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Article

Change Detection Analysis for Assessing the Vulnerability and Protective Effect of Beach Forests in Case of the Tsunami 2004 in Thailand

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Keywords: Tsunami 2004, LULC classification, Post classification comparison, Statistical modelling

Summary: The influence of environmental factors, especially of tropical coastal forests, on the damage impact of a tsunami is still discussed controversially in literature. This paper focuses on the assessment of the vulnerability and protective effect of beach forests in case of the Indian Ocean Tsunami event 2004 in Thailand, based on remote sensing and multivariate-statistical methods. With the use of a post classification comparison, we show that the variability of the damage degree on different coastal vegetation types is highly spatial and species dependent. The combinatory evaluation of results from the change detection analysis and data on coastal vegetation structure from a field survey by using multiple regression analysis further proves that beach forests can have a protective effect against tsunami waves, if they satisfy certain vegetation structural conditions. In this context specific vegetation parameters for the vulnerability as well as the protective effect of beach forests are acquired, which mainly determine its vertical and horizontal forest density. A concluding case study finally illustrates how a combination of empirical tsunami hazard assessment and the presented work could be utilized to support local coastal protection in a targeted and efficient way.

Zusammenfassung: *Change Detection-Analyse zur Bewertung der Vulnerabilität und Schutzwirkung von Strandwäldern im Falle des Tsunami 2004 in Thailand*. Der Einfluss biologischer Faktoren, vor allem tropischer Küstenwälder, auf das Schadensausmaß eines Tsunami wird in der wissenschaftlichen Literatur noch immer kontrovers diskutiert. Auf Grundlage von fernerkundlichen und multivariat-statistischen Methoden wird in der vorliegenden Arbeit die Vulnerabilität und Schutzwirkung von Strandwäldern im Falle des Tsunamiereignisses in Thailand 2004 untersucht. Mittels eines Post Classification Comparison wird aufgezeigt, dass die Variabilität des Schadensausmaßes an verschiedenen Typen der tropischen Küstenvegetation stark von deren räumlicher Lage sowie der spezifischen Artzusammensetzung abhängt. Eine multiple Regressionsanalyse auf Grundlage der Change Detection-Analyse und vor Ort aufgenommenen Daten zur Vegetationsstruktur bestätigt ferner, dass Strandwälder eine Schutzwirkung gegenüber Tsunamis haben können, wenn sie bestimmte vegetationsstrukturelle Bedingungen erfüllen. In diesem Zusammenhang werden konkrete Vegetationsparameter sowohl für die Verwundbarkeit als auch für die Schutzwirkung von Strandwäldern identifiziert, die hauptsächlich von der vertikalen und horizontalen Walddichte abhängen. Ein abschließendes Fallbeispiel zeigt schließlich, wie die hier vorgestellte Arbeit in Kombination mit einer Tsunami-Gefahrenanalyse einen Beitrag zu einem gezielten und effizienten Küstenschutz leisten kann.

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1 Introduction and Objectives

The Indian Ocean Tsunami 2004 can be seen as a turning point in tsunami science. Never before a tsunami disaster has been observed in such detail. Waves of significantly different height and inundation distances were recorded along the coastlines even in directly adjoining beach sections. These small scaled differences were mainly caused by variations of the near-shore-bathymetry in combination with heterogeneous characteristics of the onshore topography (Wieland 2009). However, the influence of certain factors on the impact of a tsunami after contact with land is still discussed controversially. This applies mainly for the possible protective effect of environmental factors, such as beach forests. Their barrier effect, which is supposed to absorb and reflect the wave force as well as to decelerate the flow rate of a tsunami, depends on several complex factors, which are characterized by co-dependence and interaction amongst them (Forbes & Broadhead 2007). Especially due to its specific vegetation structure concerning the forest density and species composition as well as its vulnerability (in the following defined as extent of destruction), not all coastal forests constitute an effective protection barrier.

The paper at hand aims at two main aspects: (1) detecting the overall impact of the tsunami 2004 on different types of coastal vegetation (mangrove forests and various types of beach forests) in the study area and (2) providing a contribution for understanding the vulnerability and protective effect of especially beach forests in case of such waves.

Moreover, the research is part of a cooperative study focussing on the analysis of near-shore and on-shore geomorphological and environmental factors, which can directly influence the inundation width, damage extent and deceleration of a tsunami – with the overall goal of supporting local coastal protection in tropical tsunami endangered regions. In this connection a tsunami hazard analysis (briefly presented in Section 3) pointed out, which geomorphological factors are mainly influencing the inundation width of a tsunami. The results are demonstrated in tsunami factorial maps and hazard maps of the of the study area. These maps allow a rapid identification of zones with increased tsunami hazard and enable furthermore a clear indication of the underlying factors, which determine the resulting hazard level. They can therefore form the basis for a more purposeful utilisation of the presented results regarding coastal tsunami protection.

2 Research Methodology

The research at hand is based on a post classification comparison of landuse and landcover (LULC) classifications before and after the tsunami 2004 (Fig. 1). After its implementation, it is possible to derive detailed information about the spatial distribution and intensity of tsunami induced damages on different coastal forest types (Section 4).

