RAP PUBLICATION 2007/1

The role of coastal forests in the mitigation of tsunami impacts

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Food and Agriculture Organization of the United Nations
Regional Office for Asia and the Pacific
Bangkok, 2007

This publication is based on “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

Printed by Thammada Press

Cover photo: Susan Braatz, FAO

Published by
Food and Agriculture Organization of the United Nations

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Acknowledgements

The authors would like to thank the Government of Finland for its contribution to the FAO-supported project “Forestry Programme for Early Rehabilitation in Asian Tsunami Affected Countries,” which provided funding for this work, and would also like to thank Thomas Enters, Mette Loyche-Wilkie, Susan Braatz, Peter Holmgren, Serena Fortuna, Doug Kneeland, Shingo Shibaba and Patrick Durst for providing comments on drafts of the report. Thanks are also due to Paul Stansell of Pelamis Wave Power, Edinburgh, Scotland, Nobuo Shuto and Fumihiko Imamura of Tohoku University, Japan and Kenji Harada of the Disaster Reduction and Human Renovation Institution (DRI), Japan.

Photo credits:
Susan Braatz, FAO (Cover); Jeremy Broadhead, FAO (Page 6, 24); Hugh Davies, University of PNG; Image bank: NOAA-NGDC, Colorado (Page 23); J.K. Patterson Edward, Suganthi Devadason Marine Research Institute, Tamil Nadu, India (Page 17); Hiroshi Hiraoka, FAO (Page vi); Fumihiko Imamura Tohoku University, Japan (Page 5,11); Hiroyuki Kameda, Kyoto University, and National Research Institute for Earth Science and Disaster Prevention, Japan (Page 26); Norio Tanaka of Saitama University, Japan (Page 13).

Layout & design: Somchai Singsa and Chanida Chavanich

Foreword

The role of coastal forests in the mitigation of tsunami impacts unexpectedly became a hotly debated topic in the aftermath of the 2004 Indian Ocean tsunami, which ranked amongst the most devastating natural disasters in recent history. A proportion of the reconstruction and rehabilitation effort was focussed on rehabilitation of coastal forests, which early information suggested had been extensively damaged by the tsunami. Information from a range of sources also suggested that mangroves and other coastal forests mitigated the effects of the tsunami. These factors and reductions in risk associated with increased distance of human habitation from the coastline provided justification for tree planting programmes and led to calls to establish coastal buffer zones in a number of tsunami-affected countries.

The effectiveness of trees and forests in shielding coastlines from tsunamis was later called into question and the surrounding debate revealed the imprecise nature of existing knowledge and the associated danger of potentially harmful policies being formulated. In response, FAO's "Forestry programme for early rehabilitation in Asian tsunami-affected countries", funded by the Government of Finland, organized a workshop on "Coastal protection in the aftermath of the Indian Ocean tsunami: What role for forests and trees?" The meeting drew together a wide range of participants and revealed the manifold nature of the subject area.

The diversity of opinion revealed the urgent need for interdisciplinary work to bridge the gap between science and policy and provide information on whether and how to plant or manage coastal trees and forests for protective purposes. The work summarised in this publication was therefore undertaken to specifically address the physical aspects of tsunami mitigation by forests, which form the core of the debate. Though the work represents the current state of knowledge on this subject, it is not intended to be exhaustive on all aspects of establishing coastal forests. It is hoped that the information provided will be used in conjunction with economic, social and environmental considerations to improve management of coastal trees and forests both in the Indian Ocean region and elsewhere in the world.

He Changchui
Assistant Director-General and
FAO Regional Representative for Asia and the Pacific

A preventable tragedy?

The tsunami of 26 December 2004 was a major natural disaster, killing some 229 866 men, women and children and causing billions of dollars in damage (United Nations, 2007). With a moment magnitude, M_w, between 9.1 and 9.3, the earthquake that caused the tsunami was the largest in the last forty years and second largest in instrumental history (Bilham, 2005). Yet, the devastation caused by the 2004 tsunami (like most other tsunamis) could have been greatly reduced in many of the thirteen countries that were hit, particularly in those countries farther from the earthquake epicentre and subject to less massive tsunamis.

While it is well documented that the lack of an adequate early-warning system for the Indian Ocean was largely to blame for the high casualty rate, the tragedy occurred for another reason, as well. Much of the coastline in many parts of Asia and the Pacific is heavily populated – an increasingly growing phenomenon seen around the world. As a consequence of this development, coastal vegetation – and the associated setback – that would have provided natural protection from hazards such as storms, cyclones or even tsunamis has been degraded, severely altered or completely removed.

In many countries the requirement for setbacks is written into land use legislation and regulations. So far, these have not been uniformly enforced and, moreover, most settlements and other developments are not planned by taking into consideration the potentially massive destruction associated with coastal hazards. Although huge, massively destructive tsunamis may have a 100-year return period, smaller, but potentially devastating tsunamis, are much more frequent in some regions. It should be recalled that Sri Lanka had exceedingly high casualties and property damage, despite being far from the epicentre and struck by waves less than a quarter of the size those striking Aceh in Indonesia. In Sri Lanka about 68 percent of wave height measurements fell between 3.0 and 7.5 meters, with a median height of only 5.0 meters. It is the lack of preparedness in many coastal areas that increases vulnerability to disaster. There will always be some degree of vulnerability in developed coastal areas, but such risks can be minimized with proper planning.

Coastal area development entails changes to the natural landscape. However, many types of development do not necessarily have to come at the expense of vegetation cover. In heavily developed urban areas the establishment of coastal forests for protection may not be easy, but it is not inconceivable. In rural coastal areas, the integration of protective forests with rural development should be the norm. In fact, the impact of the 2004 tsunami was not limited to populous cities, but included a multitude of rural communities strung along the coastline. Where mangroves and beach forests no longer existed, the damage caused by the tsunami was generally more severe. Where forests were present they mitigated the impact of the tsunami in many cases. Early warnings systems could have saved many lives. Coastal forests could have saved property, as well as lives, where the tsunami was not extremely large.

Though coastal forests are only partially effective against flooding, particularly when caused by successive, non-breaking waves of a long-period tsunami,[1] they greatly reduce impact forces and flow depths and velocities, which in turn limits the extent of flooding. Nevertheless, almost complete protection from impact damage of 6-7 meter waves can be achieved. It is even possible that a large, well-designed coastal forest could substantially mitigate the damage of a tsunami up to 8, or even 10 meters. This, of course, would also depend on the suitability of the site for tree growth, ground elevation, and the near-shore run-up slope that determine wave form and force of the waves of similar height.[2] Appropriate set-back distances, large enough to incorporate the coastal forest, would also be necessary. Yet, in rural hamlets and villages, coastal forests generally integrate well with people's livelihoods and economies.

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[1] Non-breaking waves represent about 75 percent of tsunamis.

