Nat. Hazards Earth Syst. Sci., 9, 1479–1494, 2009
www.nat-hazards-earth-syst-sci.net/9/1479/2009/

Natural Hazards
and Earth
System Sciences

Vulnerability assessment and protective effects of coastal vegetation during the 2004 Tsunami in Sri Lanka

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Received: 5 March 2009 – Revised: 23 July 2009 – Accepted: 24 July 2009 – Published: 25 August 2009

Abstract. The tsunami of December 2004 caused extensive human and economic losses along many parts of the Sri Lankan coastline. Thanks to extensive national and international solidarity and support in the aftermath of the event, most people managed to restore their livelihoods completely but some households did not manage to recover completely from the impacts of the event. The differential in recovery highlighted the various vulnerabilities and coping capacities of communities exposed to the tsunami. Understanding the elements causing different vulnerabilities is crucial to reducing the impact of future events, yet capturing them comprehensively at the local level is a complex task. This research was conducted in a tsunami-affected area in south-western Sri Lanka to evaluate firstly the role of coastal vegetation in buffering communities against the tsunami and secondly to capture the elements of vulnerability of affected communities. The area was chosen because of its complex landscape, including the presence of an inlet connecting the Maduganga estuary with the sea, and because of the presence of remaining patches of coastal vegetation. The vulnerability assessment was based on a comprehensive vulnerability framework and on the Sustainable Livelihoods Framework in order to detect inherent vulnerabilities of different livelihood groups. Our study resulted in the identification of fishery and labour-led households as the most vulnerable groups. Unsurprisingly, analyses showed that damages to houses and assets decreased quickly with increasing distance from the sea. It could also be shown that the Maduganga inlet channelled the energy of the waves, so that severe damages were observed at relatively large distances from the sea. Some reports after the tsunami stated that mangroves and other coastal vegetation protected the people living behind them. Detailed mapping of the coastal vegetation in the study area and subsequent linear regression revealed significant differences between three vegetation classes present in the area with regard to water level and damages to houses. As our region showed homogeneity in some important factors such as coastal topography, our results should only be generalised to comparable regions.

1 Introduction

The tsunami which hit the coasts of several Asian and African countries on 26 December 2004 caused some 226 000 fatalities (EM-DAT) and severe damage to livelihoods and infrastructure. It revealed the inherent vulnerability of coastal communities within the affected countries. Even four years after the event, some people had not managed to recover completely, as it could be derived from our observations and surveys. It is suggested that there are further aspects, apart from the direct impact of the waves that shape the resilience and subsequent vulnerabilities of the affected people. Some reports after the tsunami, many of which were anecdotal, stated that coastal vegetation in general and mangroves in particular protected people and saved lives by reducing the energy of the waves. The hypothesis that vegetation can diminish wave energy is still being debated scientifically. (Kathiresan and Rajendran, 2005; Kerr et al., 2006; Kerr and Baird, 2007; Vermaat and Thampanya, 2006; Cochard et al., 2008).

1.1 Vulnerability as a comprehensive approach

Natural hazards such as hurricanes, earthquakes, droughts or storm floods can cause extensive human and economic losses. It is argued that natural hazards are not catastrophes by themselves, but only turn into such when they affect human lives and assets. This aspect has led to a shift of focus, from the hazard itself and technical measures to minimize the

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impacts of hazards, to the interplay of the damaging event and the vulnerability of a society and of its infrastructure, economy and environment. The vulnerability of the different elements is shaped by human impact on these elements (Birkmann, 2006).

The concept of vulnerability is approached from different disciplines and fields of work such as academia, disaster management agencies, climate change community, and development agencies (Villagrán De León, 2006). This results in a multitude of definitions for vulnerability and related terms such as exposure, risk, and resilience depending on the approach adopted (Schneiderbauer and Ehrlich, 2004; Gallopin, 2006). For example, the International Strategy for Disaster Reduction (UN/ISDR) defines vulnerability as:

"The conditions determined by physical, social, economic and environmental factors or processes, which increase the susceptibility of a community to the impact of hazards." (UN/ISDR, 2004)

Notwithstanding the different definitions of the concept, there are a few criteria, which are commonly agreed to be important aspects of vulnerability. Vulnerability is generally seen as a composite of exposure, susceptibility or sensitivity, and resilience or adaptive capacity, although different disciplines set different foci between and within these categories (Birkmann and Wisner, 2006; O'Brien et al., 2004; Adger, 2006; Smit and Wandel, 2006; Few, 2003; Cutter et al., 2003; Polsky et al., 2003).

While exposure deals more with the impact side of vulnerability, susceptibility and resilience emphasize the internal condition of the affected society. Exposure identifies the parts of a system (people, houses, infrastructure, etc.), which are at risk of being affected from a natural hazard (Thywissen, 2006). Sensitivity or susceptibility mainly relates to the internal structure of a society and the livelihoods within this society, which shape the ability of people to cope with and recover from hazards. Resilience, as the third category, is originating in ecology (Holling, 1973), and later on has been used to characterize socio-ecological systems, taking into account the mutual dependence of the resilience of ecological and social systems through the dependence of communities on ecosystem services (Adger, 2000). It describes the ability of groups to cope with different types of external disturbances.

Another commonly agreed aspect is the complexity of vulnerability, which results from its multidimensionality, its dynamic character, and the influences from various scales (Vogel and O'Brien, 2004; Downing and Ziervogel, 2004). In order to cover as many aspects as possible, which impact on the vulnerability of systems, different types of social, economic, political, cultural, institutional, and environmental factors as well as interlinkages and feedbacks between them have to be included in vulnerability analysis (Thywissen, 2006; UNEP, 2007; Few, 2003). This complexity of vulnerability is further enhanced by its site-, level- and hazard-specific nature (Cardona, 2004; Birkmann and Wisner, 2006; Gallopin, 2006).

Although poverty and vulnerability do not describe the same condition, poor people often suffer from a higher risk of being affected more severely from any kind of hazard or disturbance (Cannon et al., 2003; Alwang et al., 2001; Cardona, 2004; GTZ, 2005; Prowse, 2003). Poor people often live in more exposed areas, as they do not have a choice where to settle, and thus tend to suffer more from the impacts of a hazard. After an event they have fewer possibilities to recover, as they have less access to various types of assets and often depend directly on the natural resources surrounding them (Alwang et al., 2001; Schneiderbauer and Ehrlich, 2004).

