition of a single tree has been elucidated (Tanaka and Sasaki, 2008; Tanaka et al., 2008b) and some investigations reported the breaking length of a forest in the tsunami current direction (Tanaka et al., 2007; Mascarenhas and Jayakumar, 2008), the breaking length of a forest has still not been quantitatively evaluated according to the tsunami condition. More study is needed to estimate the length because the breaking affects the dissipation of tsunami energy.

Implications of information obtained from flume experiments and

numerical simulations

Drag force acting on trees or vegetation

Various models and mathematical studies have shown that the magnitude of the energy reduction in a mangrove forest strongly depends on the tree density, diameter of trunks and roots, forest floor slope, the characteristics (height, period, etc.) of the incident waves, and the tidal stage at which the waves enter a forest (Mazda et al., 1997a, 1997b, 2006). Mazda et al. (2006) found that the energy of waves was reduced by 50% within 100 m in *Sonneratia* forests. Mazda et al. (1997b) and Tanaka et al. (2007) showed that another important factor is the vegetation structure, i.e., the percentage of forest floor covered by either prop roots or pneumatophores, because the drag coefficient of these structures is related to the Reynolds number based on aboveground root architecture and the gap of the projected area of aerial roots in the vertical plane (Takemura and Tanaka, 2007).

From the fluid dynamics viewpoint, more study of the drag coefficient of trees is needed because the value is assumed to change with the vegetation density, as elucidated by water flume studies using small diameter circular cylinders (Nepf, 1999; Takemura and Tanaka, 2007). In the case of a *C. nucifera* forest, the spacing (L) and diameter (D) ratio is about 20 (assuming D = 30 cm and L = 6 m), and the sheltering effect, by which the drag force on the rear side of a tree becomes quite small when the rear tree is very close to the frontal tree, is negligible as shown in experiments (Bokaian and Geoola, 1984) and analysis (Nepf, 1999). However, if dense vegetation that has many aerial roots like mangrove species, i.e., *R. apiculata* or *R. mucronata*, or like sand dune vegetation, i.e. *P. odoratissimus*, is expected to serve as a vegetation bioshield for tsunami, the sheltering effects from frontal trees or aerial roots are assumed to be quite large. Therefore, fundamental studies are required to elucidate the real drag coefficient of dense-type vegetations for the accurate estimation of the vegetation effects on tsunami energy dissipation. The drag coefficient of a real tree was investigated using a willow in a river (Armanini et al., 2005) and mangroves (Mazda et al., 1997a, 1997b, 2006) at low flow velocities. The current knowledge, however, is not adequate to fully estimate the vegetation effects on tsunami currents at high velocities because it does not include the phenomena of trees being shaken, bent down, overturned, washed out, and becoming debris in a tsunami event, which occurs in some cases.

Model simulations

Hiraishi and Harada (2003) conducted water flume experiments and numerical simulations based on the 1998 Papua New Guinea tsunami to estimate the attenuation of tsunami energy by mangroves. The model output suggested a more than 90% reduction in maximum tsunami flow pressure by a 100 m–wide forest belt when the tree density is very high (30 tree trunks per 100 m^2). Model results obtained by Hamzah et al. (1999), Harada and Imamura (2006), and Tanaka et al. (2006a, 2008b) for various types of coastal vegetation, including mangroves, were very similar. Tanaka et al. (2006a) modeled the relationship of species-specific differences in drag coefficient to tsunami height. The species differences in mitigating tsunami water depth, velocity, and tsunami arrival time behind a forest in relation to tsunami height were found to be quite large, and *P. odoratissimus* was considered more effective in reducing the velocity and water depth of the current through the forest than other common trees, including the coconut tree (*C. nucifera*) and a kind of mangrove (*A. alba*) using a numerical simulation

(Tanaka et al., 2006a). These results point out the importance of preserving or selecting appropriate species to act as tsunami barriers and offer sufficient shoreline protection.

Cochard et al. (2008) pointed out the need for much more transdisciplinary research beyond tsunamis to assess the overall value of ecosystem services by coastal forests and vegetation and to develop more accurate indicators of hazard mitigation. They recommend more detailed spatial and hydrodynamic analyses before the hazard-vegetation interactions can be realistically modeled on risk maps.