The results of the change detection analysis and additional data from a terrestrial survey are further used for multivariate statistical modelling with the objective to receive information about vegetation parameters, which are of major importance for the vulnerability as well as for the protective function of beach forests (Section 5).

On the basis of a case study, it is finally illustrated, how the combination of both de-

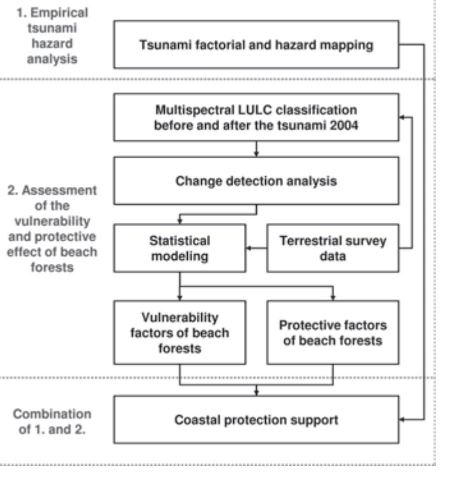


Fig. 1: Flowchart of the applied procedure for analysing tsunami influencing factors and supporting local coastal protection in the study area.

scribed research activities, the empirical tsunami hazard analysis mentioned above and the assessment of the vulnerability and protective effect of beach forests, can be used to support local coastal protection in an efficient and cost effective way (Section 6).

3 Impact of the Tsunami 2004 and its Potential Geomorphological Influencing Factors within the Study Area

The study area is located on the Malay Peninsula along the west coast of Thailand, also known as Andamancoast. It covers the coastal areas stretching from Ko Kho Khao in the north of Phang Nga province to the island of Phuket and further south to Ko Phi Phi Don in Krabi province (Fig. 2).

On December 26, 2004 at 7:58 h local time an earthquake of magnitude 9.3 on the Richter scale occurred in the Sunda-trench in front of the coast of Sumatra and triggered the fatal tsunami. Less than two hours after this event the first waves reached the study area with its touristic hotspots around Khao Lak and Phuket. Just minutes later also the coastal areas of Krabi where hit by the incoming tsunami. Due to refraction around the northern tip of Sumatra, the waves moved in an easterly direction and hit the study area in a nearly perpendicular angle. Overall velocity and energy of the approaching tsunami have been reduced by a relatively wide continental-shelf in front of the Andamancoast. Variations of coastal configuration in combination with differing characteristics of the near-shore-bathymetry caused waves of significantly different height and characteristics along the coastline. In many regions of the study area, like in the northern and eastern part of Phuket or in Phang Nga bay, the tsunami occurred as extensive flood-like inundation of low lying coastal areas, comparable to a rapidly increasing tidal gauge, reaching water heights from 1–4 m. In other parts, like in Patong and Rawai Beach in the southern part of Phuket or in Khao Lak, wave heights of up to 12 m above sea level have been recorded. Therefore the damages in the study area have been overwhelming in certain areas, but have not been distributed homogeneously. Moreover, small-scaled differences in the degree of damage along the coastline could be observed (Kelletat & Scheffers 2006).

Fig. 2: Location map of the study area, showing the Andamancoast in South-West-Thailand. (Data source: SRTM4)

Why are some areas more impacted by the tsunami waves than neighbouring ones? The factors which according to literature have the greatest influence on characteristics and impact of a tsunami can be divided into two groups. The first group is well studied and consists of morphological factors such as the width of the continental shelf, the near-shore-bathymetry (Murthy et al. 2007), offshore islands (Bryant 2008), horizontal shape of the coastline (Kong 2004) and the vertical profile of coastal topography (Synolakis & Kanoglu 1998). The second group, less studied so far, is composed of environmental factors like coral reefs (Cochard et al. 2008, Chatenoux & Peduzzi 2007), mangroves (Tanaka 2007) and beach forests (Cochard et al. 2008, Forbes & Broadhead 2007).

Based on GIS, remote sensing and multivariate-statistical methods in an integrated approach, an empirical tsunami hazard analysis considered more than 30 mainly morphological influencing factors on the tsunami impact 2004 on a regional scale (Wieland 2009). The parameters, which could be identified as most important on the impact of a tsunami, are coral reefs, wave exposition (including degree of shelter from offshore islands), several factors of coastal topography and near-shore-bathymetry. Using the resulting regression-model tsunami factorial and hazard maps were created for this specific event (Fig. 3). The calculated hazard maps show good overall correlation with the real inundated areas, measured after the tsunami 2004. The factorial maps furthermore give a possible explanation for the different impacts along the coastline also taking into account environmental factors like coral reefs.