1.2 Vulnerability framework

An extensive review of the most important frameworks for analyzing vulnerability has been conducted by Birkmann (2006). One of the most comprehensive multi-dimensional vulnerability frameworks was developed by Turner et al. (2003a). It focuses particularly on the linkages and feedbacks between social and ecological systems and thus does not restrict analyses to humans but rather looks at the integrated vulnerability of human-environment systems. The developers of the framework see vulnerability in a wider context of global environmental change and sustainability science, which aims to understand the functioning and interlinkages of human-environment systems as a reaction to these ongoing global changes.

In order to be able to capture complexity and its impacts on the vulnerability of human-environment systems, the Turner framework operates on multiple levels and also emphasizes the importance of the linkages and feedbacks between these levels. The main elements of the framework are "(i) linkages to the broader human and biophysical (environmental) conditions and processes operating on the coupled system in question; (ii) perturbations and stressors/stress that emerge from these conditions and processes; and (iii) the coupled human-environment system of concern in which vulnerability resides, including exposure and responses (i.e., coping, impacts, adjustments, and adaptations)" (Turner et al., 2003a: 8076).

Figure 1 shows the inner level of the framework, which describes the vulnerability of the local socio-ecological system. It shows the multidimensionality of vulnerability, which includes the different aspects of resilience as well as the interlinkages between the different elements of the system under consideration. The framework particularly emphasizes the feedbacks between social and biophysical systems, which implies that changes in the conditions of the human system also impact on the resilience of the environment system and vice versa (Turner et al., 2003a). In this respect, there has been a debate in the aftermath of the tsunami about the protective role of coastal vegetation in general and mangroves in particular.

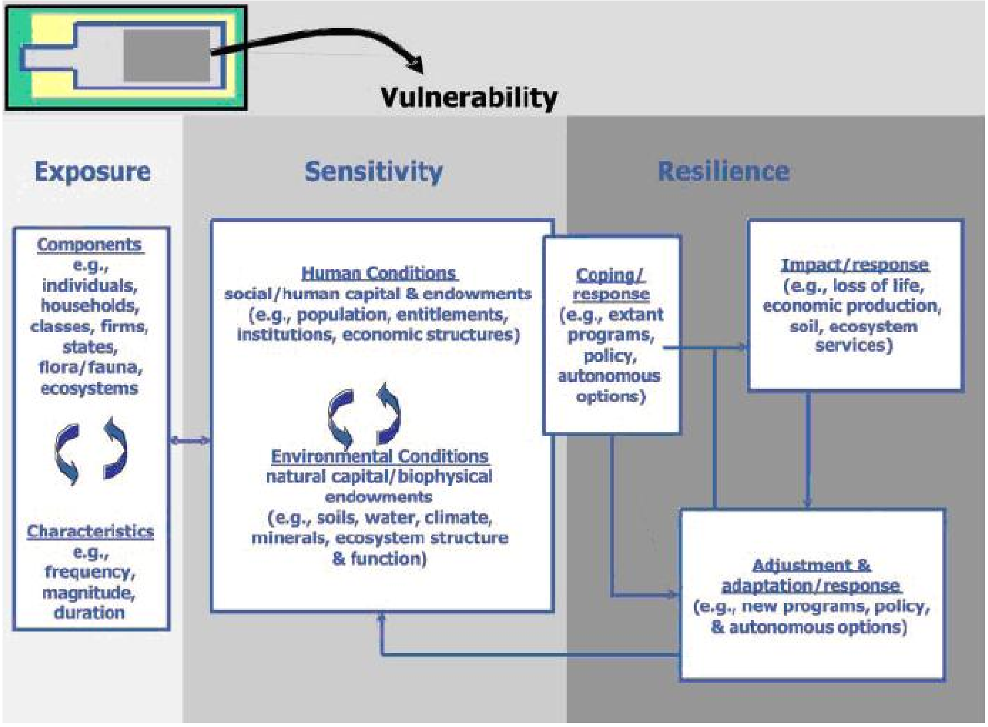

Fig. 1. Details of the exposure, sensitivity, and resilience components of the vulnerability framework. Figure at the top left refers to the full framework. Source: Turner et al. (2003a).

1.3 Impact of the tsunami and the protective effects of coastal vegetation

Coastal ecosystems belong to the most productive but also most threatened and vulnerable ecosystems in the world (MA, 2005). They are under severe stress due to population growth, overexploitation of natural resources and thus environmental degradation. In addition, coasts are particularly exposed to natural hazards such as hurricanes, tsunamis, storm surges, and sea-level rise.

The main coastal habitats in Sri Lanka are estuaries and lagoons, salt marshes, beaches and sand dunes, and mangroves. The tsunami in December 2004 hit the entire Eastern and Southern coastline of the island, and also the Western part up to Negombo slightly north of Colombo (Liu et al., 2005; Wijetunge, 2006). The impact of the tsunami on the different coastal systems varied according to factors such as coastal bathymetry, exposure, and coastal topography. Most common impacts were the filling of coastal water bodies with debris, beach erosion, uprooting of vegetation, and the salinization of drinking water and agricultural fields (UNEP, 2005; UNEP and MENR, 2005; Appanah, 2005). After the event, it was reported that different species of coastal vegetation were affected differently: while coconut palms were fairly resistant to the energy of the waves as well as to salinization effects, other common coastal trees like Casuarina suffered more from the direct and long-term consequences (UNEP, 2005; UNEP and MENR, 2005; Appanah, 2005). Mangrove ecosystems were reported to be fairly resistant against the tsunami waves, so that often only the front row was uprooted, while the trees behind were more or less unaffected (UNEP and MENR, 2005). In addition, there were anecdotal reports stating that the presence of mangrove belts saved the lives of people living behind these habitats. While different methodologies such as statistical tests and biological surveys were used to prove the protective effect of coastal vegetation (Kathiresan and Rajendran, 2005; Iverson and Prasad, 2007; Danielsen et al., 2005; Dahdouh-Guebas et al., 2005), other studies challenged these outcomes (Kerr et al., 2006; Kerr and Baird, 2007; Cochard et al., 2008). Many reports call for a holistic view, which considers further influencing factors such as coastal bathymetry and topography, but also structure and conditions of the respective ecosystem (Cochard et al., 2008; Lacambra et al., 2008; Latief and Hadi, 2006; Chang et al., 2006).