Important aspects of establishment and management of coastal vegetation

Degradation of mangrove forests and importance of reducing anthropogenic effects

Dahdouh-Guebas et al. (2005) analyzed the damage to 24 mangrove lagoons and estuaries in the coastal zone where 80% of the deaths in Sri Lanka occurred. Cluster analysis made it clear that mangroves play a role in mitigating tsunamis, except for some isolated trees. However, even when a mangrove exists, cryptic degradation of mangrove species, i.e., changes in species composition resulting from colonization by invasive species make mangrove forests vulnerable. There is a growing consensus among scientists, environmentalists, and Asian fishing communities that the tsunami mitigation capacity of mangrove forests, which also have the potential to protect coastlines from erosion and storm damage by acting as a buffer zone during oceanic events (Williams, 2005), has been considerably worsened by tourism, shrimp farms (Thampanya et al., 2006), and destruction and degradation due to industrial development. Alongi (2008) estimated the potential impact of climate change on mangroves, and pointed out that mangroves currently face a more predictable and insidious threat from deforestation (average rate of loss between 1% and 2% total area yr^{-1} (Alongi, 2002; Duke et al., 2007) than the decrement due to climate change, and warned that most of the world's mangrove forests may be lost before the peak impact of climate change. Reduction of these anthropogenic effects is quite important for sustaining disaster-mitigating functions.

Effective terrestrial vegetation structure on sand dune and coast

Considering the drag characteristics of different tree species, Tanaka et al. (2007) proposed: 1) a horizontal forest structure with mixed small- and large-diameter trees, because a dense population of small-diameter trees (d>0.1 m to withstand a tsunami less than 5 m in water depth) could reduce the velocity of the tsunami current, whereas large-diameter trees (d>0.3 m) could trap broken branches and man-made debris; 2) two layers of vegetation vertically with *P. odoratissimus* and *C. equisetifolia*, which have a strong potential to decrease the damage behind the vegetation cover; 3) broad-leaved trees behind the dense vegetation, which can be expected to trap debris and to help people escape, climb, and make soft landings, as shown in Fig. 1. Considering biodiversity, Tanaka et al. (2008b) showed an example of the vegetation structure on a sand dune. Mascarenhas and Jayakumar (2008) also consider *Casuarina* to be efficient energy dissipaters during powerful oceanic events.

Importance of maintenance as observed in Matara pilot project

A survey was conducted by a team comprising researchers from Saitama University, Japan, and the University of Peradeniya, Sri Lanka (the SU-UOP team) to examine the present situation of coastal vegetation for tsunami protection in Sri Lanka. Many government institutions and NGOs have also undertaken such projects along the southern and western coasts of Sri Lanka. An evaluation was carried out to assess whether the coastal vegetation fulfilled the functions of dissipation of wave energy and trapping debris, and offering opportunities to escape and make a soft landing (Tanaka et al., 2007). Currently, 50% of the vegetation barriers are planted in one or two rows due to land availability constraints in areas along main roads or railway tracks. Dissemination of knowledge and coordination with government institutions and research institutions are very important for establishment and management of effective coastal vegetation for tsunami protection with community participation, especially at the initial development stage.

The findings of Tanaka et al. (2007) suggested several options for coastal vegetation management that could effectively reduce the impact of tsunamis and other natural disasters in the future. Accordingly, the SU-UOP team proposed a pilot-scale coastal plantation in the Matara Thotamuna area in the southern coastal belt near the mouth of the Nilwala River, Matara City, Sri Lanka, which was severely affected by the 2004 tsunami. *C. equisetifolia* and *P. odoratissimus* were planted in a mixed culture, and their growth was monitored continuously. The average height and girth of *P. odoratissimus* were around 92 cm and 117 cm, respectively, and the average height and trunk diameter of *C. equisetifolia* were 627 cm and 4 cm, respectively, 18 months after planting (Perera et al., 2008). The project was very successful and effective compared to similar projects that suffered from poor maintenance and operation. The project indicated that support from local authorities and communities are vital to make such programs successful. For long-term maintenance of the pilot project, management of the site was handed over to the local temple. This is one of the ideas for sustainable maintenance.

