

The Asian Tsunami: A Protective Role for Coastal Vegetation

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The scale of the 26 December 2004 Indian Ocean tsunami was almost unprecedented. In areas with the maximum tsunami intensity, little could have prevented catastrophic coastal destruction. Further away, however, areas with coastal tree vegetation were markedly less damaged than areas without. Mangrove forests are the most important coastal tree vegetation in the area and are one of the world's most threatened tropical ecosystems (1).

Measurement of wave forces and modeling of fluid dynamics suggest that tree vegetation may shield coastlines from tsunami damage by reducing wave amplitude and energy (2). Analytical models show that 30 trees per 100 m² in a 100-m wide belt may reduce the maximum tsunami flow pressure by more than 90% (3). Empirical and field-based evidence is limited, however.

Cuddalore District in Tamil Nadu, India, provides a unique experimental setting to test the benefits of coastal tree vegetation in reducing coastal destruction by tsunamis (4). Cuddalore has a relatively straight shoreline, a fairly uniform beach profile, and a homogenous continental slope. Moreover, the shoreline comprises vegetated as well as non-vegetated areas and was documented by cloudfree pre- and post-tsunami satellite images.

The force of the tsunami impact in Cuddalore is illustrated by the central part of our study area (Fig. 1). At the river mouth, the tsunami completely destroyed parts of a village (fig. S1) and removed a sand spit that formerly blocked the river. However, areas with mangroves (Fig. 1, dark green polygon) and tree shelterbelts were significantly less damaged than other areas (supporting online text). Damage to villages also varied markedly. In the north, stands of mangroves had five associated villages, two on the coast and three behind the mangrove. The villages on the coast were completely destroyed, whereas those behind the mangrove suffered no destruction even though the waves damaged areas unshielded by vegetation north and south of these villages. In the south, the shore is lined with *Casuarina* plantations (Fig. 1). Five villages are located within these plantations and all experienced only partial damage. The plantations were undamaged except for rows of 5 to 10 trees nearest to the shore, which were uprooted (fig. S2).

Our results suggest that mangroves and *Casuarina* plantations attenuated tsunami-induced waves and protected shorelines against damage. Human activities reduced the area of mangroves by 26% in the five countries most affected by the tsunami, from 5.7 to 4.2 million ha, between 1980 and 2000 (5). Conserving or replanting coastal mangroves and greenbelts should buffer communities from future tsunami events. Mangroves also enhance fisheries (6) and forestry production. These benefits are not found in artificial coastal protection structures. Coastal tree vegetation can be established for investments of U.S.\$150 to U.S.\$2000 per ha (7). Mangroves, however, are suitable for planting only on coastal mudflats and lagoons, which cover ~25% of the continental coastline of the Bay of Bengal (8). Elsewhere, the conservation of dune ecosystems or green belts of other tree species, such as *Casuarina*, could fulfil the same protective role.

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Supporting Online Material

www.sciencemag.org/cgi/content/full/310/5748/643/DC1

Materials and Methods

SOM Text

Figs. S1 and S2

Table S1

References and Notes

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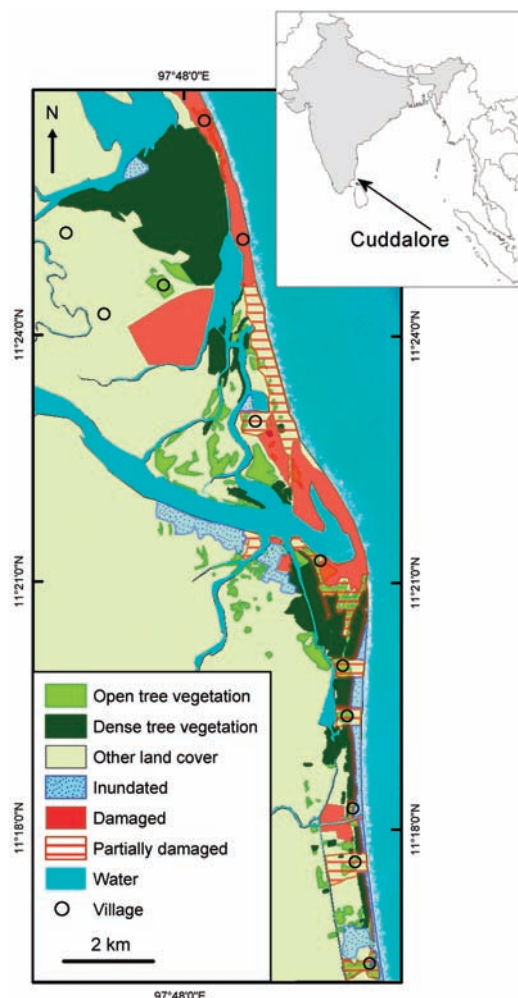


Fig. 1. Pre-tsunami tree vegetation cover and post-tsunami damages in Cuddalore District, Tamil Nadu, India.

such important qualitative information at a resolution of species and even individuals (5), the very high resolution IKONOS and QuickBird satellite imagery, to which the authors had access, has not been used to its full potential.