Given the above scientific debate, the objectives of this study were twofold: the in-depth vulnerability assessment served to detect differences in inherent vulnerabilities between different livelihood groups. This type of ex-post assessment used the analysis of concrete impacts of an event to convey vulnerabilities to future events. In the second part we aimed to find any protective effects of mangroves and other coastal vegetation in a tsunami-affected coastal strip in southwestern Sri Lanka.

2 Data and methodologies

2.1 Study area and data

The study area as shown in Fig. 2 is the coastal strip along the city of Balapitiya, which is about 90 km south of Colombo at the southwestern coast of Sri Lanka. It is located in the wet zone, receiving an average annual rainfall of 2217 mm and fairly constant temperatures with an annual mean of 27.2°C (CCD, 2004). The topography is flat, therefore this factor was not included as part of the vulnerability assessment. The population density of Galle district was 613 people per km^2 in 2001 (DCS, 2008), and is thus one of the highest of all districts in Sri Lanka. There are no data available on a lower administrative level, but population density in the study area is high as in most urban areas on the western coastline of Sri Lanka. However, there are still some remaining spots of degraded coastal vegetation immediately at the shore, consisting of varying mixtures of coconut palms, Pandanus and different shrubs. The southern border of the study region is marked by an inlet connecting the sea with Maduganga, an estuary at about 1.5 km distance from the coast. The inlet and the estuary are fringed by a thin belt of mangroves consisting mainly of Rhizophora apiculata. The inlet encloses a small island (Pathamulla), where the Rhizophora belt reaches widths of up to 40 m.

The population in the study area consists nearly exclusively of Sinhalese, complemented by a small Muslim community. All people have access to drinking water, while only 92% have access to toilets and 72% to electricity. The occupational profile is a mixture of different types of employment, small-scale self-employment, public service, fishery, and, to a lesser extent, agriculture.

Tsunami wave heights of around four to five meters were recorded for the southwestern coast of Sri Lanka (Liu et al., 2005; Wijetunge, 2006), while information from interviewed households revealed maximum heights of about 4.5 to 5.4 m. The furthest inundation distance from the coast recorded by this survey was around 1.2 km. Out of the approximately 31 000 fatalities in Sri Lanka due to the tsunami (UNEP, 2005), only 177 were reported in the DS Division of Balapitiya (HIC, 2005) with a population of roughly 65 000 in 2001 (DCS, 2008). However, the waves caused severe damages to houses, assets, and infrastructure.

The information for the vulnerability assessment was collected through a detailed questionnaire with 157 households in September 2007, with the location of the house being recorded with a GPS device. The households were selected by stratified random sampling according to their vicinity either to the sea or to the inlet. The questionnaire asked for information on household structure, different types of assets before and after the tsunami, water level at the house, as well as damage to the house and the household from the tsunami including recovery. As a first step, all water levels which appeared inaccurate, when comparing them with the other statements within this survey and with information from other studies (Liu et al., 2005; Wijetunge, 2006), were deleted. Altogether, three out of the 157 data points were deleted, one of which was relevant for the vegetation survey. Land cover of the study region was analyzed through visual interpretation of a high-resolution satellite image (Ikonos) from 2005, supported by detailed ground truthing.

2.2 Vulnerability assessment

The questionnaire was designed to capture the different factors contributing to vulnerability on the local level according to the framework by Turner et al. (2003a). In order not to go beyond the scope of this study, various external effects, which are not part of the system under consideration, but which impact on this system, were largely omitted apart from the enforcement of the buffer zone after the tsunami: indeed, immediately after the event, the Sri Lankan Government declared a coastal buffer zone of 200 m for the eastern parts of the island and 100 m for the remaining coastal strips, which was modified later on (Ingram et al., 2006; CPA, 2006). This had serious implications in the recovery process, as many people could not return to their original homes, but were relocated further inland. This had particular negative consequences for those people, who depended on living close to the sea like fishermen. Referring to the Turner Framework the study analyzed the linkages and feedbacks between the socioeconomic and the environmental system with the aim of generating a comprehensive picture of the vulnerability of the community under consideration. The survey also made use of the asset categories of the Sustainable Livelihoods (SL) Framework (DFID, 2001), as the five different categories (physical, natural, social, financial, human) ensure that all relevant assets of a household are considered. Although the rather general and broad approach of the SL Framework makes it inappropriate to be used as an exclusive tool for analyzing the vulnerability to natural hazards, it can nevertheless serve as a valuable complement and checklist for other frameworks in order to capture sensitivity and coping capacity of vulnerable people (Birkmann, 2006; Twigg, 2001).

Indicators for analyzing vulnerability were developed according to the different categories of the framework as depicted in Fig. 1. The indicators, which are listed in Table 1, focus on financial assets and occupational activities. Although there is an ever increasing emphasis on non-monetary issues when dealing with livelihoods, vulnerability, and poverty, it is uncontested that income and all other types of financial resources, which households use to achieve their livelihood objectives, are still of utmost importance for livelihoods (UNDP, 2007; DFID, 2001). Due to its relevance it was decided to include the initial income at the time of the tsunami as part of the sensitivity of a household, while changes in income and savings were included under resilience as a result of the impacts of the tsunami. This study