Sustainable maintenance and utilization

De Zoysa (2008) assessed the impact of a *Casuarina* shelterbelt from economic (agricultural crop, household goods, timber production, fuel supply), social (prevention of illegal settlements, attraction of tourists, prevalence of anti-social activity), and environmental (wind speed reduction, sand dune formation, impact on undergrowth, aesthetic value) viewpoints, and concluded that the environmental and social impacts are larger than the economic impacts. Integrated coastal zone management by the residents, city council, and tourist board is recommended in order to increase the benefits of coastal shelter belts.

Considering the Matara project by the SU-UOP team and the research by De Zoysa (2008), the author recommends an integrated coastal vegetation management system (Fig. 2) that maintains the vegetation bioshield effect for a long time. With the growth of trees, the tsunami energy mitigation effect of the vegetation may be reduced, because the tree spacing becomes larger and effective cumulative tree diameter in the stream-wise direction dN_{all} is reduced (Tanaka et al., 2007), and the trees themselves limit the light needed for the undergrowth. To keep the forest dense, proper management is needed by using the forest as a source of firewood or for timber production to thin it, and expecting the undergrowth to prevent soil erosion, and maintaining various-aged stands of trees by replanting (FAO, 2007). In particular, the front line of the forest close to the sea should be dense vegetation (i.e., a *Pandanus-Casuarina* belt) as Tanaka et al. (2007) proposed. Although *C. nucifera* cannot provide a large drag on the tsunami current, this species is an important tree for residents, and we can restrict it to or maintain it on the inland side of the coastal sand dunes. Vegetation cannot be expected to have an effect in these areas, even if we use dense vegetation, because the water motion is accelerated by the downward slope. *C. nucifera* has many uses, i.e. fruit production, fuel, timber, and coconut fiber is used as water storage and water purification materials in the substrate of manmade wetlands (Tanaka et al., 2008a). Thus, it is not necessary to remove *C. nucifera* from the coastal region if it is kept at the backside of coastal sand dunes or combined with dense *Pandanus* forest, even though the contribution of *C. nucifera* to increasing the overall drag coefficient by itself is not large.

Mangroves in lagoons are quite important and should be maintained for tsunami mitigation because they reduce the tsunami energy overtopping a sand dune or intruding into the land by a river mouth (open gap). In residential areas, broad-leaved trees that have large diameter branches should be maintained close to the houses for people to escape by climbing during a natural disaster event. It is also quite important to teach people that the coastal vegetation plays a role in preventing strong winds, salt spray, windblown sand, and storm surge propagation, as well as in mitigating tsunami inundation. The local temple or local authorities can utilize the vegetated area for education of the local residents, teaching them to keep the forest dense, control weeds, especially in the developing stage after plantation, and not to cut the forest illegally.

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REFERENCES

Alongi DM (2002) Present state and future of the world’s mangrove forests, Environmental Conservation **29**: 331-349.

Alongi DM (2008) Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change, Estuarine, Coastal and Shelf Science **76**: 1-13.

Armanini A, Righetti M, Grisenti P (2005) Direct measurement of vegetation resistance in prototype scale, J. Hydraulic Research **43**: 481-487.

Bokaian A, Geoola F (1984) Wake-induced galloping of two-interfering circular cylinders, J. Fluid Mechanics **146**: 383-415.

Clague JJ, Munro A, Murty T (2003) Tsunami hazard and risk in Canada, Natural Hazards **28**: 433–461.

Cochard R, Ranamukhaarachchi SL, Shivakoti GP, Shipin OV, Edwards PJ, Seeland KT (2008) The 2004 tsunami in Aceh and Southern Thailand: A review on coastal ecosystems, wave hazards and vulnerability, Perspectives in Plant Ecology, Evolution and Systematics **10**: 3-40.

Dahdouh-Guebas F, Jayatissa LP, Di Nitto D, Bosire JO, Lo Seen D, Koedam N (2005) How effective were mangroves as a defence against the recent tsunami? Current Biology **15**(12): 443-447.

Danielsen F, Sorensen MK, Olwig MF, Selvam V, Parish F, Burgess ND, Hiraishi T, Karunagaran VM, Rasmussen MS, Hansen LB, Quarto A, Suryadiputra N (2005)

The Asian tsunami: A protective role for coastal vegetation, Science **320** (5748): 643.