4 Change Detection Analysis for Identification of Coastal Vegetation Damages

The assessing of coastal vegetation and in particular tropical beach forests to possibly reduce the inundation width and the tsunamis' hydraulic force onshore requires at first a comprehensive analysis of the tsunami impacts within the study area. For this purpose a

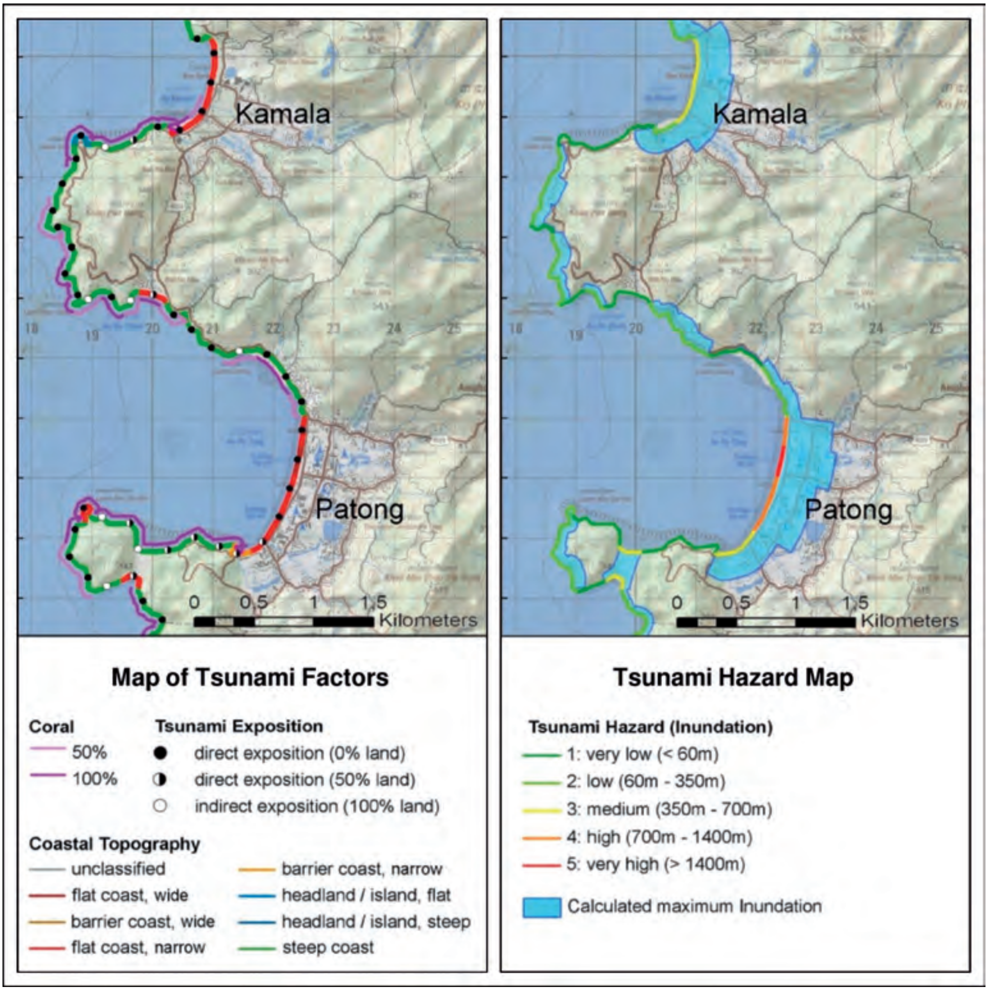


Fig. 3: Tsunami factorial (without nearshore bathymetry) and hazard map (calculated inundation areas) of Patong Beach and Kamala Beach in the south-western part of Phuket, Thailand.

change detection analysis of medium resolution satellite imagery (*ASTER - Advanced Spaceborne Thermal Emission and Reflectance Radiometer*) on the basis of a *post classification comparison* has been carried out in order to get detailed information about the spatial distribution and intensity of tsunami induced damages, especially on beach forests. Even though being dependent on the quality of the two independently produced LULC classifications (performed by a pixel-based classification algorithm with following knowledge-based post classification refinement) used as input for the change detection, the post classification comparison technique already proofed capable of achieving very accurate overall results (Lu et al. 2004). Moreover, this method minimises impacts of atmospheric, sensor and environmental/seasonal differences between multitemporal images, as the change detection analysis is not directly based on a comparison of the images' spectral values (Mas 1999).

4.1 *Base Data, Image Pre-Processing and Spectral Enhancement*

For the presented analysis, the following level 3 orthorectified ASTER images (P130/R54) with cloud cover < 5% and recording date as close as possible to the tsunami event on 26/12/2004 were used:

- Pre tsunami: Two scenes from 31/01/2002, two scenes from 07/03/2003
- Post tsunami: Two scenes from 31/12/2004, two scenes from 08/02/2005

The ASTER sensor provides a wide spectral resolution with 14 different spectral bands (VNIR, band 1-4 / SWIR, band 4-9 / TIR, band 10-14) and a medium spatial resolution between 15 and 90 m.

