TSUNAMI IMPACT ON COASTAL VEGETATION: A MULTITEMPORAL ASSESSMENT BY REMOTE SENSING

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ABSTRACT:

The Indian Ocean tsunami event of 26 December 2004 not only left massive casualties (over 200,000 people) and economic damages, but also raised environmental issues concerning the destruction and recovery of coastal ecosystems. This work focuses on the analysis of impacts to coastal vegetation and recovery using satellite mid-resolution data through remote sensing techniques and field data, on the study area of Koh Phra Thong Island, (Phang Nga Province southeastern Thailand). Field survey data and multi-spectral images (SPOT HRV, Terra ASTER) covering the period from February 2003 to January 2006 were used to map flooded areas and coastal vegetation loss and recovery following the tsunami. Satellite data were radiometrically normalized to reduce discrepancies between different sensors and acquisition conditions. Normalized Difference Reflectance change detection was performed to map the extent of flooded area. Vegetation Indexes were then used to study the multitemporal changes in coastal vegetation after the event. Vegetation change detection techniques were applied with the aim of comparing the short term (few days after the event) and long term (up to 1 year) post-tsunami imagery to the pre-tsunami reference image. Estimates of vegetation change (loss, recovery, and outward colonization) were quantified both by area and percent loss through comparing cross-tab statistics. Vegetation loss directly after the tsunami was extreme. As assessed a few days after the tsunami, up to 64% of vegetation in the flood zone was lost. After one year, different trends had developed, indicating that vegetation was recovering, but with different trajectories for different vegetation types.

1. INTRODUCTION

Mangroves are the main coastal wetlands in tropical and subtropical regions of the world (Mitsch and Gosselink 2000). Mangroves occupy important transition zones between terrestrial and aquatic environments and between marine and fresh waters. Intact mangrove forests can provide important ecosystem services, such as reducing coastal erosion and protecting low-lying areas from flooding.

On 26 December 2004, an earthquake in the Indian Ocean triggered massive waves that caused vast destruction in many coastal areas in the region (Belward *et al.*, 2007). Such a significant and tragic disturbance can also be seen as an opportunity to evaluate the role of mangroves in protecting shorelines, to determine whether mangroves were impacted differently than other habitats, and to quantify the loss of mangroves resulting from the tsunami. The current study has evaluated the impact of this disturbance on mangrove ecosystems on Koh Phra Thong, a 110 km^2 island in the Andaman Sea in southwest Thailand.

Previous studies indicate that mangrove forests, in particular, provide protection of shorelines from extreme weather events like tsunamis (Kathiresan and Rajendran 2005). Scientists who have studied coastal vegetation have shown that coastal vegetation, both mangrove and beach forests, provide protection from "extreme" events like tsunami's (Danielsen *et al.,* 2005; Danielsen *et al*., 2006) as well as "during less energetic but more frequent events, such as tropical storms" (Granek and Ruttenberg 2007). We have applied a method for studying specific vegetation cover class change using remote sensing techniques, in an attempt to determine both where there has been change in these protective ecological communities, and what types of vegetation have changed and in what magnitude.

Remote Sensing Change Detection methodologies, well known in scientific literature in this field and applied for disaster assessment (Sirikulchayanon *et al*., 2008), were employed in the present study to assess tsunami impacts on vegetation types over separate time scales. The objectives were

- to assess flooding extent using satellite data;
- to determine the effect of tsunami-related damage to the island's vegetated ecological communities, both immediate and secondary;
- to evaluate vegetation recovery after one year

Many NGOs, including the United Nations Development Programme, are funding and implementing mangrove restoration in tsunami-impacted areas (Stone, 2006). These projects require site knowledge assessments of damaged ecosystems, and the methodologies presented in this paper could be of help in this context.

2. STUDY AREA AND DATASET

Koh Phra Thong is a 100 km^2 island (15 km long x 7 km wide), located less than 5 km from the western coast of Thailand in the Andaman Sea (9.03-9.17°N, 98.25-98.33°E; Figure 1).