Dengler L, Preuss J (2003) Mitigation lessons from the July 17, 1998 Papua New Guinea tsunami, Pure and Applied Geophysics **160**: 2001-2031.

De Zoysa M (2008) *Casuarina* coastal forest shelterbelts in Hambantota City, Sri Lanka: assessment of impacts, Small-scale Forestry **7**: 17–27.

Duke NC, Meynecke J-O, Dittmann S, Ellison AM, Anger K, Berger U, Cannicci S, Diele K, Ewel KC, Field CD, Koedam N, Lee SY, Marchand C, Nordhaus I, Dahdouh-Guebas F (2007) A world without mangroves? Science **317**: 41-42.

Fernando HJS, McCulley JL, Mendis SJ, Perera K (2005) Coral poaching worsens tsunami destruction in Sri Lanka, Eos **86**(33): 301-304.

Fernando HJS, Samarawickrama SP, Balasubramanian S, Hettiarachchi SSL, Voropayev S (2008) Effects of porous barriers such as coral reefs on coastal wave propagation, J. Hydro-environment Research **1**: 187-194.

Food and Agriculture Organization of the United Nations (FAO) (2007) The Role of Coastal Forests in the Mitigation of Tsunami Impacts – Main report” www.fao.org /forestry /site /coastalprotection /en. ISBN 978-974-13-9321-3, Thammada Press.

Hamzah L, Harada K, Imamura F (1999) Experimental and numerical study on the effect of mangrove to reduce tsunami, Tohoku J. Natural Disaster Science **35**: 127–132.

Harada K, Imamura F (2000) Experimental study on the resistance by mangrove under the unsteady flow, Proc. of the 1st Congress of the Asian and Pacific Coastal Engineering, Dalian, China: 975–984.

Harada K, Imamura F (2006) Effects of coastal forest on tsunami hazard mitigation –a preliminary investigation, tsunamis: case studies and recent developments, Advances in Natural and Technological Hazards Research: 279-292.

Harada K, Kawata Y (2005) Study on tsunami reduction effect of coastal forest due to forest growth, Annuals of Disaster Prevention Research Institute, Kyoto Univ. **48C**: 161-165.

Hiraishi T, Harada K (2003) Greenbelt tsunami prevention in South-Pacific region, Report of the Port and Airport Research Institute 42(2), 23p.

Honda S (1898) Über den Küstenshutzward gegen Springfluten. Bulletin of the College of Agriculture **3**(4), Imperial University, Komaba, Tokyo, pp.281-298.

Kathiresan K, Rajendran N (2005) Coastal mangrove forests mitigated tsunami, Estuarine, Coastal and Shelf Science **65**(3): 601-606.

Kathiresan K, Rajendran N (2006) Reply to ‘Comments of Kerr et al. on ‘‘Coastal mangrove forests mitigated tsunami’’ [Estuar. Coast. Shelf Sci. 65 (2005) 601-606], Estuarine, Coastal and Shelf Science **67**: 542.

Kerr AM, Baird AH, Campbell SJ (2006) Comments on "Coastal mangrove forests mitigated tsunami" by K. Kathiresan and N. Rajendran [Estuar. Coast. Shelf Sci. 65 (2005) 601-606], Estuarine, Coastal and Shelf Science **67**: 539-541.

Mascarenhas A, Jayakumar S (2008) An environmental perspective of the post-tsunami scenario along the coast of Tamil Nadu, India: Role of sand dunes and forests, J. Environmental Management **89**: 24–34.

Mazda Y, Magi M, Kogo M, Hong PN (1997a) Mangroves as a protection from waves in the Tong King Delta, Vietnam, Mangroves and Salt Marshes **1**: 127-135.

Mazda Y, Wolanski E, King B, Sase A, Ohtsuka D, Magi M (1997b) Drag force due to vegetation in mangrove swamps, Mangroves and Salt Marshes **1**: 193-199.

Mazda Y, Magi M, Ikeda Y, Kurokawa T, Asano T (2006) Wave reduction in a mangrove forest dominated by *Sonneratia* sp., Wetlands Ecology and Management **14**: 365–378.

