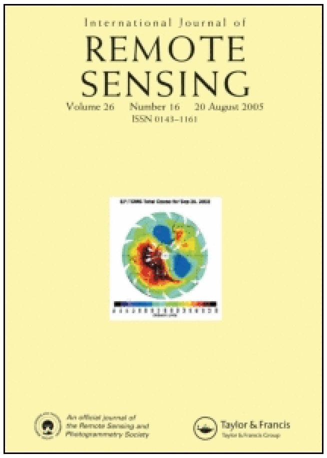

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Using remote sensing to assess the protective role of coastal woody vegetation against tsunami waves

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This paper describes how remote sensing techniques were used to study the effect of mangroves and other woody coastal vegetation as a protective measure against the 2004 Indian Ocean Tsunami. Remote sensing made it possible to compare pre- and post-Tsunami images of large areas. A study site was selected based on medium resolution Landsat imagery and existing topographic maps. Selection criteria included substantial damages reported, presence of woody vegetated and non-vegetated shorelines, homogeneous bathymetry and good coverage of pre- and post-Tsunami satellite imagery. The Pichawaram mangrove, Tamil Nadu, India, matched these criteria. Pre- and post-Tsunami Ikonos and QuickBird images were compared through the visual interpretation of pre-Tsunami coastal vegetation and post-Tsunami damage. The results were validated in the field. The analysis showed that mangrove forests and coastal shelterbelts provided protection from the Tsunami. This was concluded from analysing the spatial distribution of damage relative to woody vegetation along the coast as well as transects detailing the amount of damage behind the coastline and the coastal woody vegetation.

1. Introduction

Mangroves, and similar forms of woody vegetation, are important not only in the context of providing shelter against the Tsunami, but also as a means of protection against other forms of natural hazards. Furthermore, they have considerable economic and ecological importance. Mangroves are one of the world's most productive vegetation communities (Eong 1993, Vasconcelos *et al.* 2002). The term mangrove denotes a 'taxonomically diverse assemblage of trees and shrubs that form the dominant vegetation communities in tidal, saline wetlands along sheltered tropical and subtropical coasts' (Blasco *et al.* 1996, p. 167). The main ecological benefits of mangroves include that they provide many species of animals and plants, including fish and shrimps, with habitat, forage, breeding and nursery area (Imhoff

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et al. 1986, Teas *et al.* 1987, Dewalt and Vergne 1996, Long and Skewes 1996, Panapitukkul *et al.* 1998, Vasconcelos *et al.* 2002, Mumby *et al.* 2004, Dahdouh-Guebas *et al.* 2005, Lewis III 2005, Zharikov *et al.* 2005). They play a central role in the biogeochemical cycles of the coastal environment (Baltzera *et al.* 2004, Gonneea *et al.* 2004). They serve as a sink for organic carbon and trap both suspended particulates from the ocean (Allison and Lee 2004) and sediments and anthropogenic pollutants before they reach the sea (Long and Skewes 1996, Gonneea *et al.* 2004). They supply the ocean with nutrients and organic carbon while improving coastal stability (Blasco *et al.* 1996, Dewalt and Vergne 1996, Nguyen *et al.* 1998, Vasconcelos *et al.* 2002, Dahdouh-Guebas *et al.* 2005, Lewis III 2005) and they are reservoirs of genetic materials (Long and Skewes 1996).

Mangroves are of value to the economy and livelihood of local human populations as a source of products such as fish, shrimps, timber, poles, firewood, charcoal, wood pulp, fodder, thatch, medicinal products, bark for tanning materials and chemicals for industry (Teas *et al.* 1987, Dugan 1990, Blasco *et al.* 1996, Nguyen *et al.* 1998, Panapitukkul *et al.* 1998, Lewis III 2005). Mangroves are also important for water quality maintenance (Long and Skewes 1996, Nguyen *et al.* 1998) and for recreation and education (Long and Skewes 1996). The economic value of mangroves has been estimated at US\$10 000 per ha a^{-1} (Panapitukkul *et al.* 1998) and it has been argued that from an economic point of view the benefits of mangroves to local communities are so great that this alone justifies protecting and rebuilding them (Nguyen *et al.* 1998).

Studies indicate that mangroves provide security by acting as physical barriers against waves, currents and storms (Imhoff *et al.* 1986, Teas *et al.* 1987, Panapitukkul *et al.* 1998, Dahdouh-Guebas *et al.* 2005, Lewis III 2005, Williams 2005). Studies also indicate that mangroves inhibit coastal erosion (Blasco *et al.* 1996, Dewalt and Vergne 1996, Vasconcelos *et al.* 2002, Williams 2005) and create a buffer against floods (Dugan 1990). In an assessment of storm induced tidal surges in Bangladesh Imhoff *et al.* (1986) concluded that lives would have been saved if the mangroves were still extant. Similarly, scientists, environmentalists and Asian fishing communities have argued that had the mangroves not been degraded, the Indian Ocean Tsunami of December 2004 would have been less destructive (Williams 2005). This is supported by eyewitness reports suggesting that there was less damage in areas where the coastline was protected by natural barriers, especially those protected by mangroves (Williams 2005).