[2] It is important to note that inundation depth (flow depth), rather than wave height, is critical variable determining if a forest is able to withstand a tsunami. Inundation depth or flow depth is wave height adjusted for tide level and ground elevation (see Fig. 2 and Table 1). Consequently, depth may anywhere from 0.5 to 3.0 or more meters less than estimated or measured wave height at any location. Forests need to be designed for the expected flow depth and velocity of a tsunami.

Effectiveness of coastal forests as a solution

There is considerable evidence that coastal forests can reduce the force, depth and velocity of a tsunami, lessening damage to property and reducing loss of life. Numerous anecdotes, field surveys and scientific studies in India, Indonesia, Japan, Malaysia, Maldives, Myanmar, Sri Lanka, and Thailand of the 2004 tsunami and other tsunamis show a connection between areas with the highest levels of damage and the absence of coastal forests.[3]

The destructive force of a tsunami is subject to local factors which are often unavailable for analysis (e.g. local bathymetry and coastline configuration) and therefore the protection offered by trees and forests may not be fully quantifiable. On a case by case basis, however, studies often show reductions in the degree of damage to trees with distance from the leading edge of a coastal forest, implying that the force of the tsunami is reduced by the forest and areas to the rear are afforded protection. An additional source of information is provided by studies in which adjacent areas of coastline, with and without trees, are compared. Such studies provide core evidence of the mitigation potential of forests. Empirical findings are also supported by experiments using models and mathematical analogues of tsunami-forest interfaces. Such methods add further weight to claims of protection by forests against tsunamis.

Data from field studies across Asia shown in Figure 1 and Table 1 (*below*), show that where coastal forests failed, waves were very large or forest width was limited. In other cases, although waves were less substantial and widths were adequate, forests could still fail to provide mitigation where trees were widely spaced,of small diameter, or without branches near ground level as denoted by the symbols *w*, *s*, and *b*, respectively.[4] Conversely, some cases

[3] See, for example, Aksornkoae and Hawanon 2005, Chang et al 2006, Dahdouh-Guebas 2005, Danielsen et al 2005, Hiraishi 2006, IUCN 2005, Izumi et al 1961, Kathiresan and Rajendran 2005, Latief and Hadi 2006, MSSRF 2005, Padma 2006, Parish 2005, Ramanamurthy 2005, Ranasinghe 2006, Shuto 1987, Siripong 2006, Tanaka et al 2007, UNEP 2005, and Yasuda et al, 2006.

[4] Note, only maximum forest width and minimum wave height, where there was range in the data, are plotted (see Table 1) to give a greater safety margin in interpretation.

of successful mitigation may possibly be partially attributed to other contributing factors such as higher ground elevation or less exposure to the sea. Data allowing, Table 1 accounts for elevation in the estimates of tsunami flow depth – the most important variable determining success or failure.[5]

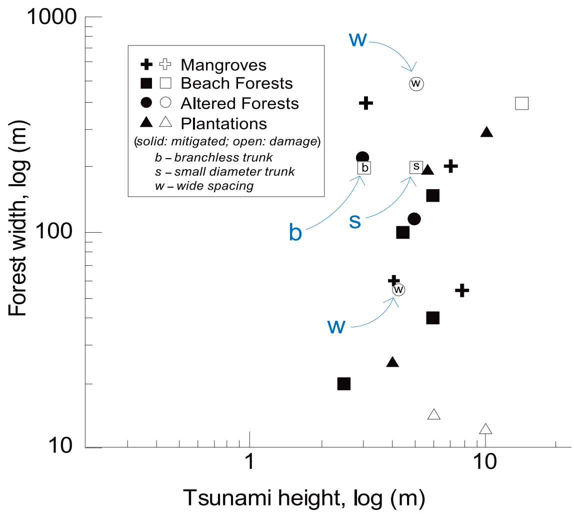

Figure 1: Evidence from 2004 Indian Ocean and 2006 West Java tsunamis of coastal forest's protective role relative to wave height and forest width. Solid shapes indicate substantial mitigation and damage reduction. Source: compiled by Keith Forbes

In the case of mangroves, for any particular elevation or distance from the sea front, tsunami hazard is consistently lower for areas behind mangroves. Furthermore, plantations of pine in Japan have proved effective against various tsunamis. Many casuarina shelterbelts in India, Sri Lanka and Thailand, established to protect coasts from cyclones, tsunami and other coastal hazards were effective against the 2004 Indian Ocean tsunami as well. Natural beach forests and plantations of tree crops, such as cashew nut with their low, widely-branching canopies or pandanus with mangrove-like stilt roots and dense foliage, have also protected coasts in many instances.[6]

There are also a significant number of cases where coastal forests failed to protect coastlines from a tsunami. Rather than an indictment of coastal forests in general, however, these failures can be attributed to a rare, massively large tsunami or insufficiency of one or more forest attributes such as forest width, density, age or some other parameter important in providing protection. This was frequently the case with degraded or altered beach forests with widely spaced trees, replacement tree species susceptible to breaking, or sparse undergrowth.

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[5] See footnote 2.

[6] Though cashew nut plantations may have widely-spaced trees, mitigation capacity comes from the high density of the branches and foliage brought close to the ground – a growth form common to the species. Wide spacing, thus, has less influence on limiting mitigation.

Casuarina shelterbelts were also ineffective in situations where they were too narrow or had become too old and were therefore without flow-resisting branches lower down on the trunk. As casuarina and similar species like pine mature, the branches and foliage at lower heights die off and the drag they provide is lost. Similarly, coconuts provide very little resistance as their trunks have no branches.

Coastal forests have also been reported to have a role protecting lives and property beyond wave energy mitigation. In India and Malaysia, there are stories of how the presence of large mangroves saved the lives of people who climbed or were able to cling to trees and escape from being dragged out to sea. Some moderately tall tree species with wide canopies growing on beaches in altered forest and plantations also provided important refuge. Coastal forests have also obstructed boats, timber and similar ship cargo and other debris from washing inland where they would cause many casualties and great damage.

A narrow shelterbelt of pine trees near Shizugawa (Miyagi Prefecture), Japan appears to have protected the houses within its shadow during the 1960 Chilean tsunami. Waves came from the Pacific (top of photo) and river mouth (left side of photo). Destruction in foreground also includes debris left by river inundation.

How coastal forests work as a barrier

The function of a barrier – whether coastal forest, breakwater, seawall, or cliff – is to absorb the impact forces and to retard the flow of large storm waves and tsunamis. A seawall, if tall enough, reflects the wave back out to sea. On the other hand, permeable structures, like breakwaters and coastal forests, partly reflect and partly transmit the water. In the case of a coastal forest, energy is progressively absorbed as it passes through the forest. Without the forest barrier, the tsunami will run-up to a maximum height determined by the magnitude and nature of the seismic event that created the tsunami and local factors such as the coastal profile, offshore bathymetry and beach slope that modify the wave's force.[7] Once the tsunami comes on shore, the amount of reduction in water depth, velocity, and force depends on how much water is reflected and energy adsorbed by the coastal forest (*see figure 2*).