Nandasena NAK, Tanaka N, Takagi T (2007) A new derivation of horizontal two dimensional depth averaged momentum equation and continuity equation which include total effect of porosity inside the vegetation, Annual J. Hydraulic Engineering, JSCE **51**: 163-168.

Nandasena NAK, Tanaka N, Tanimoto K (2008) Perspective of coastal vegetation patches with topography variations for tsunami protection in 2D – numerical modeling, Annual J. Hydraulic Engineering, JSCE **52**: 133-138.

Nepf HM (1999) Drag, turbulence, and diffusion in flow through emergent vegetation, Water Resources Research **35**(2): 479-489.

Peltola H, Kellomäki S, Hassinen A, Granander M (2000) Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland, Forest Ecology and Management **135**: 143-153.

Perera WARP, Mowjood MIM, Tanaka N, Jinadasa KBSN, Fasly MSM (2008) Effective coastal vegetative landscaping for the tsunami protection in Sri Lanka, Ann. Proc. of SLAAS.

Rossetto T, Peiris N, Pomonis A, Wilkinson SM, Del Re D, Koo R, Gallocher S (2007) The Indian Ocean tsunami of December 26, 2004:observations in Sri Lanka and Thailand, Nat. Hazards **42**:105–124.

Sasaki Y, Homchuen S, Tanaka N (2007) The role of coastal vegetation in case of the Indian Ocean tsunami - Coastal area of Thailand and Sri Lanka -, Mangrove Science **4-5**: 49-55.

Shuto N (1987) The effectiveness and limit of tsunami control forests, Coastal Engineering in Japan **30**(1): 143-153.

Takemura T, Tanaka N (2007) Flow structures and drag characteristics of a colony-type emergent roughness model mounted on a flat plate in uniform flow, Fluid Dynamics Research **39**: 694–710.

Tanaka N, Sasaki Y, Mowjood MIM, Jinadasa KBSN, Takemura T (2006a). Effective coastal vegetation species and structures with landform, sand dune and lagoon, for tsunami protection at the Indian Ocean tsunami, 15th APD-IAHR Congress, Chennai, India, pp. 1279-1285.

Tanaka N, Sasaki Y, Mowjood MIM (2006b) Effects of sand dune and vegetation in the coastal area of Sri Lanka at the Indian Ocean tsunami, In: Eds, Namsik Park et al., Advances in Geosciences **6**, World Scientific Publishing, Co.

Tanaka N, Sasaki Y, Mowjood MIM, Jinadasa KBSN (2007), Coastal vegetation structures and their functions in tsunami protection: Experience of the recent Indian Ocean tsunami, Landscape and Ecological Engineering **3**: 33-45.

Tanaka N, Sasaki Y (2007) Limitations of coastal vegetation in the 2004 Indian Ocean tsunami and 2006 Java tsunami, Proc. IAHR 32nd Congress, Venice, Italy (CDROM).

Tanaka N, Karunarathna AK, Jinadasa, KBSN (2008a) Effect of coconut coir-pith supplement on nitrogen and phosphate removal in subsurface flow wetland microcosms, Chemistry and Ecology **24**(1): 1-8.

Tanaka N, Nandasena NAK, Jinadasa KBSN, Sasaki Y, Tanimoto K, Mowjood MIM (2008b) Developing effective vegetation bioshield for tsunami protection, Civil and Environmental Engineering Systems – in press.

Tanimoto K, Tanaka N, Thuy NB, Nandasena NAK, Iimura K (2008a) Effect of open gap in coastal forest on tsunami runup: Investigation by 2-dimensional numerical simulations (in Japanese), Annual J. Civil Engineering in the Ocean, JSCE **24**: 87-92.

Tanimoto K, Tanaka N, Thuy NB, Iimura K (2008b) Effect of coastal and river forests on tsunami run-up in river (in Japanese), Annual J. Coastal Engineering, JSCE **55**: 226-230.

Thampanya, U, Vermaat JE, Sinsakul S, Panapitukkul N (2006) Coastal erosion and mangrove progradation of Southern Thailand, Estuarine, Coastal and Shelf Science **68**: 75-85.