Despite their importance, mangroves are being degraded and are disappearing rapidly throughout the world (Blasco *et al.* 1996, Long and Skewes 1996, Nguyen *et al.* 1998, Panapitukkul *et al.* 1998, Dahdouh-Guebas *et al.* 2005, Williams 2005). Losses of mangroves exceed those for tropical rain forests and coral reefs (Valiela *et al.* 2001). In 1980 mangroves covered 198 000 km of the tropical shorelines of the world, whereas by 1990 the coverage was reduced to 157 630 km and by 2003 to only 146 530 km (Lewis III 2005). Mangroves are threatened by anthropogenic pressures (Murray *et al.* 2003, Dahdouh-Guebas *et al.* 2005, Zharikov *et al.* 2005) as well as by natural erosion (Blasco *et al.* 1996), e.g. from storms and hurricanes (Murray *et al.* 2003). Mangroves are being converted to farmland, grazing land, and fish and shrimp ponds, subjected to pollution from agriculture and they are being over-exploited, leading to land degradation through, for example, increased salinity and acidification of mangroves (Pham *et al.* 1992, Blasco *et al.* 1996, Dewalt and Vergne 1996, Nguyen *et al.* 1998, Ramirez-Garcia *et al.* 1998, Vasconcelos *et al.*

2002, Páez-Osuna *et al.* 2003, Dahdouh-Guebas *et al.* 2005). Other problems stem from urban and commercial development such as the construction of roads, canals, harbours, dams and infrastructure for tourism activities and pollution from, for example, industries and untreated municipal effluents (Blasco *et al.* 1996, Long and Skewes 1996, Nguyen *et al.* 1998, Ramirez-Garcia *et al.* 1998, Vasconcelos *et al.* 2002, Páez-Osuna *et al.* 2003).

Remote sensing has been extensively used as a tool to study and map mangroves (see, for example, Baltzera *et al.* 2004, Bird *et al.* 2004, Fromard *et al.* 2004, Kovacs *et al.* 2004, Kovacs and Flores-Verdugo 2005). As early as 1972 mangroves were delineated on spatial images using Landsat images (Lewis and MacDonald 1972). Today, with high spatial resolution imagery, such mapping has become an easily manageable and cost-effective task (Panapitukkul *et al.* 1998, Mumby *et al.* 1999, Zharikov *et al.* 2005). Remote sensing images of mangroves are for the most part reliable (Pham *et al.* 1992), accurate (Kovacs *et al.* 2004, Plaziat and Augustinus 2004) and collected consistently in time and space (Green *et al.* 1997). Furthermore, the information can be obtained very quickly, almost in near real time (Blasco *et al.* 1996, Green *et al.* 1997, Froidefond *et al.* 2004). Other benefits of using remote sensing for mangrove mapping are that data can be collected in a non-destructive manner since it is not necessary to move around in the mangrove to obtain data (Green *et al.* 1997). Large, remote and inaccessible areas can therefore easily be mapped and monitored (Long and Skewes 1996, Green *et al.* 1997, Panapitukkul *et al.* 1998).

Remote sensing techniques have proven useful in monitoring, controlling, assessing and relieving natural disasters (Imhoff *et al.* 1986, Luscombe and Hassan 1993, Iglseder *et al.* 1995, Pope *et al.* 1997, Islam and Sado 2000, Zhang *et al.* 2002), for instance during floods in Bangladesh, monitored using National Oceanic and Atmospheric Administration (NOAA) Advanced Very High-Resolution Radiometer (AVHRR) data (Islam and Sado 2000) and China (Zhang *et al.* 2002). Combined with data on, for example, elevation height, remote sensing has proven an accurate and efficient way of surveying and evaluating the risks of natural disasters (Islam and Sado 2000, Zhang *et al.* 2002). Remote sensing can be used to monitor the development of a disaster to prepare the population for the extent, location and timing of the event (Luscombe and Hassan 1993, Long and Skewes 1996, Zhang *et al.* 2002). Once the disaster is occurring, remote sensing can be used to provide updated information about the event (Luscombe and Hassan 1993, Pope *et al.* 1997). After the disaster, remote sensing can be used to assess its impact and spatial distribution, enabling relief efforts to prioritize their use of resources (Zhang *et al.* 2002). The technique is attractive because it is cost-effective, can cover large areas, is timely and is an objective way of gathering data (Iglseder *et al.* 1995, Long and Skewes 1996, Islam and Sado 2000).