To gain the maximum spatial and spectral information content from the imagery and to reduce disturbing influences from clouds and cloud shadows (e. g., possible false classifications due to its high spectral similarity with LULC classes like "infrastructure" and "bare soil" in the VNIR), different pre-processing and enhancement steps had to be performed. At first an *image fusion* of bands 4–9 from 30 m to 15 m spatial resolution by use of the *High-Pass-Filter resolution merge* (HPF-resolution merge) was done. The algorithm provides out-standing results concerning the preservation of spectral information during the image fusion process (De Jong & Van der Meer 2004, Mularz et al. 2000). This step was followed by the removal of clouds through generating a binary mask. It was created by performing a supervised classification of the satellite imagery with two classes – "clouds", "land/water" – and a subsequent GIS-based enhancement (merging, buffering and eliminating of false classifications) of the classification results. Finally the NDVI as well as brightness, wetness and greenness of the Tasseled Cap Transformation (Yarbrough et al. 2005) and the first three bands of the Principal Component Analysis (PCA) were calculated in order to better separate different thematic classes within the later supervised classification process.

For a post classification refinement also a digital geological map (scale 1:250.000) was selected and an ASTER Digital Elevation Model (DEM) was implemented.

4.2 *Multispectral LULC Classification Before and After the Tsunami 2004*

The multispectral LULC classification of the pre- and post-tsunami satellite imagery, carried out within this study, consists of two main steps: a pixel based *supervised classification algorithm*, well suited for the classification of satellite images with medium spatial and wide spectral resolution, and a knowledge based *post classification refinement*. Both techniques were performed with the software ERDAS Imagine 9.1. To support the selection of training areas and the differentiation of classes during the supervised classification process, a terrestrial survey in the study area for the assessing of ground control points was already proceeded during a field trip in September and August 2008.

The supervised classification was conducted by a hybrid classification technique. The *parallelepiped classification (*also called *box classifier)* was chosen as first decision rule.

This according to Jensen 2005 very efficient classification method assigns pixels with corresponding spectral signatures to a thematic class with a predefined signature interval. All other signatures which could not thus be assigned were then classified with the second decision rule, the *minimum distance algorithm* (cf. Richards & Jia 2006).

The computed thematic images comprised 32 different thematic classes in the pre-tsunami- and 43 thematic classes in the post-tsunami-classification. After subsequent post-processing by the use of recoding as well as filtering (fuzzy convolution filtering 3 x 3) for reducing salt and pepper effects, the final LULC classifications consist of 15 thematic main classes (see Fig. 4).

Due to close spectral similarities between certain thematic classes (e. g., beach forest and tropical rainforest in shady mountain ridges) and resulting false classifications, a knowledge-based post classification refinement was carried out afterwards. Using the so called *knowledge classifier* in ERDAS Imagine 9.1 the spatial distribution of previously identified thematic classes can be modified by including further geodata like a DEM and geological maps in the classification process and assigning specific thresholds for the different classes of interest. It underlies a *hierarchical-decision-tree-structure* with (1) a *hypothesis* – the output class, (2) a *rule* – conditions for the variables, which can be defined by the user and (3) *variables* – the thematic classification and further geodata, from which characteristic values can be derived. For example, the following rule was set up for beach forest: Beach forest can only occur near to the coast (< 500 m distance from the coastline), only on sandy grounds, under a slope of 8° and up to heights of 10 m above sea level (Giesen et al. 2007), otherwise it has to be classified as tropical rainforest.

Finally, an accuracy assessment with 300 test points (selection method: equalized random with 20 samples per class) for every classification was performed to statistically evaluate the quality of the LULC classifications

Tab. 1: Overall accuracy and omission/commission error for all thematic classes of the pre- and post-tsunami LULC classification.

Thematic Classes	Pre tsunami LULC classification			Post tsunami LULC classification		
	*Pa	**Ua	***Kc	Pa	Ua	Kc
Beach forest	86,36	95	0,95	100	100	1
Open beach forest	100	100	1	100	90	0,89
Casuarina forest	100	90	0,89	100	100	1
Mangrove forest	90,91	100	1	95,24	100	1
Tropical rain forest	95,24	100	1	90,91	100	1
Sp. veg. trop. rain f.	94,74	90	0,89	80	80	0,79
Scrubland	100	95	0,95	95	95	0,95
Lawn	95	95	0,95	100	100	1
Agriculture	90,48	95	0,95	94,44	85	0,84
Plantations	95	95	0,95	75	90	0,89
Bare soil with sp. veg.	100	90	0,89	100	100	1
Bare soil	86,96	100	1	100	95	0,95
Rocks	93,75	75,00	0,74	100	90	0,89
Infrastructure	100	85	0.84	100	85	0,84
	Overall accuracy: 93,67 %			**Overall accuracy: 94,00 %**		
* Producer's accuracy ** User's accuracy ***Kappa coefficient						

Tab. 2: Classification key for assigning the tsunami-induced LULC changes into different levels of damage.

Degradation Level	Description	Signature
No damage	• No change of LULC • Positive change of thematic classes (natural or anthropogenic change, e.g. "beach forest" to "plantation")	
Medium damage	• Changes with regard to the vegetation density or loss of higher vegetation • Example: "beach forest" to "open beach forest"; "tropical rainforest" to "scrubland"	
High damage	• Changes to non-vegetated or very sparsely vegetated thematic classes • Example: "beach forest" to "bare soil" or to "bare soil with sparsely vegetation"	
Flooded area	• Changes to thematic class „water"	

(Richards & Jia 2006). Due to the implemented post classification refinement, high overall accuracies for both classifications could be achieved (see Tab. 1).