Thuy NB, Tanimoto K, Tanaka N (2008) Numerical investigation of the effects of opening gap width in forest on tsunami runup on coast, Proc. 10th Int. Summer Sym.: 61-64.

Williams N (2005) Tsunami insight to mangrove value, Current Biology **15**: R73.

List of Figures

Fig. 1 Functions of coastal vegetation during tsunami inundation (modified from Tanaka et al. (2007))

Fig. 2 Schematic of vegetation bioshield in coastal region and integrated management system

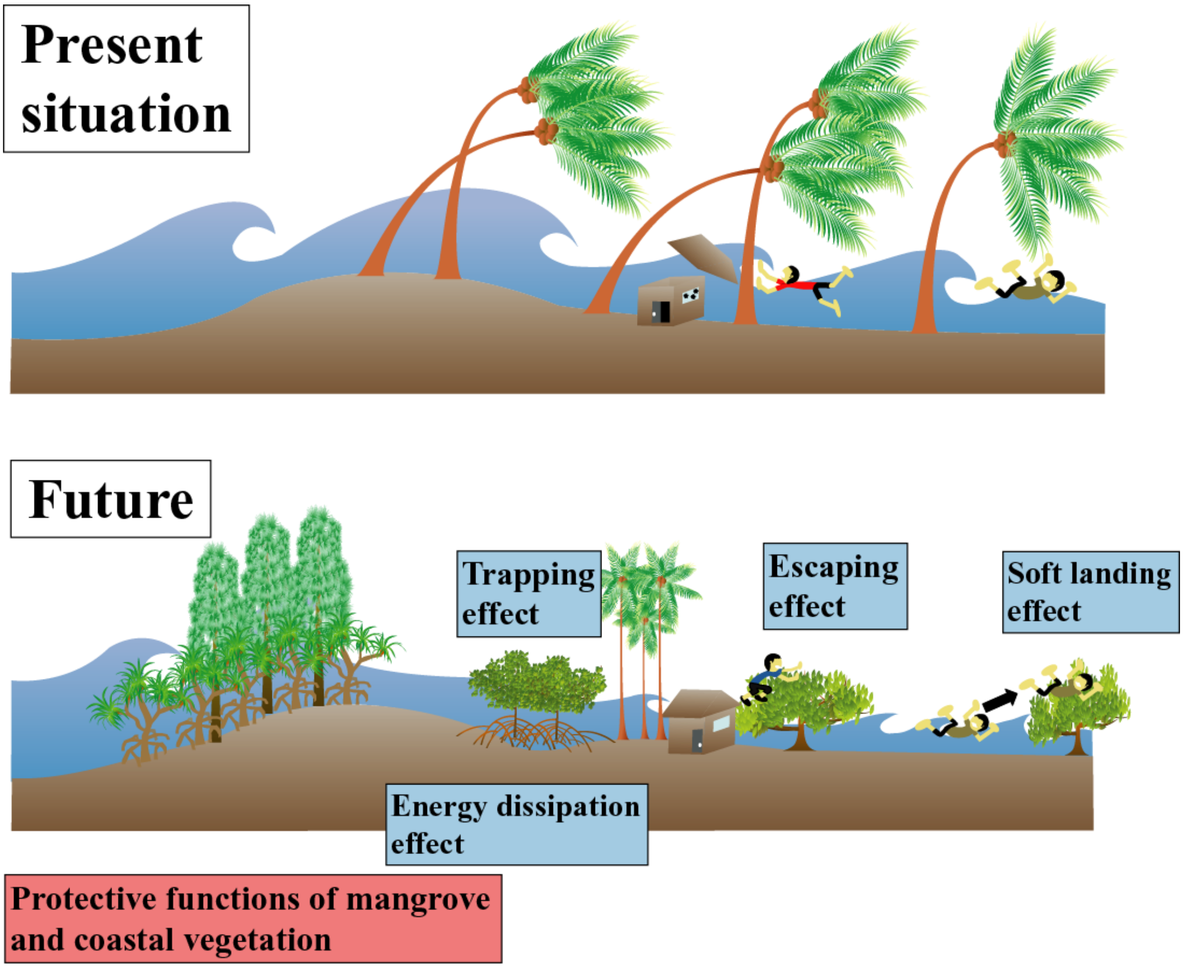
Present situation
Future
Trapping effect
Escaping effect
Soft landing effect
Energy dissipation effect
Protective functions of mangrove and coastal vegetation