Few works have done quantified studies of the possible protective role of coastal woody vegetation. After the December 2004 tsunami, Danielsen *et al.* (2005) conducted a study on the east coast of India in the Tamil Nadu province. The study used very high resolution Ikonos and QuickBird images to show how areas and settlements behind either mangroves or shelterbelts of trees provided protection. The work was criticized by Dahdouh-Guebas and Koedam (2006) for not addressing the condition and possible degradation of the tree vegetation and that the difference of construction materials of the buildings were not included in the analysis. Furthermore, it was pointed out that there were only a limited number of settlements that were located behind the protected woody vegetation. Danielsen *et al.* (2006) responded to this criticism stating that from field surveys it was documented that both the forest and the building materials were fairly uniform in the area. The criticism by Dahdouh-Guebas and Koedam (2005) of comparing inland settlements with and without protective woody vegetation initialized a re-interpretation of the data that makes up a part of the present paper. Another study that has received attention was conducted by Kathiresan and Rajendran (2005). The study area is the same province, Tamil Nadu on India's east coast and here the authors used regression analysis to identify the variables explaining the human death tolls. Significant correlations were obtained with 'distance of human inhabitation' (R^2=0.37), 'elevation from the sea level' (R^2=0.40) and 'area of coastal vegetation' (R^2=0.33). The work has been criticized for the statistical study, however, the dataset was reanalysed by two teams Kerr *et al.* (2006) and Vermaat and Thampanya (2006) that come to two opposite conclusions. Kerr *et al.* (2006) states that the only variable that is not significant is the area of coastal vegetation and Vermaat and Thampanya (2006) conclude that there was a significant correlation. In any case, the topic of studying the protective role of the vegetation is most complex as discussed above and simple statistical regression is probably not the best stand-alone tool, simply because the conditions and interrelationships between variables change as a function of the location of the observations. If the study data are biased with relatively more observations away from the sea, the significance of distance to the sea will be strong and the contrary concerning the area of the coastal woody vegetation and vice versa. Chatenoux and Peduzzi (2005) conducted a large-scale study of the Asian 2004 Tsunami and could not conclude positively on the protective effect of the mangroves.

The aim of the present study was to explore the use of very high resolution (VHR) remote sensing data to assess the possible protective role of the coastal vegetation relative to the December 2004 Indian Ocean Tsunami event. The research strategy was to identify a study area where all conditions were the same except the presence and absence of protective coastal vegetation. The work of Danielsen *et al.* (2005) is here further developed by a reinterpretation of the VHR data and an analysis of transects along the coast in order to quantify the importance of coastal woody vegetation.

2. Materials and methods

2.1 *Selection of study site*

Initially we intended to analyse the ability of mangrove forests to protect coastal communities in a number of areas affected by the Tsunami. Several criteria for site-selection, however, had to be fulfilled (see table 1).

The first criterion of the site selection process was to ascertain whether substantial mangrove forest existed in the area. Coastal areas of Sri Lanka that were hit by the Indian Ocean Tsunami had only scattered mangroves and hence these areas were excluded from the study. To determine which areas had mangroves, visual analysis of Landsat ETM images was performed. Areas covered by mangroves were identified using information about wetness from the near infrared (NIR) bands as well as the texture that is characteristic of mangroves. An interactive map available online on the United Nations Environment Programme, World Conservation Monitoring Centre website (UNEP-WCMC 2005), was also used for support. This map showed, amongst other things, the location of mangroves in the Tsunami

Table 1. Criteria for site selection. Note, that the table is based on information that was available prior to 15 February 2005. Updated damage reports and additional remote sensing data became available later.

Name and location of the mangrove	Substantial damage reported	Vegetated and non-vegetated coastline areas	Pre- and post-Tsunami satellite images*	Homogeneous bathymetry	Homogeneous topography
Pichawaram, India	Yes	Yes	Yes	Yes	Yes
Godavari, India	No	–	–	–	–
Muttupet, India	No	–	–	–	–
Kuala Jambu Air, Indonesia	No	–	–	–	–
Ulee Lhee, Indonesia	Yes	Yes	No	–	–
Ranong, Thailand	Yes	Yes	No	–	–
Takua Pa, Thailand	Yes	Yes	Yes	No	–
Phang Nga, Thailand	Yes	Yes	No	–	–
Krabi, Thailand	Yes	Yes	No	–	–
Trang, Thailand	No	–	–	–	–
Palian-Langu, Thailand	No	–	–	–	–
Kangar, Thailand	No	–	–	–	–

* No further data were included in the study after 15 February 2005; – where further analysis has not been carried out.

affected areas. Unfortunately, however, this map was partially out of date due to the rapid destruction of mangroves that has been taking place. Once the presence of mangroves was established, it was determined whether substantial damage from the Tsunami had been reported through correspondence with contacts in India, Thailand, Malaysia and Indonesia, who had visited the affected coastal areas.