4.3 *Post Classification Comparison of Pre- and Post-Tsunami LULC Classification*

The computed LULC classification is suitable for a first qualitative assessment of the tsunami damages in the study area. However, for a quantitative analysis of the impacts, especially with regard to the extent of damage on the individual beach forest classes, a change detection analysis on the basis of a post classification comparison was needed. Within this change detection technique, the classified images are compared pixel wise by producing a change detection matrix (Lillesand 2004). This generated layer provides the "from-to" information of every single thematic class, whereby its changes can be separately identified and evaluated, depending on the subject of investigation.

The changes between thematic classes in the study area have only been detected in a limited spatial area: the theoretical tsunami hazard zone. It has been defined by the maximum tsunami run-up height of 19 m above sea level and the maximum distance of tsunami inundation of 3 km inland (Choowong et al. 2007, Cochard et al. 2008) within the study area.

After implementation of the post classification comparison, the generated information has been prepared in a way that allows an accurate acquisition of the locally different degree of damage on the coastal vegetation: the classification of the "from-to" changes into a damage/degradation-scale with four different levels (see Tab. 2).

It should generally be noted, that changes between thematic classes are not necessarily caused by the tsunami. Minor changes can also be originated by clearings, construction measures or natural effects of erosion between the recording date of the pre-tsunami images and the tsunami event in December 2004. However, due to the short period of time between the recording dates, these changes are negligible compared with the impact of the tsunami.

The damage extent of the coastal vegetation and of all thematic classes detected by the change detection analysis is presented exemplarily in the following maps (Fig. 4), which show the small fishing village Thap Lamu in the south of Khao Lak (see also Fig. 2).

4.4 *Total Damage on Coastal Vegetation in the Study Area*

The four types of coastal vegetation in the study area have been affected by the tsunami in a very different way. Fig. 5 shows the degree of damage on the different forest types in total (ha) as well as in percent of the pre tsunami area.

With almost 37.000 ha mangrove forest presents by far the largest part of coastal vegetation in the study area. Furthermore this class is significantly less affected (3.51% total degradation) by the tsunami than other class-

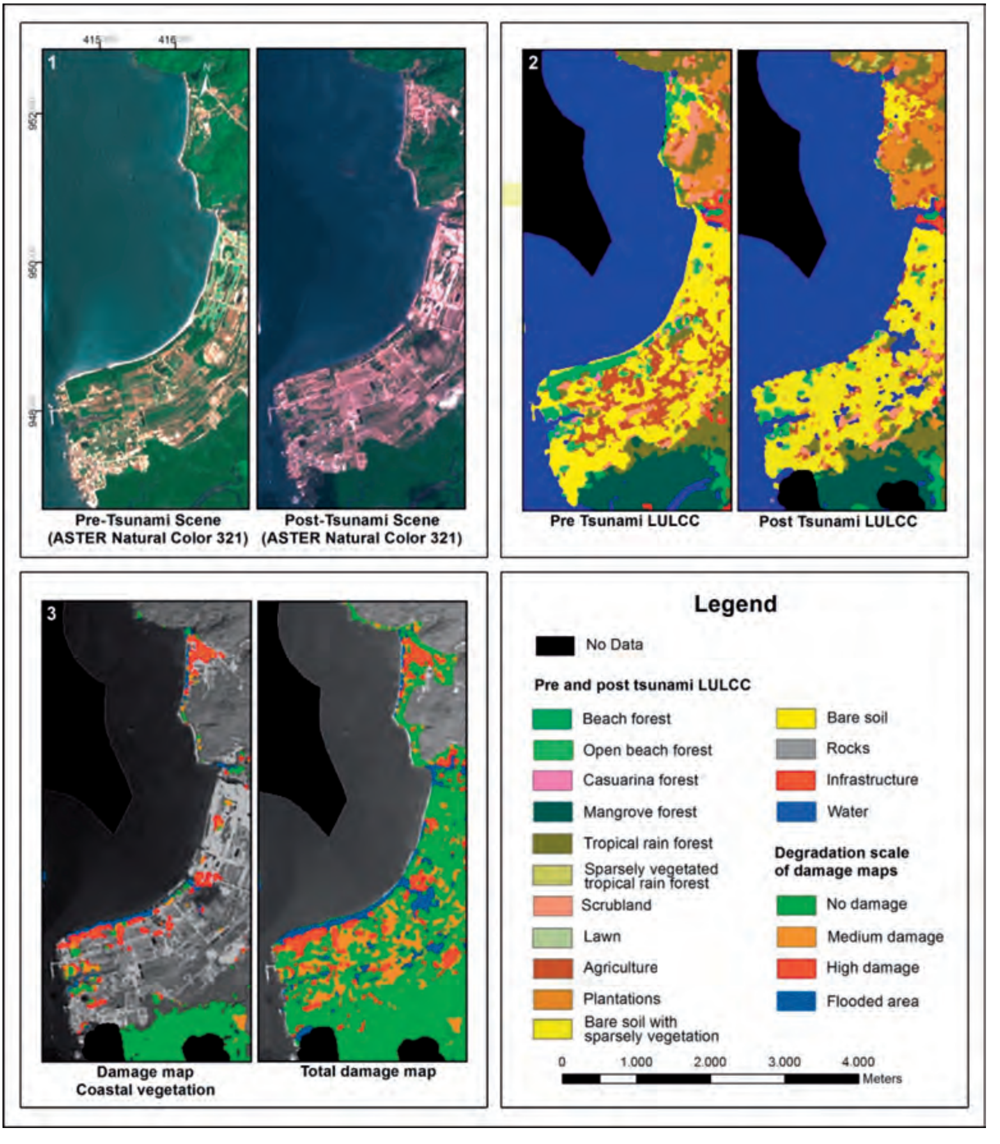
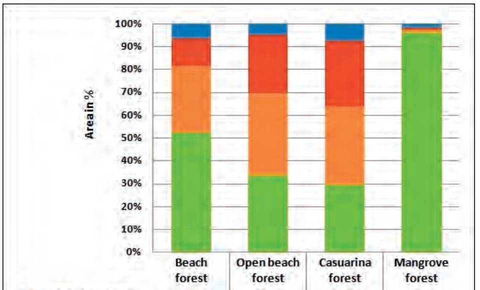