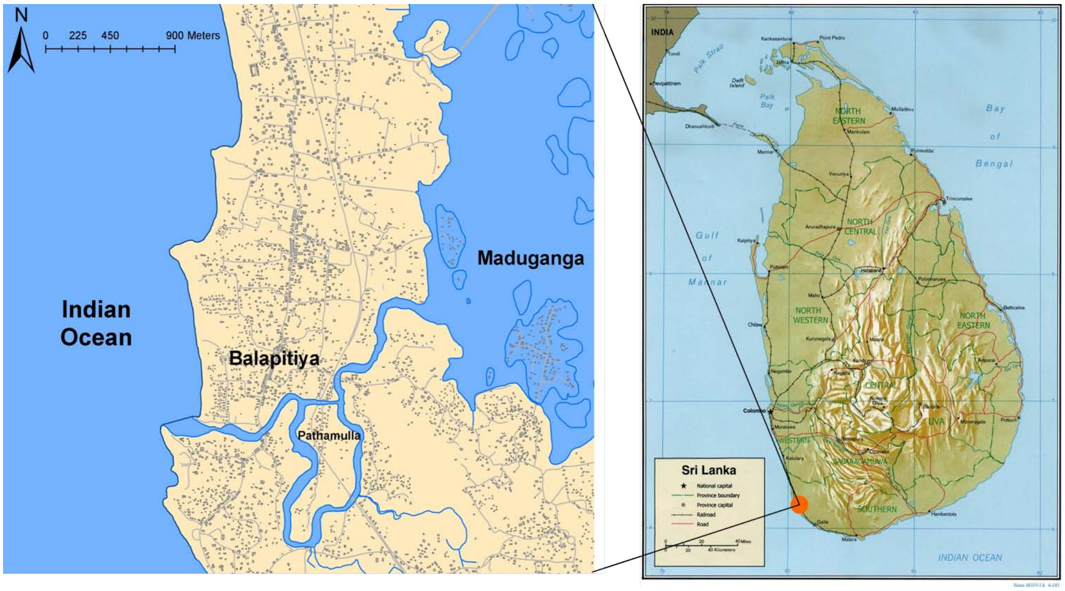

Fig. 2. Study area Balapitiya in Southwestern Sri Lanka.

referred to the income of the household head or the highest income within the household, which was the same in most cases. The study put a strong focus on income-generating activities, as they are the most important factor for generating financial assets. Furthermore people depend on different equipment for different types of occupation (such as fishing equipment or computers), which can be affected differently by natural hazards. This in turn might have an impact on recovery and resilience of the household. Birkmann and Fernando (2008) have already shown the differentials in recovery for several occupational groups in Sri Lanka after the 2004 tsunami.

Another indicator related to occupation is the period without work after the tsunami, which has a strong impact on the recovery of the household, as during this period the household does not generate any income and can thus not recover effectively. The last indicator linked to financial capital is the access to loans in order to support recovery after the event.

The information from the questionnaires and the distance measurements served as input for statistical analysis to show prevalent vulnerabilities of different social groups after the tsunami. All data were first scanned for their statistical distribution by applying the Kolmogorov-Smirnov-Test. It revealed that none of the variables was normally distributed, thus non-parametric statistical tests were used. After comparing the means of several variables with regard to different groups of households, specific statistical tests were used to check if values between the groups differed significantly.

Table 1. Indicators used for analyzing vulnerability following the framework by Turner et al. (2003a).

Vulnerability
Exposure
– Distance to the sea
– Coastal topography
Sensitivity
– Income of household
– Structure of household
– Occupations of household members
– Construction material of house
– Extent and condition of coastal vegetation
– Infrastructure (roads, water supply, electricity)
Resilience (impact, coping/response, adaptation)
– Changes in income after the tsunami
– Time without work after the tsunami
– Savings before and after the tsunami
– Loans taken after the tsunami
– Impact of tsunami on household members
– Damage to house and assets
– Support from government, organizations, friends etc.
– Damage to water supply
– Impact of other natural hazards in recent years
– Protection measures against future tsunamis
– Policies

2.3 Coastal vegetation survey

To analyze the protective effect of coastal vegetation, a detailed mapping of a coastal stretch of the study area with a length of about 1.7 km was carried out. The boundaries of the vegetation types were recorded with a GPS during a detailed ground survey. The results were included in a GIS and first scanned visually to determine any linkages between the width and composition of the vegetation belt and the water level and magnitude of the damage behind these belts. The surveyed houses were divided into four different classes according to their damage. The damage classes were adopted from the official post-tsunami survey by the Sri Lankan Government (DCS, 2005a):

- damage category 0: no damage;
- damage category 1: partially damaged, but could still be used;
- damage category 2: partially damaged, could not be used anymore;
- damage category 3: destroyed completely.

The vegetation survey also took into account the damage along the inlet connecting the lagoon with the sea up to the island of Pathamulla. In this area, the survey made use of the results of the land-cover classification, which was linked to the household surveys.

Afterwards, the southern part of the vegetation survey with a length of about 1 km was subdivided into three different sections according to the predominant vegetation type. Next, linear regression models were employed to detect any influences of the different vegetation classes on water level at the house, damage to the house, and financial damage. This analysis was applied to the first 300 m distance from the sea.

3 Results

3.1 Vulnerability assessment

Exposure

For the analysis of the influence of distance to the sea on water level and on damage, the surveyed homesteads were first divided into two groups according to their proximity either to the sea (“sea group”; 117 households) or to the inlet (“inlet group”; 40 households). The distribution of the groups is shown in Fig. 3. In order to estimate the importance of the distance parameter, the homesteads of the interviewed households were stratified into five parallel strips based on their distance from the sea. The strips had a width of 150 m each, except for the fifth class, which contained every interviewed homestead located at a distance between 600 m and 958 m. The results for the water level at the houses of the sea group according to information given by the interviewed household members can be found in Table 2. This clearly depicts the decreasing water levels with increasing distance from the sea which is logical and was expected. The mean flow depth reported in the first distance class was 291 cm, while it was 99 cm for the last class, and the overall average was 217 cm. Water levels of the five distance classes were tested to be significantly different (ANOVA: p=0.000). The subsequent pairwise comparisons with Fisher’s Protected Least Significant Difference (LSD) test showed, that the decrease in water level was mainly significant with regard to the first distance class in comparison to the other classes.

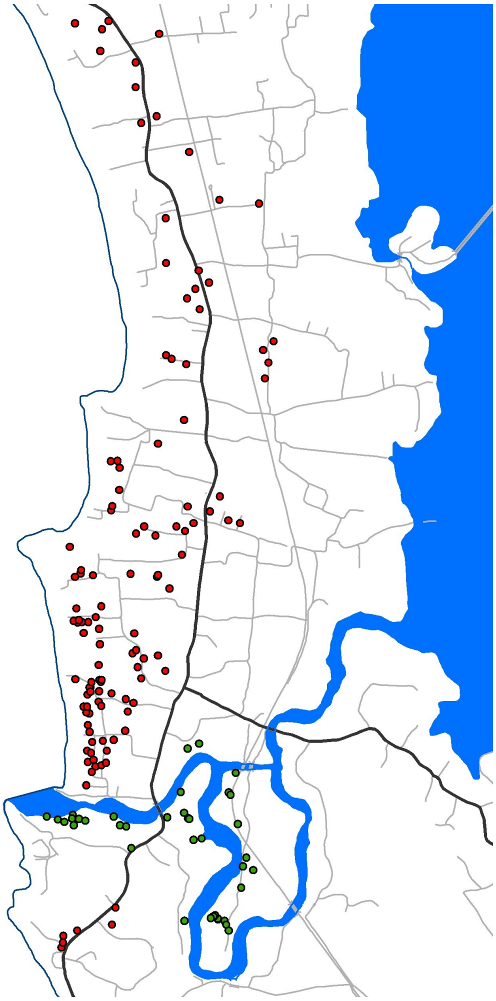

Fig. 3. Distribution of the “sea group” (red) and the “inlet group” (green) for the vulnerability assessment.