Another criterion concerned whether the area contained both vegetated and non-vegetated coastline areas. The Landsat ETM images were used to identify such areas. Good coverage of pre- and post-Tsunami satellite imagery of the area was also an important criterion. For some areas, such as Krabi, Thailand, the post-Tsunami data were not recorded until after the area had been cleaned up and therefore it was impossible to determine the damage. Furthermore, post-Tsunami data were often not available due to extensive cloud cover.

Finally, it was important that the area had homogeneous bathymetry along the coastline and a homogeneous topography to ensure that the entire coast, vegetated as well as non-vegetated, was impacted by the Tsunami equally. This was done by using the Landsat ETM images to seek out an area with no islands along the coast and with a fairly straight coastline. In order to study the protective effect of mangroves they need to be situated on a straight coastline next to similar areas without woody vegetation. Mangroves, however, are typically situated in sheltered bays or estuaries making it difficult to study their protective effect. Takua Pa, Thailand, is a good example of this. The mangrove here were located in the bottom of a bay. It was apparent that there was no damage behind the mangrove, but it was hard to tell whether this was because the mangrove itself was protected by its location within the bay or because the mangrove barricaded the waves. Such areas had to be eliminated from the study. Once all the criteria had been fulfilled naval charts were consulted to ensure that the bathymetry was homogeneous and the topography was evaluated using topographic maps. If one of the criteria was not fulfilled, the area was rejected as a study site. As can be seen from table 1, the Pichawaram area in Tamil Nadu, India, was selected because it was the only area in the Tsunami-hit region that matched all the criteria. See the location of the Pichawaram area in figure 1.

2.2 *The study site*

The study site covers about 20 km of coastline along the eastern coast of Tamil Nadu, India, (11°27′ N, 79°48′ E to 11°16′ N, 79°51′ E) (see figure 1 and 2). The Pichawaram mangrove is situated in the northern part of the study site. The rest of the site is comprised of agriculture and shrimp farms. The mangrove is connected to the Coleroon estuary in the south through a number of backwater canals. The Pichawaram mangrove, the Coleroon estuary and the interconnecting backwater canals together create a complex coastal ecosystem. This mangrove area is one of two remaining large areas of mangrove in the state of Tamil Nadu. Twelve hamlets are dispersed along the coast, some directly on the coast and others sheltered by woody vegetation. The southern part of the coast is lined with a shelterbelt of she-oak *Casuarina equisetifolia*. A linear stretch of mangrove is present behind the she-oak shelterbelt. Some villages are located between this mangrove and the shelterbelt.

A naval chart confirmed that the bathymetry of the area is homogeneous. The topography is homogeneous, smooth and the maximum height recorded within 1000 m from the shoreline is about 2 m above the mean sea level (Survey of India 1971). The study site was hit by the Tsunami from the northeast at an angle of more or less 45°. This was determined by the direction in which the trees had fallen, the

Figure 1. The arrow indicates the location of the study area. The study area stretches along 20 km of the eastern coast of Tamil Nadu and contains the Pichawaram mangrove.

Figure 2. These images show the severely damaged agricultural area southeast of T. S. Pettai. Pre-Tsunami (*a*) and post-Tsunami (*b*) images. Despite the difficulties in comparing the different types of images outlined here, it is quite clear that this area has been damaged as several of the features visible (*a*) have disappeared or become blurry in (*b*). It is also visible that the area displayed is wetter in appearance in (*b*) than in (*a*).

morphological impact of the Tsunami water and villagers' accounts. One of the reasons for the direction of the Tsunami could be that along the coast, water current moves towards the north during the southwest monsoon season (June to September), but reverses and moves towards the south during the northeast monsoon season (October to December).

2.3 *Remote sensing*

ETM Landsat satellite images obtained from Global Land Cover Facility (GLCF) were used to assist in the site selection process. The satellite image that covered the selected area was from 28 October 2000. As an aid to humanitarian and non-commercial efforts to reduce Tsunami vulnerability, the UN initiative UNOSAT made available several satellite images from the areas affected by the Tsunami including the area around Pichawaram. These data consisted of the blue, green and NIR 4 m bands from an Ikonos satellite image of 29 December 2004, only a few days after the Tsunami. The blue, green, red, NIR and panchromatic bands from a QuickBird satellite image, covering part of the scene of 31 December 2004, were also available from UNOSAT, but due to extensive cloud cover, this image only served as an aid in the analysis. UNOSAT did not provide very high-resolution pre-Tsunami data from India. A pan-sharpened 0.6 m QuickBird satellite image of 4 May 2003, covering the Pichawaram area, was therefore acquired (see summarized details in table 2).