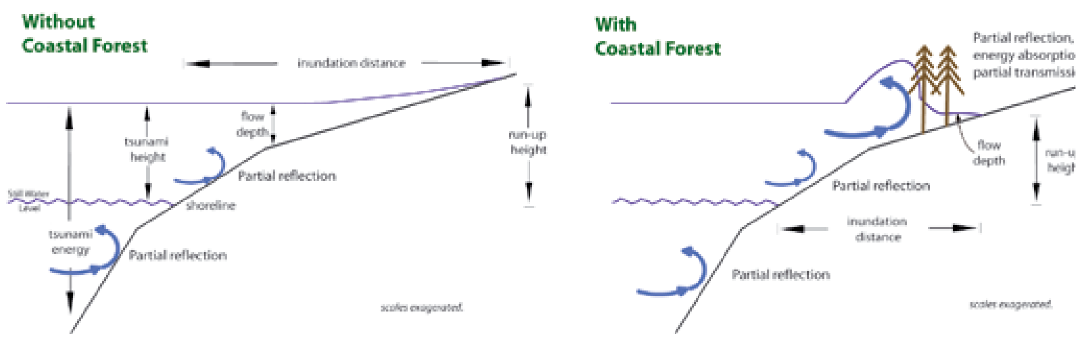

Figure 2: Tsunami wave run-up with and without coastal forest barrier. Source: Keith Forbes

[7] Bathymetry refers to the underwater topographic relief found offshore.

Implications for coastal forest management

Field observations and laboratory research have established several key parameters that determine the magnitude of tsunami mitigation offered by various types of coastal forests. These parameters include forest width, tree density, age, tree diameter, tree height, and species composition. Each parameter can be manipulated to produce the required level of mitigation. However, the relationship between the parameters is complex and characterized by co-dependence and interaction amongst them.

Forest width

Forest width is one of the most important factors in mitigation. Over the width of the forest, energy is progressively dissipated by drag and other forces created by tree trunks, branches and foliage, as well as the undergrowth, as the tsunami passes through the forest. Even when energy levels are high, the width effect remains strong. Simulations show that a 3-fold and 6-fold increase in energy from increased wavelength (period) resulted in only a small increase in energy transmission for widths greater than 100 meters.[8] However, for a narrower forest of 50 meters the loss in hydraulic force (drag force) reduction was more apparent. This suggests that the narrower the forest the greater the risk from a long period tsunami (i.e. far-field tsunami).[9] As such, increasing forest width will progressively reduce risk and potential impact.

There is evidence that some coastal areas very close to the epicentre of the earthquake that caused the 2004 Indian Ocean tsunami were protected by extensive mangroves. In a few locations

[8] Wavelength and period are related to energy. The mass of water set in motion by upward displacement caused by a submarine plate rupture, equal to width and length of the rupture zone and the height of displacement, determines the wavelength. The greater the mass, the greater the wave's energy. Period relates to speed of tsunami, which is determined by depth to seafloor and not energy. Period indirectly measures energy because it is the time for one wave to pass a point. The longer the wavelength, the longer the period.

[9] Far-field and near-field refer to the relative distance traveled by a tsunami from generation source to coastline. Far-field tsunamis have been generated far from the coastline, travel across oceans, and are characterized by long wavelengths (periods) of great energy. Near-field tsunamis originate much closer to the coast, and are characterized by shorter wavelengths, but can arrive without warning. They have great energy also, but because of greater wave height, rather than long wavelength.

on the Aceh coast, Nicobar Islands and Andaman coast, mangroves were sufficiently wide to mitigate the massive near-field tsunami.

Width effect remains intact under a broad range of conditions. Simulations show a coastal forest of 200 meters width reduced the hydraulic force of a three meter tsunami by at least 80 percent, and flow velocity by 70 percent for all scenarios examined (Harada and Imamura, 2003). Despite increases in tsunami height, period and wave length and changes in forest density, the reductions in force appear robust for a forest of this width. However, the maximum tsunami height tested was only three meters. Larger waves may cause breakage and the percentage reduction would likely fall. On the other hand, smaller waves, although having less force and depth, may pass under the canopy with little mitigation afforded by the forest.

As forest width decreases, the importance of undergrowth and lower branches becomes apparent, particularly for shorter period tsunami (i.e. near-field tsunami). The lack of undergrowth allows much of the tsunami to pass below the forest crown with little reduction in force. Compared to the 70 percent reduction in velocity for a three meter wave at 200 meters width, for a one meter wave the reduction is only 43 percent. For small tsunami (around one-meter in height), which generally pass below the canopy, a doubling of forest width from 100 to 200 meters produced negligible additional velocity reduction.

Field evidence also shows that forest width is a critical parameter in mitigation. Japan's coasts are frequently struck by tsunamis, and protection forests of Japanese pine (*Pinus thunbergii and P. densiflora*) planted in the 1930s and earlier – up to 200 meters in width – have reduced damage to houses, and stopped fishing boats and aquaculture rafts washing inland.[10] Pine forest widths of at least 20 meters are needed to withstand flow depths of one to three meters. For larger waves, width (w) would need to increase according to the relationship $w = 20(H/3)^{0.5}$, where H is wave height above ground, to maintain the mitigation effect (Shuto, 1987). For example, width was at least 26 meters for a five meter inundation height. Unfortunately, data do not exist to extrapolate the relationship beyond five meter heights with confidence. Though mitigation is said to occur if the forest is not destroyed, the amount of mitigation was not documented in the historical records.

Some plantations not specifically established for coastal protection also exhibited mitigation effects. In Thailand, a large grove (250-300 meter in width) of cashew nut trees (*Anacardium spp.*) protected a house situated 450 meters from the shore, while nearby houses 700 meters from the shore were destroyed by the 10-meter near-field

[10] Protection forests in Japan serve multiple roles including protection from storm waves and tsunamis, and from salt spray and sand abrasion which detrimentally affect agricultural crops, and recreation.

tsunami.[11] Also in Thailand, mangroves exhibited mitigation effect for 5-10 meter tsunamis if widths were sufficient to absorb wave energy through breakage. For example, only the first 50 meters of a *Rhizophora* mangrove was destoryed by an 8-meter tsunami in Phang Nga province. Similarly, in Sri Lanka, *Rhizophora spp.* and *Ceriops spp.* were severely damaged in the first 2-3 meters, while the remaining 3-4 meters were much less damaged by a 6-meter tsunami. Once the destructive forces are spent, the remaining forest will further mitigate the tsunami flow.

In beach forests, sufficient forest width is necessary to absorb enough of the tsunami's energy to reduce flow velocity and depth before exiting the forest. In Indonesia, for example, 40 meters of beach forest was effective in the 2006 West Java tsunami in reducing 6-7 meter waves to just 1.6 meters (Latief and Hadi, 2006). In Sri Lanka, *Pandanus spp.* and *Cocus nucifera* arrested the 2004 tsunami at 100 meters for 4.5-5.5 meter wave (Ranasinghe, 2006), and elsewhere at 155 meters for a 6.0 meter wave (Tanaka *et al* 2007). However, it is likely that coconut trees contributed significantly less than the pandanus given the relative difference demonstrated elsewhere in Sri Lanka: pandanus forests, 10 meters in width reduced inundation distance by 24 percent while 110 meters width of coconut trees was necessary for an equivalent reduction. Similarly, a band of pandanus in front of a coconut grove 100 meters in width reduced the distance by another 30 percent. The difference in mitigation capacity is attributed to the greater density of the pandanus.