Fig. 1

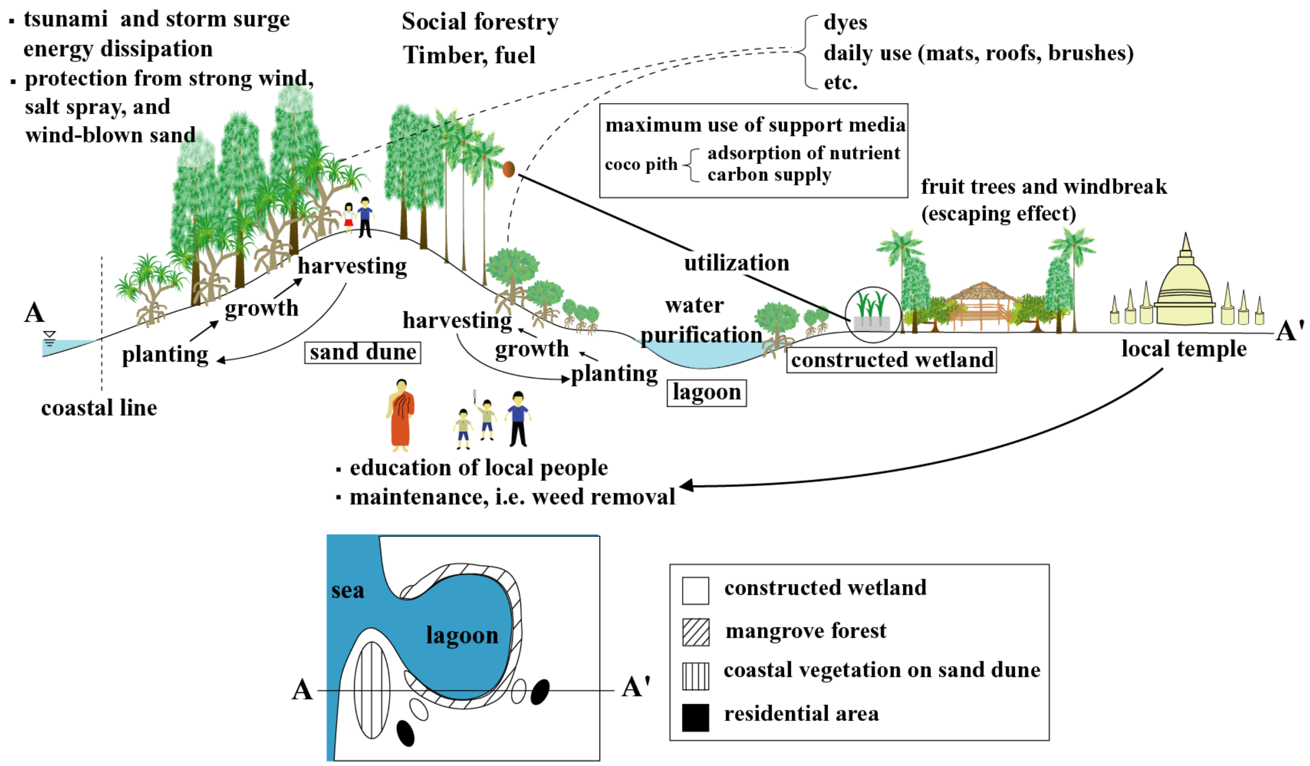
· tsunami and storm surge energy dissipation
· protection from strong wind, salt spray, and wind-blown sand
Social forestry
Timber, fuel
dyes
daily use (mats, roofs, brushes)
etc.
maximum use of support media
coco pith
adsorption of nutrient
carbon supply
fruit trees and windbreak (escaping effect)
utilization
water purification
harvesting
growth
planting
harvesting
growth
planting
A
A'
sand dune
lagoon
constructed wetland
local temple
coastal line
· education of local people
· maintenance, i.e. weed removal
sea
lagoon
A
A'
☐ constructed wetland
▨ mangrove forest
▥ coastal vegetation on sand dune
■ residential area

Fig. 2