Second, the authors do not identify variation in house construction or variation in mangrove settings as possible factors influencing damage to the villages. The image of the mosque as the only building left standing in Banda Aceh after the tsunami hit (6) suggests that the architecture of buildings or the materials that are used for their construction may have been a determining factor in withstanding the tsunami wave. Their fig. 1 suggests that there are at least two different types of mangrove settings: fringing forests and riverine forests (7). This may have influenced the impact of the tsunami as well.

Finally, only three of the villages analyzed are located behind a potential barrier. Most of the villages were very close to the ocean (see Danielsen *et al.*'s fig. 1), in which tsunami destruction, somehow attenuated by beachfront *Casuarina* plantations, is evident. A comparison between villages located at a (similar) distance from the coastline but protected to various extents by different types of barriers or no barriers at all is not made. Such a comparison could have accounted for the variation in distance to the coast.

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Response

WE AGREE WITH DAHDYOUH-GUEBAS AND KOEDAM on the need for better understanding of the tsunami mangrove shield. However, we believe the relatively homogenous coastal characteristics of our study site minimized intrasite differences in the energy of the incoming tsunami and allowed the benefits of a tsunami tree shield to be studied.

The few (1) field-based and quantitative studies of the shielding function of mangroves against wind-induced waves (2, 3) cannot be generalized to tsunamis. The hydraulic resistance of mangroves to tidal flow (4, 5) differs substantially from their resistance to wind-induced

waves (3), suggesting that the protective capacity of mangroves varies according to the time scale of the waves (6). Tsunami waves have a period of 1 to 2 hours (7), compared with wind-induced waves (<20 s) and tidal flow (diurnal and semidiurnal). As tsunami waves behave differently from other waves (8), their hydraulic properties cannot be estimated by interpolation.

Analysis of QuickBird (0.6-m pansharpened pre-tsunami) and IKONOS (4-m multispectral post-tsunami) images and ground surveys by scientists with 13 years of experience in the study area demonstrated quantitatively



Tsunami-stricken areas near the coastal outskirts of Banda Aceh, Indonesia, on 27 December 2004.

(see our table S1) (9) the benefit of the tsunami tree shield. Assessing the impact of mangrove condition in modifying relative protection would require analysis of matched pairs of pre- and post-tsunami 0.6-m QuickBird or 1-m IKONOS images, which were not available. Field surveys indicated, however, that forest condition was relatively uniform.

Variations in house construction and physiognomy of the mangroves are potential caveats. Across the study area, there were no significant differences in house construction, but variations in the physiognomy of mangroves require further study.

Unprotected villages in the northern portion of the study site were compared with villages partly protected by *Casuarina* in the south, but no villages with and without mangroves were equidistant from the coast. Despite this analytical weakness, our results and data from Sri Lanka (10) suggest that by maintaining or planting coastal forests, humans enhance protection of coastal areas against tsunamis. Observations of tropical cyclone impact (11) further suggest the need for a coordinated strategy (12) to maintain or restore coastal wetlands, forests, or sand dunes—especially along vulnerable tropical and subtropical coastlines. Such a strategy would not only provide protection against tsunamis but also mitigate the impacts of storms and sea level rise (13).

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Below is a letter to the editor critiquing Danielsen *et al.*'s paper, published a little over two months later. Included is Danielsen *et al.*'s response.

Coastal Vegetation and the Asian Tsunami

THE BARRIER FUNCTION OF COASTAL VEGETATION during the recent tsunami disaster has been highlighted by the results of F. Danielsen *et al.* ("The Asian tsunami: a protective role for coastal vegetation," *Brevia*, 28 Oct., p. 643). Their conclusions confirm assumptions made earlier by Pearce (1), Williams (2), and many others. Although the authors used a limited analytical approach on a single Indian lagoon, there are some caveats they did not address.

First, the authors assessed pre-tsunami vegetation cover using remotely sensed data and categorized vegetation as dense, open, and no trees. However, as highlighted by Dahdouh-Guebas *et al.* (3), "cryptic ecological degradation" in the field may be masked on remotely sensed imagery, and mangroves that appear healthy by species composition and density on remote sensing imagery may in fact be subject to strong qualitative degradation. The concept of cryptic ecological degradation in mangrove forests is even more important in light of these forests having provided less protection during the recent tsunami than 24 other Sri Lankan lagoons, as evident from cluster analyses (4). Considering the ability to extract

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