The island remains largely undeveloped, and the vegetation communities are diverse and expansive. Mangrove forests are found mostly on the eastern coasts lining the seven major tidal inlets (Khlong Ko Khat). Evergreen forests are found on both the east and west coasts existing in areas of relatively high elevation (30m-45m above sea level). Swamp forests are the most common vegetation on the western coast, lining a series of lagoons running parallel to the coastline. Agriculture has developed on the west coast in the form of coconut plantations and in the northeast and southeast in the form of cashew

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plantations. Beach forest (commonly *Casuarina* spp. plantations) is usually found in areas where coconut plantations are not viable.

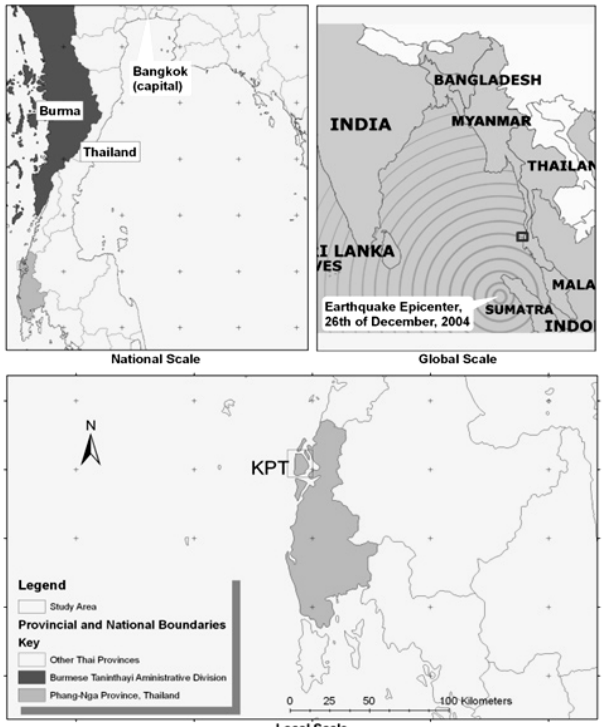

Figure 1. Study Area: Ko Phra Thong Island, located in Phang Nga province, southeastern Thailand

When the tsunami wave swept through the island on 26 December 2004, from the southwest, vegetation communities were flooded and some were mechanically destroyed. Mangrove forests have been heralded for protecting against more widespread destruction due to their properties of wave energy dispersal (e.g., Kathiresan and Rajendran, 2005). However, the western coast of Koh Phra Thong has low densities of mangrove. Other vegetation associations, including beach forest, beach shrub, coconut plantations, and savanna grasses, were more dominant in the wave impact area and more exposed to flooding and destruction.

The primary data sources were imagery from the Terra ASTER sensor and imagery from the Spot5 HRVIR sensor. We obtained imagery from four acquisition dates and times for this study: 19 February 2003 (ASTER), 30 December 2004 (Spot5 HRVIR), 8 February 2005 and 26 January 2006 (ASTER). It is important to note that all the images were acquired during the same time of year, ensuring that the vegetation was at the same approximate phenological stage and facilitating comparisons. ASTER data from 19 February 2003 (Center pt; 9.0973° Lat, 98.0469° Lon) was used to determine the vegetated land cover status before the tsunami, ASTER data from 8 February 2005 (Center pt; 9.0797° Lat, 98.1681° Lon) data was used to determine the vegetated land cover in the immediate aftermath of the tsunami, and ASTER data from 26 January 2006 (Center pt; 9.0797° Lat, 98.1681° Lon) was used to determine the longer term vegetation response to the tsunami. Spot5 HRVIR data from 30 December 2004 (Centre pt; 9.0433° Lat, 98.4178° Lon) was used in delineating the area flooded by the tsunami and to complete Aster data from February 2005 for areas covered by clouds.

These images were in the WGS 1984 geographic coordinate system and were then reprojected to the Universal Transverse Mercator (UTM) projected coordinate system, in Zone 47, with the WGS 84 Spheroid and Datum.

