RAP PUBLICATION 2007/1

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

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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

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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.

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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

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[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]

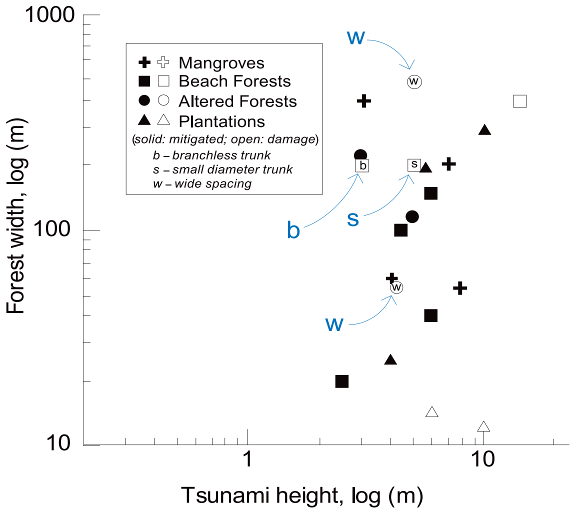

Figure 1: Evidence from 2004 Indian Ocean and 2006 West Java tsunamis of coastal forest's protective role relative to wave height and forest width. Solid shapes indicate substantial mitigation and damage reduction. Source: compiled by Keith Forbes

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*).

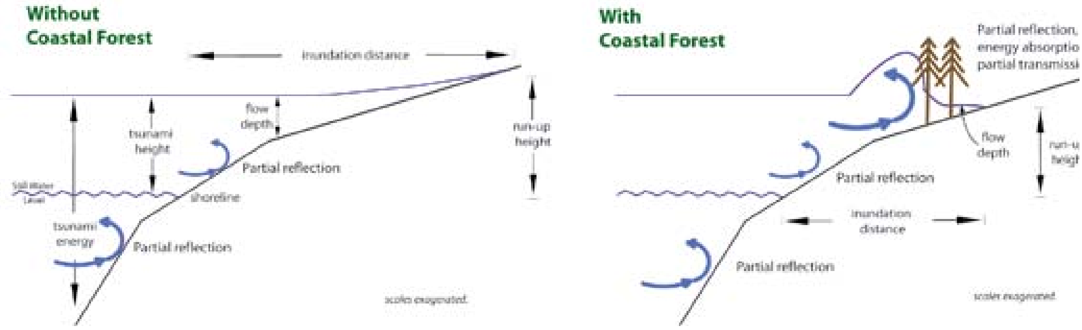

Figure 2: Tsunami wave run-up with and without coastal forest barrier. Source: Keith Forbes

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[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

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[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

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[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.