In other instances, forests failed to protect coasts during the 2004 tsunami. Insufficient width was one cause. For example, in Sri Lanka an area of highly populated settlements behind shelterbelt plantations of *Casuarina equisetifolia* were not protected. The shelterbelts were, however, only 10-15 meters wide and were themselves badly damaged, which indicates the trees were perhaps also not very large as maximum wave heights were only 6-9 meters. For other species, even a width of 200 meters may be insufficient. Evidence, also from Sri Lanka, documents that a 200 meter wide mangrove of *Sonneratia spp.* were uprooted or collapsed under the tsunami. Factors other than width, such as immaturity, stem diameter, or anchorage strength, may have contributed to the failure.

Consequently, width alone is not sufficient to protect coastal areas from moderate size tsunamis. Yet, when other factors are also in place, evidence shows that for waves less than 6-8 meters, width as little as 50-100 m can provide substantial mitigation. Even 10 meters of dense pandanus at the beach head can have a significant effect.

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[11] The plantation was fronted by a five-meter wide *C. equesetifolia* shelterbelt. By the time tsunami struck the cashew plantation wave height above ground level was six meters.

Coastal forest at Shizugawa Park (Miyagi Prefecture) on the Sanriku coast of Japan. Heavily populated, the coast is subject to frequent tsunamis. This forest is reported to have reduced damage from 1960 Chilean tsunami (Izumi 1961 in Harada and Imamura, 2003). Note the trunk deformations caused by storms and tsunamis. Such forests still serve additional uses, such as recreation

Forest density

A coastal forest provides a permeable barrier. Spacing of trees (horizontal density) and the vertical configuration of above-ground roots,[12] stem, branches and foliage (vertical density) define the overall density (also called vegetation thickness) or the permeability of a barrier.

Though forest density may have a less pronounced mitigation effect relative to width, density directly relates to the forest's ability to reflect a tsunami, as well as absorb its energy. A wave encountering a permeable barrier of stems, branches and foliage (and above-ground roots with some species), is partially reflected and partially transmitted into the forest where its energy gradually adsorbed.

Moderate densities are the most effective in tsunami mitigation. If too sparse, like most coconut groves, waves will pass through unmitigated. On the other hand, if the forest is too dense, like some mangroves, a large wave may completely level the forest and pass over unmitigated.[13]

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[12] Above-ground roots also provide additional vertical density, in the case of some mangrove species and some beach forest species like pandanus.

[13] Very high vegetative densities can provide too much resistance at the forest front, overcoming the ability of trees and soil to withstand the force. One of the most advantageous features of coastal forest over other types of coastal defences is its characteristic of allowing a portion of the tsunami to pass through the forest with its force gradually attenuated, where a solid wall may be broken apart, lifted up, or overtopped.

Vertical density, and not just horizontal density, is an important factor in determining a forest's potential for mitigation. A forest with sparse undergrowth and trees with few branches at lower levels will provide less mitigation than a forest with high vegetation density from the ground to the canopy. Mangrove with high stilt roots or uneven-aged forests with multistoried, dense undergrowth, are examples of forests that have high densities in the lower strata.

In general, increasing the vertical and horizontal density will enhance the mitigation effect of a coastal forest. Increased reflection and energy absorption at higher densities are responsible for observed reductions in water depth and flow velocity (current), respectively. And because the hydraulic force is the product of flow depth, density of seawater, and the square of flow velocity[14], it consequently drops as density increases. The mitigation effects for a simulated coastal forest of waru (*Hibiscus tiliaceus*) at Sissano, Papua New Guinea have shown a substantial reduction in inundation depth and hydraulic force. The maximum drop in hydraulic force for one location was 275 000 Newtons per meter to 90 000 Newtons per meter, or about 67 percent reduction, with a forest barrier of four large waru trees per 100 m^2 (Hiraishi and Harada, 2003).

Evidence from the field also corroborates that vegetation thickness or density is an important mitigation parameter. Coconut trees (*Cocus nucifera*), for example, have been shown to be more effective when densely grown. In Kerala, India, densely planted coconut groves protected the coast (Chadha *et al.*, 2005) and in Sri Lanka, damage extended to only 100 meters where spacing was about three meters between trees or about 14 stems per 100 m^2.

In general, however, coconuts are planted with wide-spacing and also do not have low branches to reduce flow rates. Furthermore, village coconut groves typically lack understorey vegetation and thus drag at lower levels is limited. For example, where spacing between trees in the Sri Lanka case above was 4-40 meters the tsunami passed through the 500-meter wide coconut grove unmitigated (Tanaka *et al.*, 2007). Similarly, in Sri Lanka and Indonesia, houses in and behind coconut groves were destroyed (Tanaka *et al.*, 2007). Elsewhere in Sri Lanka where the tsunami was only 2.5 meters in height, widely-spaced coconut trees provided little mitigation. The lack of lower branches and understorey vegetation greatly reduce the mitigation potential of coconut groves. Significant protection from scouring and erosion by the extensive root mats of coconuts has, however, been documented.

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[14] Strictly speaking 'hydraulic force' is pressure per unit length (breadth) on a building wall or some other obstruction (i.e. Newtons per meter). It is estimated by $F_D = \eta \rho u^2$ where η is flow depth, ρ is density of seawater, and u is wave or flow velocity (Harada and Imamura, 2003). Force is the product of wave mass and its speed as it hits the wall.

Mangroves typically form denser stands and provide greater tsunami mitigation. Densities that are too high may increase the risk of catastrophic failure. Although, even if this does occur, the dense root system of an incompletely uprooted tree can still provide resistance to tsunami flow – a level of resistance that may even exceed the drag of the branches. Broken branches snared by standing trees at the front established as the forest progressively collapses provide additional resistance.

In India, dense mangrove (*Rhizophora spp.* and *Avicennia spp.*) was associated with low damage in 96 percent of surveyed cases (Danielsen *et al* 2005). Density was reported at between 14-26 trees stems per 100 m^2. In Thailand, evidence shows a clear relationship between mangrove coverage and degree of damage to houses (Chang *et al* 2006). Exposed villages had the highest levels of damage and those behind mangroves the least with villages partly covered by mangroves exhibiting intermediate levels of damage – an experience also noted elsewhere.

The importance of undergrowth and resistant soil substrate is also revealed in case of plantations. Much higher forest widths are required for mitigation if a dense understorey of vegetation is absent. Also, poor soil resistance to scouring caused by the high flow velocities of the tsunami can result in uprooting trees and reduction of the mitigation effect (Shuto 1987, Tanaka *et al.* 2007, Dengler and Preuss 2003).