In addition, orthophotos from pre-tsunami and post-tsunami and were used to validate vegetation cover map exploiting also additional field data collected on site during measurement campaign in summer 2002 and 2008. A pre-tsunami land cover map (Figure 2), produced by the SEUB Nakasathien Foundation for the Phra Thong Island Conservation Project, was utilized in the vegetation indices interpretation (Thai Forestry Department, SEUB) to assess impact on the different land cover typologies.

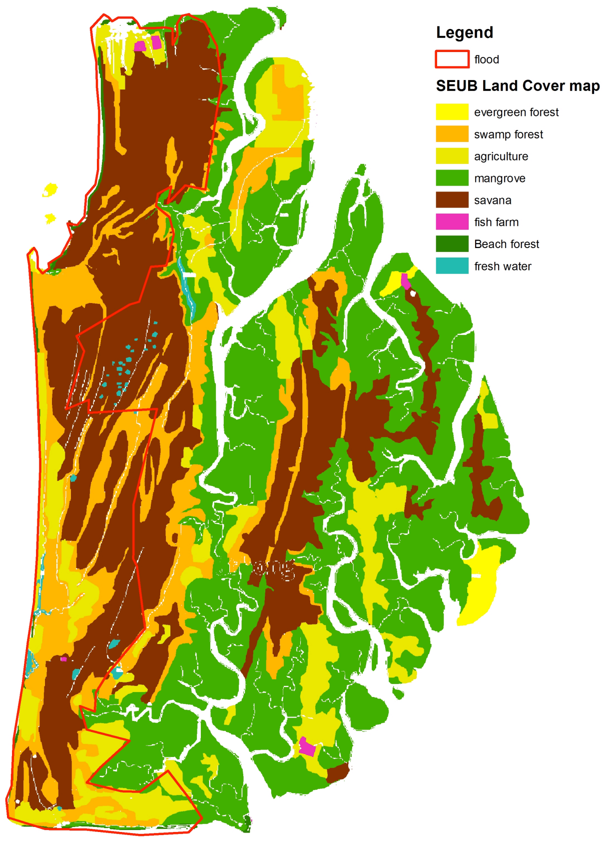

Figure 2. Land Cover Map (pre-tsunami) of the study area of Koh Phra Thong island, produced by Thai Forestry Department and SEUB. Flooded area boundary in red colour

3. METHODOLOGY

3.1 Flood mapping

Flooded area delineation was done using Principal Components Analysis over Normalized Difference Reflectance (NDR) values over pre-flood and post-flood data. Multisensor data comprises pre-flood Terra ASTER scene acquired on 19 February 2003 and post-flood SPOT HRVIR scene acquired on 30 December 2004, 6 days after the tsunami. The multitemporal couple was processed (geocoded and corrected for atmospheric effects) and radiometrically normalized with Pseudo Invariant Features (PIFs) selection and linear regression, to produce NDR values mapping the reflectance difference features between pre- and post-flood situations on the island.

In order to map surface features changes, the NDR data were used as a input for Principal Components Transform (Villa *et al.*, 2009). The second Principal Component was chosen as representative of the flooding features signature and from the analysis of field data collected after the tsunami by local authorities, a threshold was set for discriminating flooded areas from non-flooded ones (Figure 3). Post-processing over thresholded data aided in deriving the flooded area boundary, ans was subsequently used for vegetation damages and recovery analysis.

3.2 Vegetation presence mapping

Over pre-processed data, the Normalized Difference Vegetation Index was calculated and thresholded in order to derive vegetation maps for every timestep. NDVI is a commonly used metric for vegetation density. Values of NDVI range from between 0 and 1, 1 indicating a very high density of vegetation. In general, NDVI thresholding is the process by which the NDVI map produced in the previous step is converted into a vegetation presence-absence map. The spatially-linked point field data are first classified as vegetation or not vegetation. The vegetation field data points, overlaid with the NDVI map, are then used to extract the NDVI values at those points, thus assessing the phase of NDVI thresholding.