Fig. 4: (1) Examples of the pre- and post-tsunami ASTER-imagery, (2) the computed LULC as well as (3) the resulting tsunami damage maps.

es. However, studies have shown that mangroves are usually strongly damaged if they get in direct contact with tsunami waves (Tanaka et al. 2006). Therefore the result of the change detection analysis confirms the assumption of Cochard et al. 2008 and Chatenoux & Peduzzi 2007 that this type of coastal forest is, in contrast to the other presented types, more likely to be found in areas which are protected from the open sea, e. g., lagoons or river estuaries. Thus they are rarely located in direct exposition to potential tsunami waves. As a result mangroves are less affected, but also do, due to its preferred growing locations, not seriously offer very much coastal protection for settlements and infrastructure in case of a tsunami.

Beach forest is the second largest type of coastal forest in the study area. This dense deciduous forest, consisting of different species



	Beach forest	Open beach forest	Casuarina forest	Mangrove forest
Inundated area in ha	216,04	88,51	37,82	606,75
High damage in ha	427,51	458,88	142,67	277,42
Medium damage in ha	1012,55	644,01	169,71	412,31
No damage in ha	1838,59	608,04	147,96	35689,04
Total in ha	3494,69	1799,44	498,16	36985,49
Total damage in %	47,39	66,21	70,30	3,51

Fig. 5: Degree of damage on the different coastal forest types caused by the tsunami 2004 in the study area.

of "barringtonia formation" (see Cochard et al. 2008), has been damaged to 47.39%. Open beach forest, a more sparsely vegetated forest has been harmed to 66.21%. The smallest forest type, the casuarina forest, only consists of one species – *Casuarina equitesifolia*. With 70.3% degradation in total, it was most affected by the tsunami waves. After Tanaka et al. (2006) this high proportion of damage can be explained by the high vulnerability of especially young casuarina populations (< 0.1 m Diameter at Breast Height DBH). In situ investigations confirmed this observation (Günthert 2009).

5 Statistical Modelling of the Vulnerability and Protective Effect of Beach Forests

As already mentioned, the degree of damage on beach forests in the study area locally differs a lot. To assess, whether these different damage pattern are solely attributed to the different energy potential of the tsunami or also depend on the vegetation structure of the various forest sections, a linear multivariate regression analysis has been conducted (Section 5.1). As data input three different sources were taken: (1) On-site measured run-up heights of the tsunami 2004 (Tsutji et al. 2006), (2) damages within the test sites as a result from the change detection analysis and (3) more than 10 vegetation parameters from 11 coastal test sites with a size of 2 ha.

For the selection of the test sites during the terrestrial survey, care was taken to ensure, that these areas were representative for the whole beach section. After selecting a representative test area, following parameters have been assessed: Forest width, number of individuals of the species, average height of the species, average height of the trees' first branch, average diameter at breast height of the species, basal stem area of the species, average distance between the individuals, canopy cover, relative abundance and relative dominance of the species as well as type, height and coverage of the undergrowth.

Besides this, a second regression analysis was carried out to get further information about the possible correlation between the vegetation structure of beach forests (8 test sites with a size of 2 ha) and damage on settlements (within an area of 4 ha directly behind the test sites). This would be another indication for the controversially discussed protection function of beach forests in case of a tsunami (Section 5.2).

5.1 *Multivariate-Statistical Operations for Detecting Influencing Factors on the Vulnerability of Beach Forests*

The regression analysis for evaluating *the damage on beach forests* (dependent variable) within the 11 test sites implied four independent variables shown in Tab. 3. By these parameters, 94.8% of the damage variance could be explained (Adjusted R^2: 0.984; F-test at a significance level of 5%: 0.00; T-test at a significance level of 5%: ≤ 0.029; condition index: ≤ 9.904). Its quantitative influence is expressed in unstandardized coefficient (absolute influence on the dependent variable) and standardized β-coefficient (relative influence on the dependent variable).