Two-layer beach forest structure of *Panadus odoratissimus* (foreground in photo) and *Casuarina equisetifolia* at Kalutara, Sri Lanka.

Forest age and tree diameter

Forest age (the average age of trees of the dominant size class) is directly correlated with both tree height and diameter. Increases in age, diameter and height generally enhance the mitigation effects of coastal forests. Diameter growth also enhances the breaking strength of trunks and branches. It also raises the resistance of the forest being toppled, up to a point after which resistance falls. On more mature stems the rate of increase in strength, stiffness and diameter slows relative to accumulation of mass in the canopy such that mechanical failure is more likely if the tree is subjected to an external force (Niklas and Spatz, 1999).

Simulation exercises for forest widths of 200 meters show that forest growth or aging can have a significant effect on tsunami mitigation (Harada and Kawata, 2005). It is assumed that the branch-free understorey climbs by about 5 cm per year, with branch height equal to 0.5 meters at 10 years and increasing to 2.5 meters by 50 years. The initial tsunami height used in the simulation was three meters with a period of 60 minutes. Results reveal that the youngest forest, a 10-year old pine forest, provides the greatest mitigation effect, if it is not washed away. In the case of a large tsunami, however, a 10-year old pine forest with an average diameter of 7 cm would likely not withstand a massive wave or succession of waves (Shuto, 1987). As forests grow older the mitigation effect falls at a marginally decreasing rate, until there is little difference in mitigation between a 40- and 50-year old forest.

Post-tsunami field surveys in Sri Lanka and Thailand showed that older *Casuarina equisetifolia* shelterbelts withstood the tsunami, but failed to provide protection (IUCN 2005a, Tanaka *et al.*, 2007). The tsunami passed through the shelterbelt without resistance from lower-level branches or undergrowth, a condition typical of the species. For a coastal forest of mature casuarina (e.g., 80 cm dbh) the mitigation effect is marginal and only slightly more than *Cocos nucifera*. Very young stands, on the other hand, less than 10-15 cm diameter were uprooted and washed away providing no mitigation. A similar forest-age effect was found for *Manikara spp.* in Sri Lanka (Tanaka *et al.*, 2007).

On the other hand, slightly older plantations of *C. equisetifolia* (e.g. of 15 cm dbh and above) are more effective (Tanaka *et al.*, 2007; Wetlands International, 2005). They are second only to *Pandanus odoratissimus*, which ranked the highest in mitigation effect (Tanaka *et al.*, 2007). Besides the high drag resistance young casuarina trees provide over the full height of the tree (close to 10 meters), immature trees were not broken easily by the tsunami.

Typical widths of shelterbelts in Sri Lanka and India are in the range of 10 to 20 meters. In the face of the 2004 tsunami, either the trees were too young (2 years old) so that they were uprooted and swept away, or too old (50-100 cm dbh) and hence provided little resistance because of the moderately wide spacing and species' minimal branching at lower levels. Shelterbelts of an intermediate age would have provided more protection. In India, houses situated within plantations were mostly protected by 35-year old shelterbelts with average diameters at breast height of about 10-20 cm and densities of 19-22 trees per 100 m^2 (Danielsen *et al.*, 2005). At 200 meters in width, however, they were 10 times the width of typical shelterbelts, which makes direct comparison with earlier mentioned cases difficult.

Moreover, examination of data from five tsunamis in Japan shows that diameter at breast height is an important determinant of stem breaking strength in coastal pine forests and that tree diameter of 10 cm or more is required to withstand an inundation depth of 4.65 meters. For larger waves, diameter (d) would have to increase at the rate of, $d = 0.1H^3$, where H is water depth; so for a 6-meter wave, a diameter of over 22 cm would be necessary (Shuto, 1987).

Because the mitigation potential declines with age for *Pinus spp.* and *Casuarina spp.*, particularly for smaller tsunamis, management is required to produce uneven-aged stands with a range of tree sizes and branches at all levels to enhance mitigation potential. However, a trade-off exists between stand age and breaking strength and uprooting resistance. Older trees have stronger trunks and branches, and more extensive root systems to anchor the tree in the soil. However, beyond a certain age, older trees become prone to breakage, especially near the trunk base (Niklas, 1999).

Other vegetation types may show the opposite relationship whereby mitigation potential increases with age. Mangroves are a prime example, but other species and forest types that retain dense understorey growth would qualify equally. Mangrove species that exhibit stilt-rooting (along with the beach forest Pandan trees) are unique in that density increases at lower levels as they grow older. In *Rhizophora spp.*, for instance, the density in the lower 0.3 meters of a young grove could equal 300-550 stems per 100 m^2 (Massel, Furukawa and Brinkman,1999). As the grove ages, roots reach a height of 1.0 meter or more above the ground and increase in girth, thereby reducing porosity and increasing reflection of incident waves. Field research in the Tong King delta, in northern Vietnam supports these results and show that the hydraulic resistance of *Kandelia candel* mangrove forest increased with age (Mazda *et al.*, 1997).

Forest height

Height of the dominant and codominant trees in a coastal forest has a direct bearing on the forest's frontal area projected towards a tsunami. The taller the forest the greater the reflective area of the barrier 'wall' and the lower the potential it will be overtopped by a tsunami. Assuming forest density is sufficient to resist the wave and the soil cohesion is strong enough to withstand additional leverage from force high in the tree, especially at the front edge of the forest, increasing tree height will enhance resistance to the tsunami.

Height of dominant and codominant trees is a function of tree age, tree species and growing conditions. Inadequate water supply, poor soil fertility or soil depth, etc. will stunt forest growth and reduce stand height. Heights of sub-dominant and suppressed trees depend on the rate at which the gaps or openings in the canopy are created either through tree fall or thinning. The manipulation of height at lower strata is important in maintaining a continuous barrier throughout the height of the forest.

Some mangrove species, even in the lower tidal areas, can reach considerable heights if left undisturbed. Trees heights between 30 and 50 meters have been reported in Latin America, Africa, and Asia (Dahdouh-Guebas, 2006). In Kenya, seaward *Avicennia marina* can reach 20 to 30 meters with stems several meters in circumference. In West Papua, Indonesia, 30-meter-tall mixed *Camptostemon schultzii–Avicennia spp.* are found, and in other parts of Indonesia *Rhizophora spp.* greater than 30 meters of height have been documented. In Panama, *Rhizophora mangle* and *R. racemosa* can grow up to 45 to 50 meters high (Dahdouh-Guebas, 2006).

Some beach forest species can also reach significant heights. For example, *Terminalia catappa*, is a large deciduous stately tree, and although branchless below the canopy, grows up to 25 to 40 meters in height with a spreading crown. *Pongamia pinnata* is another beach forest species that can grow up to 25 meters tall, but more commonly reaches only about 12 meters. Both *Terminalia* and *Pongamia* are frequently retained as ornamentals in altered forests. *Casuarina equisetifolia*, which is found in beach forests, altered forests and plantations, grows to heights of between 6 and 35 meters. The trunk is branchless up to 10 meters on large specimens and in older stands this reduces mitigation effectiveness at lower elevations.