Following the NDVI thresholding procedure, two histograms (vegetated and not vegetated) were then compared with each other to determine a threshold NDVI value between vegetated and not vegetated pixels. All pixels with an NDVI value above this threshold were classed as vegetation while all pixels below this value were classed as non-vegetation. The threshold is selected through expert decision and ancillary data. Three separate threshold NDVI values which satisfied these criteria were selected for each of image and designated as (1) a high sensitivity vegetation threshold, (2) a medium sensitivity to vegetation threshold, and (3) a low sensitivity to vegetation threshold (Figure 4).

A combination of auxiliary data--Ikonos (21 April 2005) and high resolution (1m) orthophotos--were used to check these classifications and assess the mapping accuracy, because of their extremely high resolution. Independent test pixels were selected by photointerpretation to assess accuracy computing a error matrix (REF). When deciding on how to classify a pixel, as vegetation or non-vegetation, a rigorous four-faceted pixel characteristic method was used. The four characteristics considered before classifying the pixel were: (1) colour, (2) texture, (3) tone, and (4) context.

4. RESULTS AND DISCUSSION

4.1 Flood extension and Damages assessment

Figure 3 represents the results of Principal Component transformation, second component, applied over NDR values. The method is highly sensitive in highlighting changes related to soil wetness and sand displacement. Blue to dark red colours show the areas that are likely to be affected by tsunami flooding. A good agreement can be found with the field-measured flood boundary (green line in Figure 3).

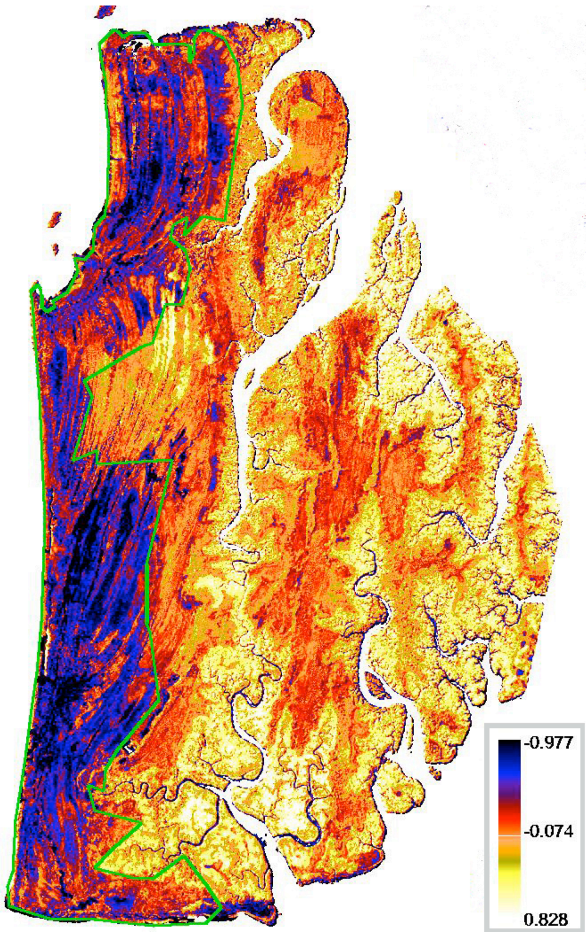

Figure 3. Second Principal Component of NDR values for Koh Phra Thong island, and superimposed (green colour) flooded area boundary.

Vegetation cover maps are presented in Figure 4. The red boundary represents the tsunami flooded area as detected by change detection analysis. The left image shows the status of vegetation cover before the event, the central image depicts the effect of direct mechanical impact of the tsunami on vegetation as recorded 37 days after, and the image on the right shows the situation after 13 months.