As expected, the local energy potential of the tsunami, expressed by the *run-up height*, is mainly responsible (β-coefficient: 0.997) for the extent of vegetation damage within the 11 test sites. This run-up height is the result of the spatially different topographical and bathy-

Tab. 3: Variables and its calculated coefficients of the regression analysis for evaluating the damage on beach forests.

Variables	Un-standardized Coefficients	Standardized Coefficients
Tsunami run-up height	9.76	0.997
Average forest height	−2.784	−0.843
Average height of the trees' first branch	−3.383	−0.561
Average distance between the species	−2.519	−0.262

metrical conditions on the shoreline. If it would increase about one meter, the total damage of the coastal forest would rise about 9.76% (see unstandardized coefficient, Tab. 3)

The statistical model also verifies the significant influence of structural parameters on the vulnerability of beach forests. The *average height of the forest* (Fig. 6, red arrows) is almost equally important (β–coefficient: 0.843) for its resilience than the run-up height and can be considered as the main structural risk parameter. This coincides with studies of Cochard et al. (2008), who stated, that "*the most important factor whether a tree survives a tsunami wave (...) appears to be its size*". It can be assumed, that forest height is directly correlated with the forest age, tree diameter and in most cases with higher rooting depth of the trees. These factors directly enhance the breaking strength of trunks and branches as well as the risk of undercutting. But above a certain age, the resilience of a tree declines because of the lowered elasticity of the tree stems. This fact could not be considered in the presented regression analysis.

The variable "average height of the trees' first branch" (Fig. 6, blue arrows) gives evidence about the *vertical density* within the stand. With increasing height of the first branch by 1 m, the non-vegetated range from the ground to the canopy gets greater. As a result the forest provides a more permeable barrier (Forbes & Broadhead 2007) whereby the waves' hydraulic force on the trees is attenuated and the damage on the forest is reduced by 3,38%.

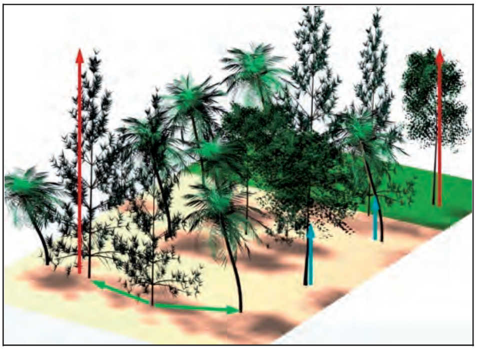


Fig. 6: Most important vegetation parameters in a beach forest concerning its vulnerability and protective effect in case of a tsunami.

The "average distance between the single species" (Fig. 6, green arrows) as an indicator for *the horizontal forest density* (β-coefficient: 0.262) also influences the permeability and thus the damage on the forest (unstandardized coefficient: −2.591).

5.2 *Multivariate-Statistical Operations for Detecting Influencing Factors on the Protective Effect of Beach Forests*

Several studies suggest the major role of beach forests as a protective barrier by absorbing and reflecting the waves' energy as it passes through the forest (e. g., Cochard et al. 2008, Forbes & Broadhead 2007). By evaluating a second multivariate statistic operation, the study at hand could confirm this point of view about the mitigation effect of beach forests by detecting a statistically significant correlation between specific structural parameters within 8 test sites and the damage on settlements behind them (3 test sites could not be integrated in the calculation because of the absence of settlements behind them). The regression analysis for evaluating *the damage on settlements and infrastructure behind beach forests* (dependent variable) contained two independent variables (see Tab. 4), by which 93.3% of

Tab. 4: Variables and its calculated coefficients of the regression analysis for evaluating the damage on settlements and infrastructure behind beach forests.

Variables	Un-standardized Coefficients	Standardized Coefficients
Average height of the trees' first branch	6.137	0.682
Number of different species	−10.132	−0.468

the damage variance could be explained (Adjusted R^2: 0.933; F-test at a significance level of 5%: 0.01; T-test at a significance level of 5%: ≤ 0.008; condition index: ≤ 7.726).

The "average height of the trees' first branch", which gives information about the *vertical density* (as explained in Section 5.1), has the greatest influence on the damage extent of the infrastructure behind the test sites (β-coefficient: 0.682). With an increase of the height of the first branch, the damage on settlements would also increase about 6.1%. This can be explained by the higher permeability and therefore reduced mitigation effects: a stand with sparse undergrowth and trees with few branches at lower levels (e. g., coconut forest; old casuarina forest) has very low reflection and energy absorption effects. As a result it hardly reduces the inundation depth and hydraulic force of the tsunami. The wave thus streams almost unabated throughout the forest and unloads its whole energy on the infrastructure behind.