Table 2. Flow depth at the house for group 1 (houses close to the sea). (ANOVA: p=0.000; Kruskal-Wallis: p=0.000). 15 households were omitted due to missing data.

Distance to sea in classes (m)	Mean (cm)	N	Std. deviation	Minimum (cm)	Maximum (cm)
0–150	291	27	82.1	120	450
151–300	228	32	83.1	90	450
301–450	180	24	54.7	90	300
451–600	169	11	105.8	30	360
>600	99	8	47.1	30	165
Mean/total	217	102			

For the analysis of the inlet group, five houses were excluded as there were no data available. The average water level of the remaining 35 houses was 119 cm, with a maximum distance to the inlet of 116 m.

The results of the damage analysis for houses of the sea group, which are displayed in Table 3, are similar to those of the analysis of the water levels. Fisher's Exact Test showed the significance of the results of the cross tabulation (p=0.000). As the construction material and style were quite homogeneous in the study area (concrete or brick walls with tile or asbestos roofs), these factors were excluded from the analysis. The cross tabulation showed that with increasing distance from the sea, houses tended to be less damaged, which again was expected. Once more, damage values were particularly high for the first class, in which 85% of the surveyed houses could not be used after the tsunami or were even destroyed completely.

In a further step, damage to homesteads of the inlet group was analyzed. Two out of the 40 analyzed houses did not show any damage, 27 were partially damaged (26 could still be used), and 11 were destroyed completely. The average distance of the completely destroyed houses of this group to the sea was 623 m, while for the most severely affected houses of the sea group this value was 180 m. This clearly indicates the channelling effect of the inlet. It is suggested that not only flow depth influences the damages, but also the energy of the waves that is focused by the narrow inlet and thus contributing to their destructive force. A similar effect with regard to bays and estuaries has been observed by Cochard et al. (2008). This hypothesis is supported by the relatively low water level reported for these houses, which was 119 cm on average as described above. The width of the inlet is 50 to 70 m for the first 500 m and narrows down to 20 to 40 m after the bridge (see Fig. 7 in Sect. 3.2). While 27% of the houses of the inlet group were completely destroyed, 70% showed only minor or no damages. From this discrepancy it can be assumed that the energy of the waves was in part also attenuated by other factors, although this study could not reveal which ones were of significance.

The correlation (Spearman: r_s=-0.44, p=0.000) between the overall financial damage suffered by the households and the distance to the sea (p=0.000) showed a similar trend of decreasing amount with increasing distance as displayed in Table 4. The relatively high value for class 4 is due to one household that reported extremely high damages. When this household was not considered in the analysis, the value for class 4 went down from 602 000 Rupees (Rs.) to 461 000 Rs. The results of this analysis are even more meaningful when taking into account that there is a positive correlation between distance to the sea and income per capita in 2004 of the surveyed households, i.e. poorer households tend to live closer to the sea (data not shown).

Table 3. Distribution of damages to the house by distance to the sea (Fisher's exact test: p=0.000) for houses of the "sea group"; correlation (Spearman: r_s=–0.482, p=0.000). Five households were omitted due to missing data.

	Damage to house				
Distance to sea in classes (m)	None	Damaged partially (could be used)	Damaged partially (could not be used)	Destroyed	Total
0–150	0	5	2	28	35
151–300	0	19	3	12	34
301–450	0	14	5	5	24
451–600	0	8	1	2	11
>600	1	3	4	0	8
Total	1	49	15	47	112

Table 4. Mean overall financial damage by distance to the sea (ANOVA: p=0.003; Kruskal Wallis: p=0.000). Four households were omitted due to missing data.

Distance to sea in classes (m)	Mean (Rs.) (×1000)	N	Std. deviation
0–150	963	38	976
151–300	590	42	530
301–450	448	27	251
451–600	602	18	680
>600	327	28	657
Mean/total	611	153	705

Sensitivity

Extent and condition of coastal ecosystems as a major factor of sensitivity is analyzed in the next section. For evaluating further aspects of sensitivity and coping with regard to the impacts of the tsunami, all surveyed households were divided into groups according to the main occupation of the household. With regard to income before the tsunami, the analysis revealed that there were no significant differences between the different occupational groups (data not shown). According to the Turner framework sensitivity is mainly formed by endowments and human capital. The analysis of the household structure did not produce any significant differences between the different livelihood groups. Further external factors such as institutions or economic structures were not part of this survey.

Resilience

Total income at the time of the survey of the different occupational groups was determined to see if changes with respect to the pre-tsunami situation could be observed after the event. The results in Table 5 show that employed households and households mainly working in the government sector experienced increases in income. This could be seen as the normal development due to the high inflation rate within the country, which was 10.6% in 2005, 9.5% in 2006, and 19.7% in 2007 (IMF, 2008). However, the values for income were not adjusted to the inflation rate, as the intention of this analysis was restricted to the comparison of the different occupational groups. The income (not adjusted for inflation) of fishery and labour households rose only modestly when compared to the pre-tsunami situation. Households without jobs or with pensions and particularly self-employed households suffered most from the tsunami in terms of income generation, so that three years after the event they had less financial resources available than before the event even without adjusting for inflation. Comparing the average income of the different groups in 2007 produced significant differences for total income (p=0.005, shown in Table 6) and income per capita (p=0.048) with employed households having ca. 4600 Rs. more and official households having 7900 Rs. more than the average household of this study. On the other hand, self-employed households had 4300 Rs. less and labour households had 7500 Rs. less than the average.