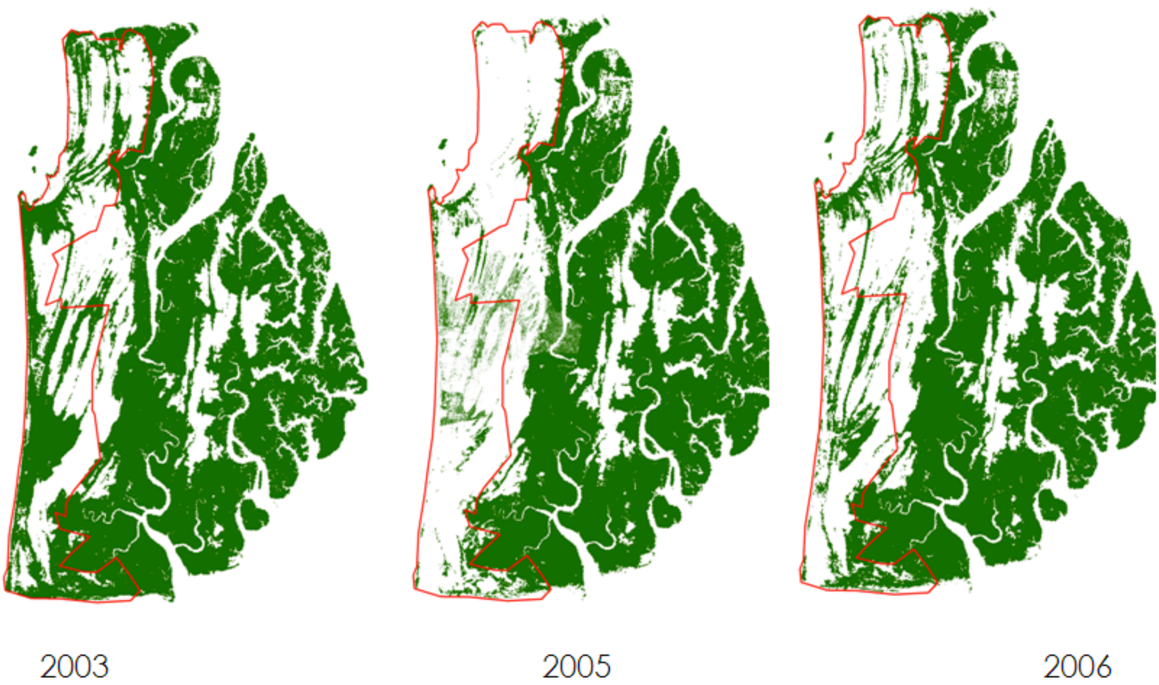

Figure 4. Vegetation Cover Map derived through NDVI for February 2003 (pre-tsunami, left), February 2005 (post-tsunami, centre) and January 2006 (1 year after, right). Vegetation cover is highlighted in green colour. Flooded area boundary in red colour.

Table 1 includes the summary statistics from each presence-absence map, as determined by the above procedure. The accuracy of the thresholds is strong enough to accept the classification as more than 90% accurate in nearly all cases. These results allowed us to proceed with post classification change detection analysis.

		Aster (19-02-2003)	
	Producer's Accuracy (%)	*User's Accuracy (%)*	*Kappa Statistic*
Vegetation	89.0	93.7	0.87
Not Vegetation	94.0	89.5	0.79
Overall Accuracy		**91.5%**	
Overall K		**0.83**	
		Aster (08-02-2005)	
Vegetation	95.0	93.1	0.86
Not Vegetation	93.0	94.9	0.89
Overall Accuracy		**94.0%**	
Overall K		**0.88**	
		Aster (26-01-2006)	
Vegetation	93.0	95.9	0.91
Not Vegetation	96.0	93.2	0.86
Overall Accuracy		**94.5%**	
Overall K		**0.89**	

Table 1. accuracy assessment of pre and post Tsunami vegetation presence maps

4.2 Vegetation trends

Change detection analysis allowed us to highlight trends in vegetation land cover classes following the tsunami. Single date image processing can be used to assess the impact on the ecosystem but do not guarantee that real natural ecosystem losses can be evaluated. Remote sensing assessment of vegetation composition with medium-high resolution images such as ASTER can be strongly affected by pixel mixture that can bias the evaluation of vegetation loss. In particular, this tsunami produced a huge amount of sand load that covered the west coast of the island. Sand can influence the spectral response recorded by the sensor reducing the vegetation signal. In this way, some areas with sparse vegetation cover can be interpreted as strongly impacted even if no vegetation removal occurred. Multi-temporal analysis allowed us to check for permanent loss of vegetation cover, to highlight secondary longer term effects of the tsunami impact, and to assess which ecosystems appeared to recover or be newly colonized