The second variable within the regression model, the "number of different species" (β-coefficient: −0.468), also influences the vertical density. With a larger number of species the forest has a more heterogeneous structure with different growth heights and habits. So the mitigation effect will increase by this variation of the vertical stand structure and damage on settlements can severely be reduced (unstandardized coefficient: −10.132). Own investigations on Phuket, Thailand show, that a beach forest with four different species (*Casuarina equisetifolia, Pandanus tectorius, Terminalia catappa, Cocos nucifera*) offered much greater protection from the tsunami than others with only two species (*Cocos nucifera, Casuarina equisetifolia*), at a similar run-up height (Günthert 2009).

6 Potential Afforestation Measures for Increasing the Protection from Tsunami Waves: The Case Study of Kamala Beach

The following case study shows how a combination of empirical tsunami hazard assessment (see Section 3) and the presented work could possibly be applied to support local coastal protection in a targeted and efficient way. By using tsunami factorial and hazard maps it would be possible to rapidly identify zones of increased tsunami hazard together with its causes. Within the identified zones the empirically derived coefficients, presented in Sections 5.1 and 5.2, could be utilized to calculate the possible vulnerability and protective effect of beach forests by use of a regression equation. If the mitigation effect of the specific forest is considered to be low, the effectiveness of potential afforestation measures could also be statistically modelled.

The capacity of a beach forest to withstand and buffer any tsunami impact strongly depends on the magnitude of the impact. In areas, where the tsunami force was overwhelming, the buffering role of vegetation was probably fairly negligible (Cochard et al. 2008). Therefore especially those areas with a less seriously threat are preferred for afforestation measures.

The test site of Kamala Beach (2 ha) (see Fig. 2), an important tourist centre on the west coast of Phuket island, is classified by the tsunami hazard map as an area of medium tsunami inundation hazard - the calculated inundation width amounts between 350–700 m (Fig. 3). During the tsunami 2004 the test site has been hit by a wave of 4 m height, whereby the village of Kamala behind the test area got damaged by 66%. The coastal forest within the test site, which only consists of *Casuarina equisetifolia* (see Tab. 5) was damaged by

Tab. 5: Vegetation structure of the test site "Kamala Beach".

Species	Number of individuals	Ø-height in m	Ø- height of first branch	Ø- distance between individuals
Casuarina e.	347	39	4,5	3,6

15.25%. (all damage parameters are based on the results of the change detection analysis, but were also similarly calculated by the regression equation).

Overall, this very old forest has a low vertical and horizontal density and therefore did not offer sufficient protection against the tsunami waves. To gain a better protective effect of this vegetation barrier, afforestation measures have to be conducted, but in a way that allows a state of balance between vulnerability and protection. If the forest would be afforested too dense (calculated theoretical damage on settlements of 0%), a large wave may completely level the forest and pass over unmitigated. This effect is usually accompanied by its total destruction (damage on forest of 100%), resulting in an additional hazard for the coastal village from the debris laden water (Forbes & Broadhead 2007).

So on the one hand the desired afforestation project needs to improve the green belts' vertical density by replacing a part of the casuarina species by smaller trees with a proven robustness against tsunami waves – like *pandanus tectorius*, a species with supported aerial roots. On the other hand, additionally planted trees of *hibiscus tiliaceus* which are cultivated for tsunami protection in Japan, directly enhance the horizontal density of the forest as well as the vertical stand structure.

Tab. 6 shows the vegetation structure of the test site after potential afforestation measures (the several parameters of the new species have been recorded in a similar manner on other test sites, the same applies for the new species composition and its species proportion).

The statistical modelling of the vulnerability and protective effect of the afforested test site led to the following results: The damage on settlements would now amount 35.58%

Tab. 6: Vegetation structure of the test site "Kamala Beach" after afforestation measures.

Species	Number of individuals	Ø-height in m	Ø- height of first branch	Ø- distance between individuals
Casuarina e.	209	39	4,5	2,5
Pandanus t.	138	8,6	1,85	
Hibiscus t.	150	12	2	

(damage reduction of 30.42%). At the same time the damage on the beach forest would amount 51.81% (damage increase of 36.56%).

Thus the protective effect of the beach forest could be increased significantly. The waves' energy would be reduced by the improved absorbing and reflecting effect of the afforested vegetative barrier (resulting in a greater damage on the beach forest) and the settlements behind are protected in a more efficient way in case of a future tsunami.

7 Conclusions and Outlook

The described approach for a comprehensive assessment of the vulnerability and protective effect of tropical beach forests by using change detection and terrestrial survey methods in combination with multivariate statistic modelling proved to be very effective. However, due to the limited number of test sites, the determined statistical parameters can hardly be considered representative for other tropical coastal regions affected by the tsunami. But its high statistical quality (adjusted R^2: > 93%) leads still to the assumption, that this study provides valid evidences for the significance of specific vegetation structures, which determine whether a tropical beach forest provides a protective effect in case of a tsunami or not. Attention should also be paid for the forest's vulnerability. The buffering effect of vegetation barriers is always accompanied by its partly or full destruction and can in the latter case lead to an even greater threat for settlements by increased debris flow.

Further investigations should now be done to validate and enhance the statistical models for the vulnerability and protective effect of beach forests from the study at hand. In this context, it would also be interesting to explore its transferability to other tsunami endangered regions like Chile and/or Japan.

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