Forest height is also important in relation to the risk of overtopping by a tsunami, which limits the mitigation capacity. Mitigation is a function of the volumetric occupancy of submerged forest[15] (Latief and Hadi, 2006), but water passing above the forest canopy will flow relatively unabated. For narrow coastal forests, plunging of the water behind the forest can also impart larger inertia forces than normal because of acceleration and impact forces. Erosive scouring will also be more significant just beyond the coastal forest because of turbulence and strong downward forces. Furthermore, a tsunami can strike buildings at greater heights of because of the upward deflection by a barrier (Preuss, Radd and Bidoae, 2001).

Tall coastal forests are also subject to greater leverage force that increases the chances of breakage and uprooting (Niklas and Spatz, 1999). The tendency towards uprooting is, however, partly countered by greater stem weight, which lowers uprooting chances (Gardiner, Peltola and Kellomaki, 2000). Despite these caveats, coastal forests have a potential advantage over seawalls in that they are taller and less expensive for an equivalent height.

A 300-400 year old coastal forest established to protect agricultural land and community in a hazardous bay, Oki Bay (Kochi Prefecture), Japan.

Species composition

The make-up of the coastal forest has important implications for the level of tsunami mitigation. Two critical aspects of tree species composition and forest type are the vertical configuration of roots, bole, branches and foliage, and understorey development. As

[15] The volume occupied by portion of the forest below the water level defines the volume of solid obstruction (the trees) relative to volume of water flowing through the forest. The greater is the ratio of solid to water the less the water able to pass, greater the obstruction, and greater the surface area creating drag resistance.

discussed above, variation in vertical density affects drag resistance at different heights in the forest, and hence overall resistance to tsunami flow. Drag resistance at lower layers is determined primarily by the shade tolerance of plant species in the understorey and the rate of creation of canopy openings. Tree species that retain lower branches or have stilt rooting contribute significantly to density at lower layers.

Tree species have a characteristic profile projected towards the tsunami. The variation in projected area at different elevations in the tree directly affects the overall reflection and drag resistance properties of coastal forests consisting of these trees species. Forest types common to Asian and Pacific coastal areas can to a large extent be classified according to their vertical configuration characteristics. For example, moderate height and lack of branches below the canopy characterise one type of tree that has specific mitigation properties, and are represented by species such as *Cocus nucifera* and mature *Casuarina equisitifolia*. These species can be found in plantations, altered forests, and beach forests.

Other species of other forest types may have different profiles, and consequently different mitigation potential. *Pandanus odoratissimus*, representative of a beach forest species with stilt-rooting and dense foliage, and *Rhizophora apiculata*, representative of large tidal-zone mangroves, exhibit the greatest drag resistance, especially within the lower strata (Tanaka *et al.*, 2007). Mature *Casuarina equisetifolia* and *Cocus nucifera* provide little resistance to tsunami at any elevation in the tree. On the other hand, while the plantation species, *Anacardium occidentale*, and a mangrove species of small tidal zones, *Avicennia alba*, provide little resistance at lower heights, their wide, multi-branching crowns provide significantly more drag resistance at greater heights. Such characteristics are of great importance in relation to larger tsunamis.

Changes in species composition resulting from colonisation by invasive species can affect the capacity of coastal forests to mitigate tsunami. Mangroves in particular are affected by a process called cryptic ecological degradation, in which introgressive mangrove-associated vegetation or minor mangrove species slowly start to dominate a forest of ‘true’ mangrove species (Dahdouh-Guebas *et al.*, 2005). The invasive species do not have the same mitigation capacity as ‘true’ mangrove species. This slow degradation usually results from human activities. From a mitigation standpoint, it is dangerous because people assume that some degree of protection exists because mangroves are still present. Instead, coastal areas become more vulnerable because the degradation progresses largely undetected, when compared to loss of mangrove area, which is easily observable.

Tree species diversity also seems to be an important factor determining the degree of protection. According to WWF-India, the Machilipatnam port, located inland of the Krishna mangroves in Andhra Pradesh, India, was completely unaffected by the tsunami, despite its vulnerable location near the mouth of a canal. A survey discovered that the mangroves in the area are relatively rich in species, and that "these species-rich stands were considerably taller and denser than stands elsewhere that were dominated by just a few species" (Maginnis and Elliott, 2005).

With regard to altered forests, which are characterized by a significant proportion of tree species not native to beach forests, evidence from Sri Lanka suggests that introduced ornamental and fruit tree species broke more easily than native species when struck by the tsunami. Replacing species adapted to storm waves and winds, these introduced species diminish the overall mitigation capacity of the beach forest. However, this does not imply that all native species retained in the altered forest have high breaking strengths. For example, *Borassus flabellifer* (palmyra)—commonly kept as an ornamental tree—is more vulnerable to tsunamis than *Cocus nucifera*.

Combining parameters for special circumstances

Density, diameter, height, age and the other parameters that effect mitigation are not independent of one another. They therefore have to be considered in an ecological context to assess what is and what is not possible in terms of tsunami mitigation. For example, it may not be possible to establish high density mangroves on beaches exposed to rough seas, or to have large diameter trees on shallow sandy soils.

Beach forests, mangroves and other forest types each have specific ecological requirements for successful establishment. Even within these forest types every species will require levels of freshwater, salinity, organic matter, etc. to be within certain limits. This is particularly the case with mangroves where some species are more tolerant of high salinity than others, such that the species associations gradually change according to inundation frequency, evaporation, freshwater flushing, etc. Consequently, ecological conditions will constrain the 'design options' for a coastal forest.

Once species suitable for a site are determined, the parameters of forest density, tree diameter, height and age can be manipulated to obtain the desired level of mitigation. Because different variables have similar effects on tsunami mitigation the same level of mitigation can result from raising or lowering the importance of a parameter and making a compensating change in one or more other parameters. For example, if the maximum width of a proposed coastal forest is constrained by existing land uses, a compensating increase in density (vertical and horizontal) may be able to achieve the desired level tsunami mitigation.[16]

Coastal forests can be designed in a number of possible combinations of width and density (or some other parameter combination) to deliver the required levels of mitigation in hydraulic force, flow velocity or depth. For example, one model shows that a width of at least 200 meters for a pine forest of 10 trees per 100 m^2 would reduce hydraulic force to just 10 percent of the tsunami's initial force (Harada and Imamura, 2006). Consequently, buildings constructed to withstand 20,000 Newtons per meter (N/m) of pressure and built behind such a coastal forest could survive a tsunami generating 200,000 N/m of force. If land was not available for the full 200 meters, the model shows that increasing density to 50 trees per 100 m^2 would allow width to be reduced to 100 meters and still get only 20,000 N/m pressure as the tsunami exits the coastal forest.