Figure 5 shows the different vegetation trends that occurred in the flooded zone of the island. Red colour shows the vegetation surfaces that are permanently lost after the tsunami. Orange colour shows areas where long term effect produced successive vegetation losses. Those areas are often near the high-impact red zones. Green areas are those where vegetation recovery occurred, and blue zones are likely to show new colonisation, probably by herbaceous or pioneer species.

Statistics for the different land cover types as identified by the SEUB map are reported in Figure 6. It appears that for some classes (i.e., swamp forest, savanna), there is a strong recovery after 1 year from the event. Other areas appeared to sustain long term impacts, perhaps due to sand deposition and physical, abiotic changes that reduced the vegetation cover (e.g., evergreen forest).

In general, the west coast of the island presented a modest mangrove cover before the tsunami, about 500 ha; only 50% of those mangroves were impacted by the tsunami. The beach forest was strongly impacted by the flooding that physically eradicated the trees. The recovery observed by NDVI change analysis is now mainly due to new pioneer species, as verified by field surveys in 2008. Evergreen forest cover was primarily located in the west of the island, and represented a small surface area (8 ha). This vegetation cover was one of the most affected by direct flooding and long term effects: no re-growth was detected. Savanna and swamp forest represent the two dominant land cover in the flooded area. Both ecosystems experienced as much permanent vegetation loss as of recovery (20-30%).

The savanna land cover type also showed new patches of vegetation not detected by previous satellite observation. Those areas surround existing patches of herbaceous vegetation that can expand or contract depending on annual meteorological conditions. Agricultural land was strongly impacted by flooding causing a loss of more than 40% of the crops. For this vegetation cover, secondary effects and recovery processes are easily to be interpreted as natural effect due to human intervention of harvesting and replanting. Figure 5 demonstrates the expected trend in the flooded zone. Without mangrove forest to protect the shoreline from flood effects and the wave's mechanical force, 64% of vegetation in the flood area was lost in the immediate aftermath of the tsunami. The rate of loss was also extremely rapid: 916.61 hectares of vegetation were lost in the month after the tsunami as reported by field interviews. This is the equivalent of almost 10 km^2 of vegetation. Conversely, the non-flooded, eastern part of the island experienced relatively minimal effects from the tsunami (data not shown).

There is also evidence that the vegetation community is recovering in the flooded zone. By January 2006, about 4585 hectares of vegetation were regained, bringing vegetation cover to about 60% of pre-tsunami cover. One year after the tsunami, there was evidence of vegetation colonizing previously un-vegetated land.

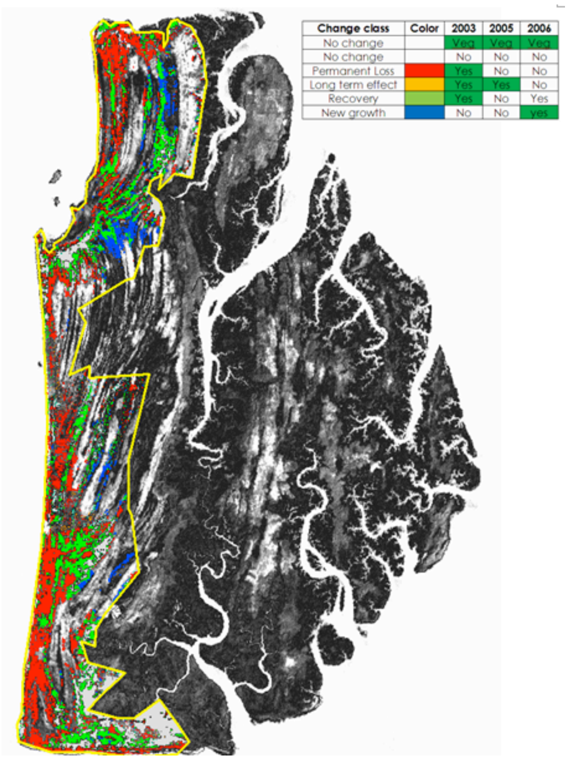

Figure 5. Change Assessment Map for vegetation cover in flooded area (highlighted in yellow), summarizing vegetation loss and recovery from per-tsunami to post-tsunami and to 1 year after the event. On the background, the panchromatic scene for February 2003.