Another analysis investigated connections between the occupational groups and the period without work after the tsunami. Table 7 shows that households depending on fisheries had to spend eight months on average without their main income, while this period was only 2.7 months for the other groups. Pairwise comparisons (with LSD) after conducting an ANOVA (p=0.001) highlighted the significant differences only between the fishery households and all other occupational groups. Most of the fishing boats and nets were destroyed or lost, and although most fishermen received new working material eventually, identification of the needs and start of support took some time. This result is supported by another study conducted in Sri Lanka after the tsunami (Birkmann and Fernando, 2008) as well as by official statistics, which state that the number of fishermen within the surveyed GN divisions decreased from 364 to 123 after the tsunami, which was a reduction of 66.2% (DCS, 2005b). While some other industries (coir, tourism) faced similar reductions, the number of people still working in government employment was 95% and for other employment 73.6%, compared to before the tsunami.

In addition to the different livelihood groups, another subdivision was implemented according to total income as well as income per capita. The households were grouped according to their status at the time of the tsunami. For total income, classes of 5000 Rs. were chosen in order to have an equal number of cases per class. The fifth class summarizes all households with an income over 20 000 Rs. The same procedure was used for income per capita, where steps of 1000 Rs. were used, so that the fifth class includes all households with a per capita income over 5000 Rs.

Table 5. Mean of change in income (not adjusted for inflation) between December 2004 (before the tsunami) and September 2007 between the different occupational groups (ANOVA: p=0.004; Kruskal-Wallis: p=0.003). 17 households were omitted due to missing data.

Main income source of household	Mean (Rs.)	N	Std. deviation (×1000)
fishery	96	39	6
employed	5207	38	13
self-employed	–4560	20	13
labour	843	16	2
official	5065	16	9
pension/no job	–2381	11	10
Mean/total	1277	140	10

Table 6. Mean of total income of household 2007 within the different occupational groups; (ANOVA: p=0.018; Kruskal-Wallis: p=0.005). 11 households were omitted due to missing data.

Main income source of household	mean (Rs.) (×1000)	N	Std. deviation (×1000)
fishery	14	40	12
employed	21	38	22
self-employed	12	23	7
labour	9	16	5
official	24	17	16
pension/no job	15	12	18
Mean/total	16	146	16

Table 7. Mean period (months) without work after the tsunami within the different occupational groups (ANOVA: p=0.001; Kruskal-Wallis: p=0.001). Category "pension/no job" was left out in this analysis. Four additional households were omitted due to missing data.

Main income source of household	Mean	N	Std. deviation
fishery	8.0	41	9.3
employed	3.1	42	5.9
self-employed	3.5	25	4.1
labour	2.3	15	3.4
official	1.1	17	1.8
Mean/total	4.3	140	6.8

The analyses of various variables by income classes produced no significant results. Concerning changes in income after the tsunami, no significant differences between the classes could be detected. It only showed that all classes had increases in income except the households with the highest income (over 20 000 Rs.), which experienced losses of about 3000 Rs (p=0.283 for all classes). The variable "time without work" also did not show any differences between the different income classes. When analyzing savings of the households before and after the tsunami, as well as loans taken after the tsunami, no significant differences could be found between the occupational groups and between the different income groups (data not shown).

When testing differences in financial help from the Sri Lankan Government by occupational groups, two main results were observed (Table 8): while fishery-led households received 42% more support than the average household of this study, labour households received 64% less. Pairwise comparisons (with LSD test) showed significant differences for fishery (against employed, labour, official, and pension/no job households) and labour households (against fishery, employed, and self-employed households). The reason for fishermen receiving more money might be a special focus of the government, as it was recognized after the tsunami that fishermen were one of the most affected groups in Sri Lanka (Jayasuriya et al., 2005; UNEP and MENR, 2005; UNEP, 2005; BBC, 2005). Financial help from the government has to be added to the support from international NGOs, which also identified fishermen as a special target group. It is therefore rather surprising that fishermen had not managed to recover better three years after the tsunami. Some fishermen reported that they still did not have appropriate equipment such as nets and larger multi-day boats to go fishing so that they had to look for new jobs or had to start working as a laborer on other boats. Other respondents mentioned that catches decreased after the tsunami. This was probably due to an oversupply of small boats after the tsunami, which was observed after the tsunami and which caused overexploitation in near-shore areas (BBC, 2005; IRIN, 2007; Sonvisen et al., 2006). These two aspects might serve as an explanation for the weak recovery of this livelihood group. Another reason for the strong support from the government might be their particular exposure, as fishery-led households often live very close to the beach. While the average distance of all occupational groups to the sea is 355 m, this value is only 201 m for fishery households (Kruskal-Wallis: p=0.000). 75% of all houses of fishery households could not be used after the tsunami or were destroyed completely (damage categories 2 and 3), while this was only 39% on average for the other groups (Fisher's Exact Test: p=0.001).

The low support for labour households is likely to be due to the fact that they suffered less financial damage than the other groups (Table 9). Their overall damage was roughly 24% of that of all surveyed households.

Table 8. Mean financial support from the Sri Lankan Government within the different occupational groups (ANOVA: p=0.001; Kruskal-Wallis: p=0.000). Two households were omitted due to missing data.

Main income source of household	Mean (Rs.) (×1000)	N	Std. deviation (×1000)
fishery	210	40	191
employed	140	42	96
self-employed	152	27	90
labour	54	16	52
official	130	17	91
pension/no job	105	13	90
Mean/total	147	155	130

Table 9. Mean overall financial damage from the tsunami within the different occupational groups (ANOVA: p=0.052; Kruskal-Wallis: p=0.000). Three households were omitted due to missing data.