The main challenge of comparing the pre- and post-Tsunami images lay in identifying the areas that had been damaged. The damage pattern was fairly complex and could not be resolved by doing a straight forward mapping of changes in land cover, since visual interpretation was needed in most cases to confirm whether any damage had taken place or not. The analysis was constrained by the spatial and spectral differences between the two images. Consequently, it was decided to analyse the limited study area making visual interpretations and focus explicitly on identifying the woody vegetation and the damage. The first step in the analysis was to determine which areas were protected by vegetation and the vegetation was therefore digitized. Vegetation was divided into three categories: *dense woody vegetation*, *open woody vegetation* and *no woody vegetation*. *Dense woody vegetation* included the mangrove and shelterbelt areas whereas *open woody vegetation* included all other woody vegetation such as degraded mangrove and openings in the shelterbelt that contained only a few shelterbelt trees. *No woody vegetation* refers to any areas that do not contain woody vegetation. The pre-Tsunami woody vegetation cover was then compared with the post-Tsunami woody vegetation cover, which revealed some of the damaged areas.

We then identified and digitized post-Tsunami damage, dividing the damage into four categories: areas that had been *severely damaged* (all or most of the physical structures had been destroyed, removed or damaged); *partially damaged* (some damage but most of the physical structures were intact); *undamaged* (no damage visible on the ground or on the satellite images); and areas *inundated* by water but otherwise undamaged. Although these areas were damaged, they could be restored relatively easily in contrast to the *partially damaged* areas that needed reconstruction. Thus, prawn farms that had been inundated by water, but suffered no structural damage, were categorized as *inundated*. Some of the areas included in the *inundated* category, such as the inundated beach, had no physical structures to be

Table 2. Remote sensing data used in the study.

Name	Acquisition date	Bands available	Resolution
Pre-Tsunami Landsat ETM	28 October 2000	All bands	30 m
Pre-Tsunami QuickBird	4 May 2003	Pan-sharpened blue, green, red	0.6 m
Post-Tsunami Ikonos	29 December 2004	Blue, green, NIR	4.0 m
Post-Tsunami QuickBird	31 December 2004	Blue, green, red, NIR, pan	2.4 m

NIR, near infrared.

damaged, but by categorizing them as *inundated* we could show the spatial extent of the flooding. The analysis was supported using ground truth, which included descriptions of damage and digital photography on the ground.

Figures 2, 3 and 4 provide examples of how the pre- and post-Tsunami images were interpreted. Figure 2 shows the severely damaged agricultural area southeast of T. S. Pettai. The post-Tsunami image (figure 2(*b*)) shows that all features in the agricultural land have either disappeared or are blurred compared to the pre-Tsunami image (figure 2(*a*)). Furthermore, the entire area appears wet in the post-Tsunami image indicated by the darker appearance. Figure 3 shows the images from the undamaged village T. S. Pettai with the pre-Tsunami image in figure 3(*a*) and the post-Tsunami image in figure 3(*b*). It can be seen that all features appear intact in both images. Figure 4 shows the eastern part of the undamaged hamlet of Kodiyampalayam and the severely damaged agricultural areas southeast of the hamlet. Figure 4(*a*) and 4(*b*) are the pre- and post-Tsunami images. Figure 4(*c*) shows the result of the interpretation (same legend as in figure 5). Kodiyampalayam was protected from the sea by sand dunes, whereas its agricultural areas were unprotected and damaged. The features of the hamlet appear intact in the post-Tsunami image, whereas some of the agricultural features visible in the pre-Tsunami image have disappeared. Figure 4(*d*) is taken in the hamlet, and figure 4(*e*) is from the agricultural fields. Although the visual analysis is fairly clear, the ground truth supported the analysis.

3. Results

3.1 *Visual interpretation*

A map showing the damage and the presence and absence of the woody vegetation is shown in figure 5. The white-contour indicates the extent of the study area, the dark-green refers to *dense woody vegetation*, the light-green to *open woody vegetation*, the red to areas *severely damaged* by the Tsunami, the red-striped to areas only *partially damaged* and the dotted blue to areas *inundated* by water, but otherwise undamaged.

The large dark-green area in the northern part of the map is the Pichawaram mangrove. Five hamlets are situated near this mangrove. Two of them, Kannagai Nagar and Pillumedu, are located on the coast whereas three hamlets, T. S. Pettai, Vadakku Pichawaram and Therkku Pichawaram, are behind the mangrove. Ground truth data showed that the two hamlets on the coast were completely destroyed, whereas the three hamlets behind the mangrove suffered no destruction at all. Just north of these hamlets (and west and north-west of Kannagai Nagar), areas at the same distance from the sea, but without protection from woody vegetative, were inundated. Though there are minor differences in the topography in this flat area, it is interpreted that the mangrove yielded protection to the hamlets against the waves of the Tsunami. In the case of the hamlet T. S. Pettai this is very clear.