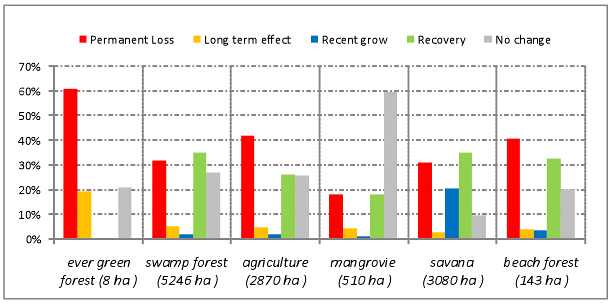

Figure 6. Vegetation Change Graphs for flooded area, for different vegetation cover, depicting loss and recovery scenarios in percentage over the whole vegetation class area (included in brackets).

There are also confounding anthropogenic variables which could artificially increase the amount of colonization and increase the percent loss (from -31.6% to -40.9%). Through examining the auxiliary reference imagery and personal communications with island residents, it appears that some parts of the evergreen forests were cut before February 2003. These areas were then replanted between the logging date and the tsunami. Hence, what we witness as vegetation colonization is likely a coincidence. The increase in area lost after the tsunami in the flood zone could also be due to anthropogenic effects from logging to construction.

Mangrove forests, as expected, were the vegetation type best able to sustain the tsunami's impact with the smallest losses of vegetation and very few secondary effect consequences. Those results confirm the resilience of this land cover. By way of comparison, the data indicate that swamp forest is also a relatively resilient vegetation cover, as compared to savanna grasses, and beach vegetation. Though mangrove forest remains more resilient, mangrove area is far less extensive in the flood zone. In comparison to these relatively resilient vegetation classes, beach forest demonstrated a stronger ability to bounce back from a storm or tsunami but not protect itself or others from such an event. Based on field observations, we have seen that the recovery we detected in the beach forest category via remote sensing was in fact colonization by new species, and not regrowth of damaged older beach forest.

Savanna grasses, on the other hand, appear to be a fragile ecological community which was significantly disrupted by the tsunami in short term. There is evidence that savanna grasses can recover quickly, as over 30% returned one year after the tsunami impact.

5. CONCLUSIONS

Remote Sensing techniques were used in this paper to better understand how vegetation, and more specifically, mangrove classes have been affected by the 2004 Indian Ocean tsunami. Using three vegetation presence/absence maps, from February 2003 (pre-flood), February 2005 (post-flood) and January 2006 (1 year after), immediate tsunami damage was compared to long term tsunami damage. It was discovered that, though there was extensive damage directly after the tsunami, the majority of vegetation communities are on a trajectory of recovery. While we found evidence of biophysical damage affecting rates of colonization and recovery in all vegetation types, mangroves were the most resilient class of vegetation. As expected, mangroves were least affected by the effects of the tsunami in the short and long term; however, mangroves in the flooded zone were sparsely dispersed and covered a small land area before the tsunami, and were thus protected from the largest waves. Our results also suggest that vegetation classes other than mangroves were also quick to recover from damage. For Koh Phra Thong, mangroves may not be the panacea for coastal protection since they do not appear to occur within the major flood zone. They may thus not be exposed to the brunt of storms or more extreme weather events due to limited spatial extent, geomorphology, and community development constraints. In this case, other vegetation types, like swamp forest and beach forest, may provide more effective vegetation cover for shoreline protection. This data are useful for the future of vegetation management on the island and in the greater region, as well as for management of reconstruction of damaged areas in the frame of a future risk reduction perspective.

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