Coastal forest (center of photo) established to protect low-lying plain of Tsukihama city (Miyagi Prefecture). The town is especially vulnerable to large tsunami created by the bay. A denser, 90 meter forest forms the first line of defence, while a less dense, mixed forest, 100-190 meters wide is found behind an intervening area limited to agricultural land and buildings.

[16] It is important to note that by including coastal forests in the mitigation strategy for a coastal area set-back widths can be greatly reduced where the appropriate safe distance was determined for a beach in the absence of barrier.

Can coastal forests become a liability?

There are two important caveats concerning the protective role of coastal forests. In some situations, the presence of a coastal forest can be detrimental. The most important caveat is the risk of complete destruction of a coastal forest and the hazard from the debris flow that results. The second caveat is the tendency for gaps in the coastal forest at river mouth openings and elsewhere to accelerate the tsunami flow rate and channel more energy towards a smaller area.

Catastrophic failure

Given a large enough tsunami, all coastal forests can be a liability.[17] Moreover, even in the case where a forest could conceivably mitigate a tsunami 6, 7, or perhaps up to 8 or 10 meters, it could become a liability if it is “under-designed”. If forest width, density, tree diameter, or soil substrate strength are insufficient, a tsunami can uproot trees or break tree trunks and branches, and level the forest. The broken material becomes debris that can be carried inland by the tsunami. This was particularly evident in near-field zones such as the coastal areas of Aceh, Indonesia in the 2004 Indian Ocean tsunami where mangrove debris was found 2-3 km inland. The damage caused by debris laden water flows can exceed the damage caused by water alone because of the greater mass and inertial forces of the objects carried along.

Considering the mechanics involved in breaking or uprooting a tree, five factors are relevant:

- breaking strength and elasticity of tree stems, branches, and roots;
- rooting depth, size and mass of root anchorage plate;
- soil resistance to uprooting shear forces;
- combined drag and impact forces of wave; and
- maximum height at which force applied.

[17] However, in the case of a very large tsunami (20-30 meters in height) the extra force in the debris would be just ‘over-kill’, as the wave itself would be sufficient to level all buildings not built to tsunami code. This would imply that building standards would need to consider debris forces in their code as well.

While the last two factors cannot be controlled, the environmental conditions can be managed to minimize the chances of breaking or uprooting. The ability of tree stems, branches and roots to withstand tsunami forces depends on their diameter and on the density and structure of the wood, which can be manipulated through management.

Stem and branch diameter (or more precisely cross-sectional area) is a major factor determining horizontal breaking strength. Even a small increase in stem diameter will dramatically increase the breaking strength and mechanical stability of a tree.

Wood density and structure directly affect strength, and depend on tree species and growing conditions. The wood of species that are resistant to breakage are either rigid and dense (with sufficient diameter), or elastic and forgiving. Growing conditions that encourage rapid growth in conifers can lower wood density, shorten fibre length and increase proportion of juvenile wood (Evans and Turnbull, 2004). For ring-porous species fast growth enhances strength, while for diffuse-porous species growth rate has little effect on strength (Jagels, 2006).

The characteristics of the root-soil interface are also critical in determining the resistance of a tree to a tsunami. Failure of the anchorage to hold the tree firmly upright will result in uprooting and loss of mitigation effect, as well as additional tsunami debris, potentially endangering people and infrastructures. Resistance to uprooting depends on the soil properties and the nature of the root system (i.e., rooting depth and root mass), which are determined by tree species and growing conditions (Gardiner *et al*, 2000).

Rivers, channels, and other gaps in the barrier

Generally, a gap in the coastal forest will increase risks and potential damage. Gaps are found at the mouth of rivers and mangrove channels opening onto the sea. Homesteads, beach access, and roads also create openings in the forest barrier. A tsunami encountering a gap in a barrier will be funnelled into the gap with the flow accelerating as it moves into the constriction. Yet, for very large gaps the acceleration field does not develop and the presence of a coastal forest would not increase hazard. Moreover, the acceleration hazard is localized and limited to the area within and immediately behind the gap. Areas behind the coastal forest can still be protected from the tsunami. In the channel or gap, increased flow velocity and likely increased force, can be expected although flow depth will actually drop in most cases (Struve *et al.*, 2003).

Over a length of coastline the net mitigation effect of a coastal forest would be positive in most cases. In other words, tsunami hazard will be much greater in the absence of a coastal forest, as opposed to one in which there are some gaps. If, however, habitation is concentrated in the gaps, then total cost of damage may exceed the value of protection.

Also, if there are many gaps in the forest barrier relative to forest length, then the increased hazard at the gaps may exceed the mitigation potential of the forest beyond the gaps. Mangroves seem to be a special case, because of the numerous channels that weave through the forest and allow for rapid lateral dissipation of water volume and energy. Beach forests, altered forests and plantations cannot laterally disperse the water as fast. The rapid dispersion in mangroves would reduce effect of gaps. Nevertheless, gaps constitute a deficiency that increases tsunami hazard at specific locations, and because it is not realistic to consider a coastal forest without frequent breaks in the barrier, careful planning of settlement location in conjunction with forest establishment will always be necessary.

School saved by coastal forest? The impact of the 1998 PNG tsunami on the coastal forest near Sissano, north coast Papua New Guinea is shown here. The tsunami cleared 550 m of forest after overtopping a palm fringe. The inundation was only 70 cm when it reached the school. The school and students survived.

Conclusions

Returning to the original question: Was the tragedy caused by the 26 December 2004 Indian Ocean tsunami, and the destruction and death cause by tsunamis in general, preventable? This publication partly answers that question by evaluating the role played by coastal forests in the mitigation of tsunami damage. Evidence from post-tsunami surveys, field research and model simulations strongly support the notion that coastal forests can provide significant mitigation of tsunamis and storm waves. All forest types, with the exception of altered forests, demonstrate the ability to mitigate tsunami energy and force, reduce flow depth and velocity, and limit inundation area. These forests include mangroves, beach forests and plantations. Healthy, undegraded natural forests offer good protection to coastal areas, but plantations of closely-spaced trees with low, widely-branching canopies or significant ground vegetation can also provide equally good protection. Altered forests found around homesteads, hotel resorts and other development areas, on the other hand, are generally too widely-spaced, lack ground vegetation, and have introduced trees species not adapted to coastal wind and wave forces, and so are structurally weaker.

Notwithstanding the positive role many coastal forests have played, other forests proved to be ineffective against the tsunami waves. Evidence shows that coastal forests failed where waves were very large; forest width was limited; or trees were widely spaced, of small diameter or without branches near ground level. Any forest type could be susceptible, though degraded natural forests, altered forests and plantations are more likely to be deficient in one respect or another.

Besides failing to protect a coastal area, forests can become a liability under some circumstances. First, if a forest is levelled by a tsunami, the broken material will become floating debris with increased destructive force. Greater forest width can overcome the problem, but for very large tsunami such great widths may not be feasible. Small diameter trees associated with young plantations, and some mangroves are susceptible to uprooting or breakage along the trunk, but branches of larger trees are also at risk of breaking. A weak soil substrate also increases chances of uprooting. A second caveat relates to the gaps found in forest barrier created by homesteads, roads, beach access and other development. Unless very wide, these gaps increase flow velocity and force in and immediately behind the gap. Coastal planning therefore needs to recognize this hazard and minimize the creation of gaps, avoid vulnerable development within gaps, and make other contingencies as necessary.