Main income source of household	Mean (Rs.) (×1000)	N	Std. deviation (×1000)
fishery	666	41	513
employed	682	42	635
self-employed	600	27	339
labour	178	15	132
official	942	16	1584
pension/no job	413	13	501
Mean/total	619	154	707

One part of the questionnaire focused on drinking water supply to the households and damages to this supply during the tsunami. At the time of the tsunami 25.5% (40 households) received their drinking water from a well, while 72% (113 households) were supplied by a tap. The remaining three households received their drinking water from a lorry (bowser; information missing from one household). The questionnaire investigated the type of damage to the water supply, the time it took to restore it, and if there were any permanent changes after the tsunami. While most affected households reported several damages for both sources, taps were mainly affected by the physical destruction of the structure. On the other hand wells also faced contamination with saline water or other contaminants. Significant differences between the water sources can be found when comparing the time the household had to spend without proper water supply. While this value was 1.6 months for taps, households depending on wells had to wait for 5.8 months until water supply was properly restored (Kruskal-Wallis: p=0.003). The nine households interviewed in the small village of Owilana on the southern tip of Pathamulla island all reported that they were supplied from a public well on the mainland, which was not affected by the tsunami. Without these nine households the duration without water supply for households depending on wells increased to 7.7 months. The survey further revealed that altogether 24 households faced permanent changes in their drinking water supply after the tsunami. But while households with wells made up only one quarter of all surveyed households, they contribute 92% (22 households) to the number of households with changes in water supply. At the time of the survey, one household depended on a water tank, six on bowsers, and the remaining 15 households were supplied from a public tap. The two other households lost their private tap and also depended on a public tap.

One of the first policy measures of the government after the tsunami was the declaration of a buffer zone of 100 m from the sea, where no rebuilding was allowed with several exceptions for hotels with a structural damage of less than 40% (Ingram et al., 2006). In December 2005 the buffer zone was withdrawn in its original form, and the set back zones laid out in the Coastal Zone Management Plan were enforced. These varied from 35 to 125 m, depending on conditions in the respective area (CPA, 2006). Within the study area it could be observed that most people respected the former extent of the buffer zone, as no rebuilding could be seen within the first 100 m from the coastline. When asked for a reason, people often mentioned the ban to rebuild in these areas. Interviewees also mentioned that the government particularly tried to relocate people formerly living very close to the coast.

3.2 Protective effect of coastal vegetation

Figure 4 shows the results of the vegetation survey along the coastal strip of Balapitiya, together with the surveyed households classified into the different damage categories. It also contains the GPS points of locations, where only the foundation of a house was left at the time of the survey. As the people had moved to other places, no questionnaires were conducted at these locations. The mapped vegetation was dominated by coconut trees, Pandanus, and different types of shrubs in various mixtures. In some parts, there was hardly any vegetation left and houses were situated next to the beach, while in other parts there was a dense belt of shrubs and trees without buildings up to a distance of 300 m from the beach. Dense in this regard refers to a type of vegetation cover, which makes it more or less impossible to walk through.

The division of a part of the survey resulted in three different vegetation classes, which are based on visual inspection: the first section just north of the inlet consisted of a belt of Pandanus backed by a loose coconut plantation with more or less no undergrowth (see Fig. 5). The width of this strip was between 30 and 50 m. The next section consisted of only very few trees, but had a dense undergrowth of different shrubs with an overall density of 80 to 220 m (see Fig. 6). Finally, the main element of the third section again was coconut trees, this time with less Pandanus in the forefront, but with denser undergrowth than the first class and a width of 100 to 220 m (see Fig. 7).

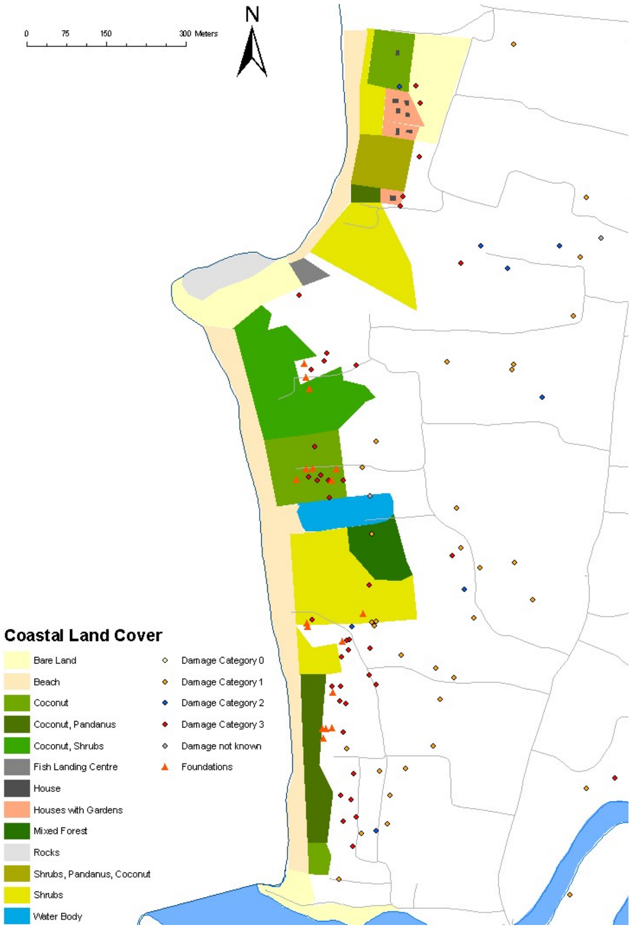

Fig. 4. Coastal vegetation survey including the surveyed households divided into the different damage categories and mapped foundations.

In order to test and estimate the size of the vegetation effect on flow depth at the surveyed houses, an appropriate regression model had to be chosen. The predictions of the linear ($F=\beta_0+\beta_1 \cdot D$)[1] and exponential model ($F=\beta_0 \cdot e^{-\beta_1 \cdot D}$) were compared within the range of the sampled data[2]. The analysis revealed that the mean of the relative differences between the predictions of the two models, calculated at all distances, was 0.1%, with a maximum of around 2%. This maximum is equal to a difference in flow depth of 19 cm. It was therefore decided to use the simpler linear model for further analysis, although this also implied different extrapolated predicted water levels for the three vegetation classes at a distance of 0 m, as it can be derived from Fig. 8.

When applying the full linear model ($F=\beta_0+\beta_1 \cdot D+\beta_2 \cdot V+\beta_3 \cdot D \cdot V$) with V being the vegetation class, a

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[1] F=Flow Depth; D=Distance to the Sea

[2] For the analysis of the protective function of coastal vegetation the range of sampled data was between 75 and 300 m distance from the shore.

Fig. 5. Example for vegetation class 1, belt of Pandanus in the front and loose coconut plantation without undergrowth behind.

Fig. 6. Example for vegetation class 2, only few trees, but partly dense undergrowth of different shrubs (denser than classes 1 and 3).