The southern half of the map shows a coastline almost completely lined with a *Casuarina* shelterbelt (see figure 5). This shelterbelt was planted to protect the coast against cyclones and has an approximate width of about 200 m and a minimum width of about 60 m. Five hamlets, Madavamedu, Kottahaimedu, Olakottahaimedu, Koozhayar and Thoduvai, are situated within this shelterbelt. The shelterbelt is not as dense in front of these villages, as in the other areas, because fishermen wanted free access to the sea and probably because of general human activity. The southern part of the map shows that areas protected by dense

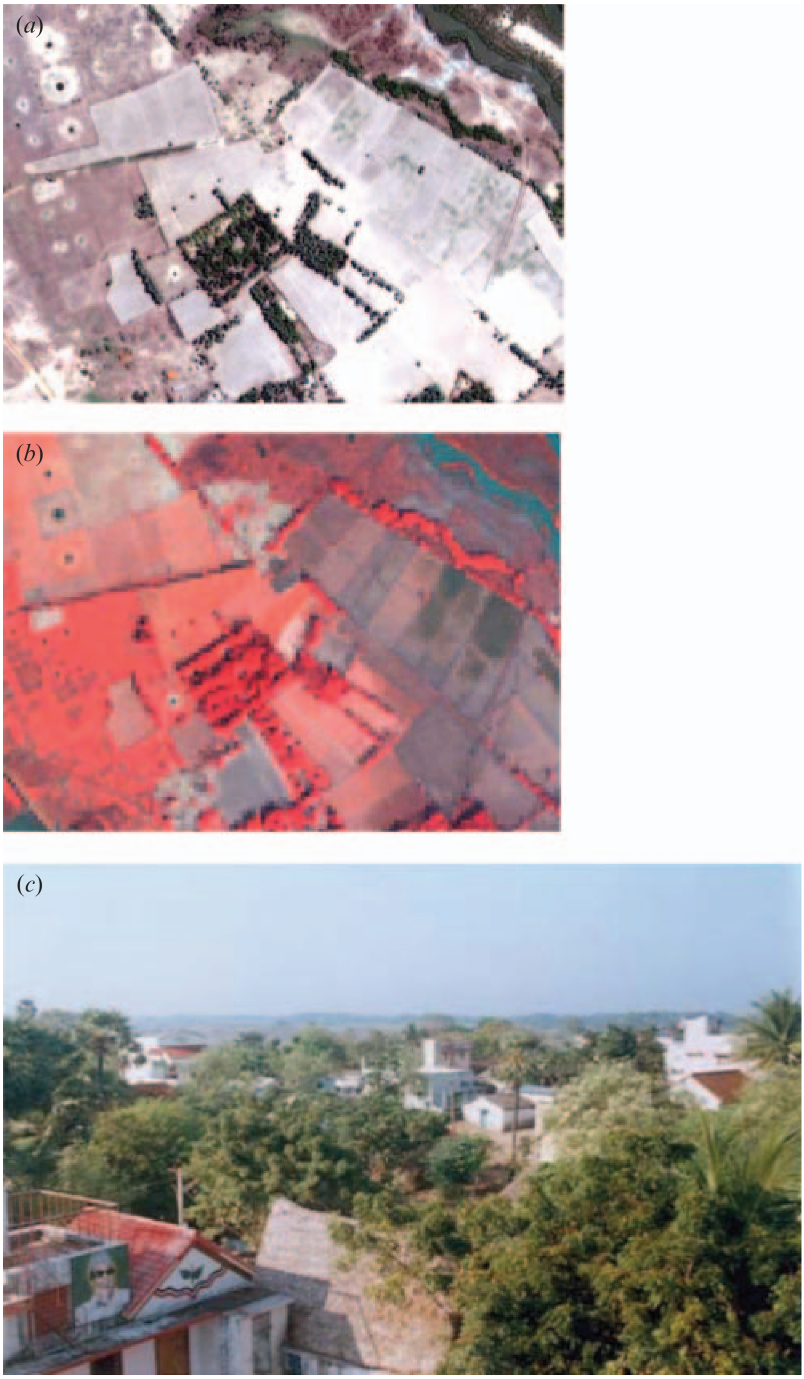

Figure 3. The village of T. S. Pettai is shown, which was undamaged; (*a*) pre-Tsunami and (*b*) post-Tsunami. As opposed to the agricultural area discussed in figure 2, the features visible in the pre-Tsunami image are also quite visible in the post-Tsunami image, indicating that this area has not been damaged. The post-Tsunami image furthermore is not particularly wet in appearance. (*c*) Ground truth image of the same village, documenting that the hamlet has not been damaged.

Figure 4. These images show the eastern part of the undamaged hamlet of Kodiyampalayam and the severely damaged agricultural areas southeast of the hamlet; (*a*) pre-Tsunami, (*b*) post-Tsunami and (*c*) shows the resulting classification (for key refer to figure 5). (*d*) Ground truth image of the hamlet and (*e*) ground truth image of the agricultural fields.