While it is not feasible to establish a coastal forest "biosheild"– unbroken and of sufficient width and density – along the entire length of every coastline prone to tsunami, they can play a major role in protecting coastlines in Asia and the Pacific. Given their low cost of establishment and maintenance relative to other protective structures such as rock and cement seawalls and other 'hard' barriers, and their potential for generating other economic and environmental benefits, these 'soft' structures may justifiably become more widely utilized.

Extensive control forest in Ibaragi Prefecture on the Pacific coast of Japan. Such forests are designed to mitigate coastal hazards (strong coastal winds and blown sands, storm surge and tsunamis) and protect inland agriculture and habitation.

Wave height (m)	Water depth (m)	Protect or Failed	Near- or Far-field	Forest type	Width (m); spacing (m)	Special circumstances	Country, location	Source
15-30		fail	near	Beach	~400 +	Casuarina and other trees up to 50 cm dia snapped or uprooted; 5m sand dunes also levelled	Lhoknga, West Aceh, Indonesia	Latief and Hadi, 2006
10		fail	near	Plantation	~10 m in 1 or 2 rows	Casuarina shelterbelt 50 cm dia withstood but spacing too wide; 10 cm dia broken	Phang Nga, Thailand	Tanaka *et al*, 2007
~10+	10 (6)	protect	near	Plantation	250-300	Cashew nut grove	Ranong, Thailand	Tanaka *et al*, 2007
8	~5	protect	near	Mangrove	> 50	First 50 m broken above aerial stilt roots; mitigation by remaining mangrove	Phang Nga, Thailand	Tanaka *et al*, 2007
7-12		fail	near	Mangrove	10 ha; 150 stems/m^2	Dense, healthy mangroves snapped or uprooted	near Banda Aceh, Indonesia	Wetlands International, 2005
7-9	4-6	protect	far	Mangrove	200	Uprooted and collapsed, but enough energy absorbed that damage to village reduced	near Hambantota, Sri Lanka	Wetlands International, 2005, Ranasinghe, 2006
7		protect*	far	Mangrove	~5-6 m	* River bank vegetation on estuary reduced water depth	Yan Oya River, Sri Lanka	Yasuda et al., 2006
6-9		fail	far	Plantation	10-15	Casaurina shelterbelt badly damaged and uprooted in sections; tree diameters not documented	Batticaloa, Sri Lanka	IUCN 2005b
6-7		protect	near	Beach	40	Near-field 2006 West Java tsunami	Cikalong, West Java	Latief and Hadi, 2006
6	~4.5-5	protect	far	Beach	155; dense	Mostly due to pandanus (10m); also coconut, mangrove	near Rekawa, Sri Lanka	Tanaka *et al*, 2007
5.2-6.8		protect*	near	Altered	100	* Protection by coconut grove from erosion	Phang Nga, Thailand	Hiraishi, 2006
5-6	3	protect	far	Altered	> 100; 3	Houses within first 100 m damaged; relatively dense coconut	Kalutara, Sri Lanka	Tanaka *et al*, 2007
5.0-5.5		fail	far	Beach	200	Shrubs and small diameter trees (7-10 cm dia) broken and swept away	Yala, Sri Lanka	Tanaka *et al*, 2007
5	3	fail	far	Altered	500; 4-40	Widely-spaced coconut with habitation within	Hikkaduwa, Sri Lanka	Tanaka *et al*, 2007
4.5-5.5		protect	far	Beach	100; dense	Mostly due to thick pandanus; also coconut	near Galle, Sri Lanka	Ranasinghe, 2006
4.5		protect	far	Plantation	200; 2.5	Large damage reduction by 35-yr old casuarina (10-20 cm dia) shelterbelt	Tamil Nadu, India	Danielsen et al., 2005
~4-7	3-5	protect	both	Plantation	20-26; 1.6	Japanese pine, with undergrowth	45 observations throughout Japan	Shuto, 1987
4-5		protect	near	Mangrove	50; dense	Inundation distance was 400 meters at the sandy beach	Ranong, Thailand	Siripong, 2006
4-5		protect	far	Mangrove	10-15 ha surround	Distance from sea and elevation also contributed	Tamil Nadu, India	Kathiresan and Rajendran, 2005
~4	2.5	fail	far	Altered	54; 7	Widely-spaced coconut grove	Oluvil, Sri Lanka	Tanaka *et al*, 2007
3-7		protect*	near	Mangrove	~400; dense	* Reduction of beach erosion in mangrove area	Nicobar Islands	Ramanamurthy et al., 2005
3		fail	near	Beach	200	Mature casuarina (50-100 cm dia) no lower branches	Ranong, Thailand	Tanaka *et al*, 2007
2-3	~1-2	protect	far	Altered	~200 +	Relatively dense planted coconut, beach forest and horticultural groves	Kerala, India	Chadha et al., 2005
1.5-2.5	~1-2	protect	far	Beach	15-20; dense	Shrubs, small trees; Low, mostly non-breaking waves	Maldives	UNEP 2005

Table1: Collated information on tsunami damage in relation to wave and forest characteristics for the Indian and Pacific Oceans

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Following the Indian Ocean tsunami of December 2004, tree planting campaigns were initiated in coastal areas to rehabilitate devastation wrought by the tsunami and to afforest coastlines cleared of trees in the preceding decades. These efforts were partly justified on the basis of claims that trees and forests had provided protection against the tsunami. Such claims were later questioned, however, and the lack of clear information available to decision makers became apparent. ***The role of coastal forests in the mitigation of tsunami impacts*** attempts to bridge the gap between science and policy by presenting and synthesising information on tsunami protection and forests drawn from empirical studies, simulations and mathematical models.

The protection afforded by coastal trees and forests is related both to the size and force of the tsunami and factors related to the trees/forest and underlying substrate. Tsunami force and size are dependent on the nature and proximity of the initiating event, the local coastal formations and under-sea topography or "bathymetry". The degree of mitigation offered by a coastal forest is determined by the width of the forest, its horizontal and vertical density, and the distribution of structural elements. Tree diameter and height are additional key factors as are the strength and elasticity of the trees and the soil substrate. Rivers and gaps in coastal forests are, however, likely to result in local increases in destruction and, in the case of forest or trees being destroyed, broken remnants may also increase damage by acting as projectiles carried by the water.

Because of unpredictability at the local level, prospective protection forests should be assessed in accordance with likely wave sizes, forest related features and in view of associated caveats before any protective potential can be assumed. Early warning systems and evacuation plans must also be implemented as necessary and complementary measures to protect lives from massive tsunamis. Trees and forests may, however, provide protection at lower cost than engineered coastal protection structures and can also offer additional benefits.