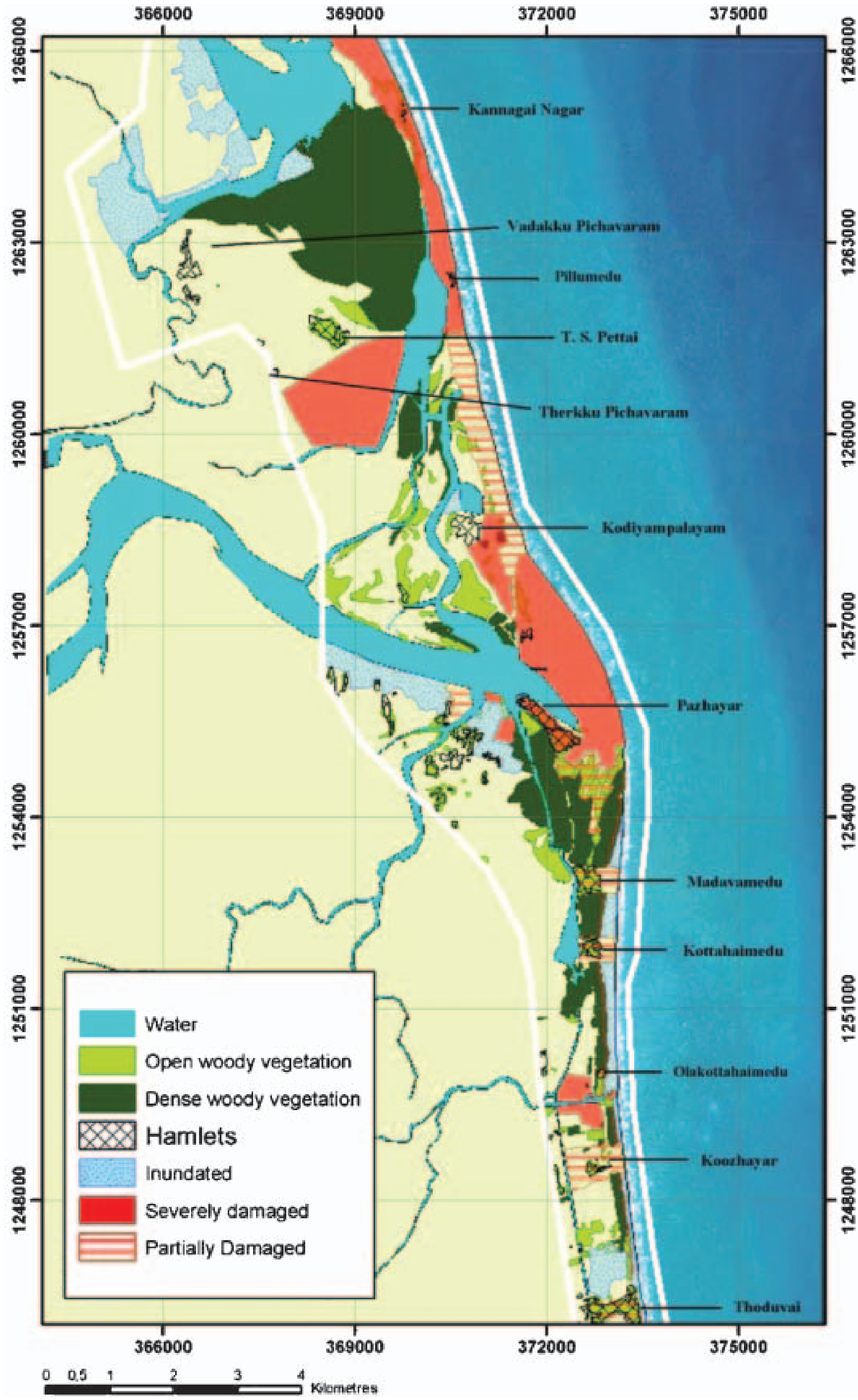

Figure 5. Map depicting the extent of the damage and the areas covered by woody vegetation. It shows that areas protected by the woody vegetation have experienced less damage. The map is based on pre- and post-Tsunami interpretation of Ikonos and QuickBird very high-resolution satellite data. The present map is the result of a reanalysis of the map published by Danielsen *et al*. (2005).

shelterbelt were not affected by the Tsunami, but where the shelterbelt was less dense, damage occurred. In terms of determining the significance of the density of woody vegetation as a measure of protection against the Tsunami, this area provided the best example since only the density of the woody vegetation changed along a coast with otherwise same conditions.

The central part of the map illustrates the intensity of the impact from the Tsunami. A sand spit formerly partially blocked the mouth of the river Coleroon but it has almost completely disappeared because of the Tsunami. Parts of the hamlet Pazhayar, which is situated near the spit, were *severely damaged* and the rest of the hamlet was *partially damaged*. Finally, one hamlet, Kodiyampalayam, situated north of the spit, was separated from the sea by the sand dunes and was not damaged, while its agricultural areas were completely destroyed (see figure 4).

3.2 *Transect analysis*

The protective role of the vegetation was assessed using transects and by plotting the width of the potentially protective woody vegetation (the length of the transect containing woody vegetation) against the length of the damaged areas behind the vegetation (the accumulated length of the transect where damage had been recorded). One hundred transects were spaced equally covering the entire coastline with an average distance of 200 m between them. Their orientation was northeast–southwest, the same as the impact of the Tsunami wave. Figure 6 shows the result, with woody vegetation divided into *dense* and *open woody vegetation*. It can be seen that the most damage occurs when there is no sheltering woody vegetation present (vegetation length=0 m) and for a number of transects with woody vegetation, no damage has been recorded (damage length=0 m). With ca. 100 m of sheltering woody vegetation, the damage has been reduced to the point that it affects less than 800 m along the transects. With 500 m of sheltering woody vegetation, the damage is reduced to less than 500 m. The damage recorded for large lengths of woody vegetation, e.g. more than 1000 m, is mainly caused by edge effects, when neighbouring gaps in the protective woody vegetation allow the tsunami wave to impact areas behind woody vegetation, as is the case at Olakottahaimedu and south of T. S. Pettai (see figure 5). The same situation explains a single outlier point (damage=1600 m and vegetation=700 m).

4. Conclusions

The analysis of pre- and post-Tsunami QuickBird and Ikonos satellite images showed that woody vegetation along the coast provided some degree of protection to the areas behind. Visual interpretation and identification of the damaged areas showed clearly that the Pichavaram mangrove forest in the northern part of the study area did protect the hamlets behind it. In the southern part of the study area a 200 m broad *Casuarina* shelterbelt provided protection, apart from the areas where human activities had reduced the width of the shelter belt. An analysis of transects aligned with the impact angle of the Tsunami quantified these results and showed that for a number of transects, the presence of woody vegetation did protect the area behind. With 100 m of protective woody vegetation presence, damage would affect a maximum of 800 m along the transects.

It proved challenging to identify a study area where all conditions where similar expect the presence and absence of potentially protective woody vegetation. Remote

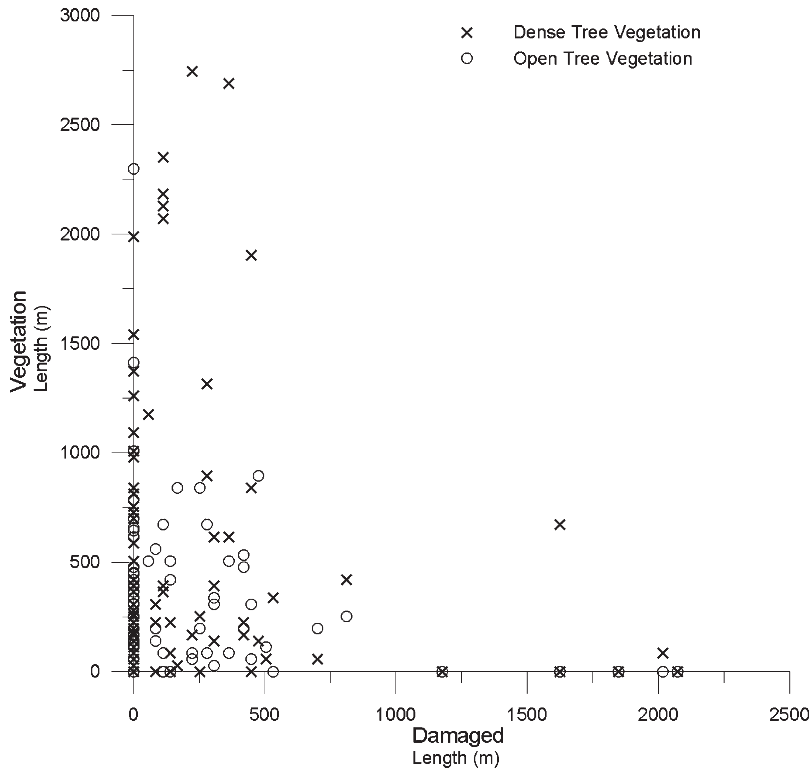

Figure 6. One hundred profiles were established along the coast. These were oriented northeast–southwest to match the direction of the tsunami wave. The length of protective woody vegetation is plotted against the length of the damage behind the woody vegetation.

sensing images and methods proved to be a useful and efficient technique for assessing the differences in impacts of the Tsunami. Visual interpretation was used because of the complexity of assessing the damage as well as the difference between 0.6 m pan-sharpened pre-Tsunami QuickBird and 4 m multispectral post-Tsunami Ikonos images.

The results support the many eyewitness reports suggesting that coastal woody vegetation protects the coastline against the sea. It is most likely that when a tsunami wave reaches a certain magnitude, e.g. 10 m as was the case in Banda Ache, then the effect of a healthy coastal environment, including the presence of coastal woody vegetation, will be limited as shown by Baird *et al.* (2005). The role of protective coastal woody vegetation should be addressed when the Tsunami-affected areas are being rehabilitated and further studies from other locations are needed to confirm the present findings from Pichavaram.

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