Fig. 7. Example for vegetation class 3, mainly loose coconut, with less Pandanus in the forefront (compared to class 1), but with denser undergrowth.

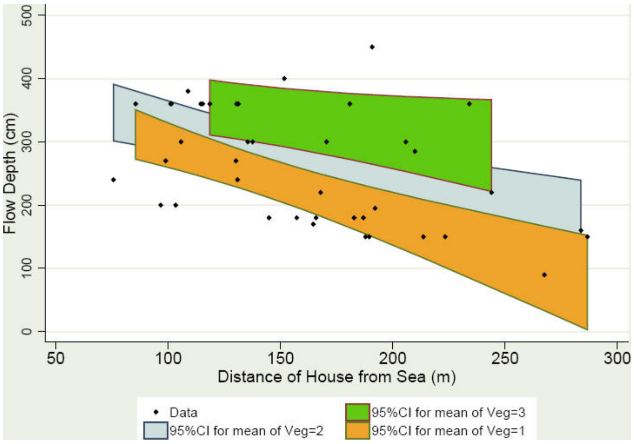

Fig. 8. Results of the simple linear regression model with 95% confidence bands for the three vegetation classes. Class 3 shows significant differences compared to the other two classes (see Table 10).

Table 10. Linear regression model ($F = \beta_0 + \beta_1 \cdot D + \beta_2 \cdot V$) with flow depth as dependent variable and distance of houses to the sea and vegetation classes (dummy) as independent variables. Vegetation class 3 was used as reference category. Overall vegetation effect proved to be significant (Wald Test p=0.003).

	Unstandardized coefficients β	Standard error	Standardized coefficients β_s	Sig.
Constant	500	47		0.000
Distance of house from sea (m)	–0.97	0.21	–0.58	0.000
Vegetation class 1	–116	32	–0.64	0.001
Vegetation class 2	–71	33	–0.37	0.039

significant interaction effect between the variables "vegetation class" and "distance to the sea" could not be detected (p=0.424). In order to increase the explanatory power, it is appropriate to test the fit of a more complex model against a simpler model, in this case against a model without the interaction $D^{*}V$ (Rothmann et al., 2008). As no difference concerning the fitting between the two models could be found (log-likelihood ratio test: p=0.366), it was decided to continue with the simpler model. Due to the higher power of this simpler model the overall vegetation effect proved to be significant (Wald test: p=0.003), as well as the distance effect (p=0.000). The results, displayed in Table 10, show significant differences between both the first and the second vegetation class when compared to the third class, which was used as the reference category in the model. The results were stable under bootstrapping with 5000 replications, in so far that the distribution is adjusted for standard errors, confidence intervals, and tests. Bootstrapping is a nonparametric method of statistical inference, where repeated samples with replacement are drawn from the original data to approximate the sampling distribution of the statistic (Moore and McCrabe, 2005; Garson, 2009).

In order to estimate the size of the vegetation effect at different distances from the sea, confidence bands were calculated. Figure 8 shows the 95% confidence bands for the three vegetation classes and differences between vegetation class 3 and the other two classes, particularly class 1 at all distances. The comparably large confidence intervals do not point to real variations of the water level, but are rather due to limitations linked to estimates of water heights by respondents.

In a second approach, the intercept of the linear model, i.e. the water level at distance zero for all vegetation classes, was set to 450 cm, which is a reasonable height based on information given by the surveyed households and from other studies (Liu et al., 2005; Wijetunge, 2006). The simulations confirmed the results of the first model. By setting the intercept of the model at the same value for all vegetation classes, it was shown that the slopes of the regression lines for the three vegetation classes were different. This proved that the reduction of the water level with increasing distance from the sea was different for all three vegetation classes. Again, bootstrapping with 5000 replications proved the stability of the results, which are displayed with 95% confidence bands in Fig. 9.

The effect of the three vegetation classes on the damage category of the surveyed houses as well as on overall financial damage from the tsunami was also estimated. Again, the tests were adjusted for the distance of the houses to the sea. While no significant vegetation effect on financial damage could be detected, the results on the damage categories confirmed the findings of the first model linked to water levels. Again, a significant interaction effect could not be found (p=0.806). However, after removing the interaction (log-likelihood ratio test: p=0.781), the overall model was significant (p=0.000) as well as the vegetation effect (Wald test: p=0.020), and the distance (p=0.000) due to the higher power of a simpler model. The differences between the vegetation classes are shown in Table 11 (p=0.007 for class 1 vs. 3, p=0.042 for class 2 vs. 3). Clearly, these results are not independent from the first findings, but they serve as an additional proof that the different vegetation classes had different effects on the impacts of the tsunami, i.e. on water level as well as on damage to the surveyed houses.

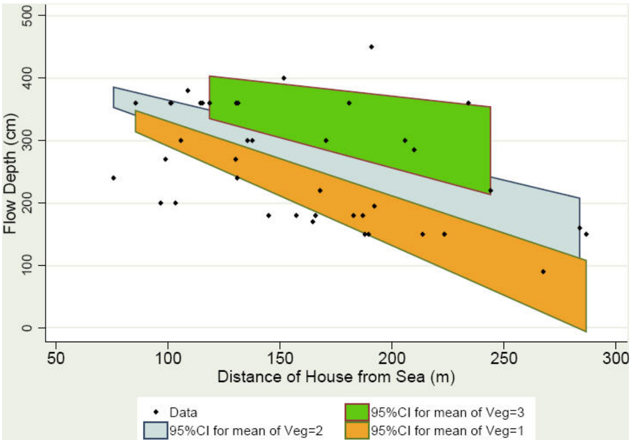

Fig. 9. Results of the linear regression model with flow depth set to 450 cm at a distance of 0 m with 95% confidence bands for the three vegetation classes. Class 3 shows clear differences compared to the other two classes.

Table 11. Linear regression model with damage categories as dependent variable and distance of houses to the sea and vegetation classes (dummy) as independent variables. Vegetation class 3 was used as reference category. Overall vegetation effect proved to be significant (Wald Test p=0.020).

	Unstandardized coefficients B	Standardized coefficients Beta	Sig.
Constant	4.7		0.000
Distance of house from sea (m)	–0.001	–0.7	0.000
Vegetation class 1	–0.7	–0.4	0.007
Vegetation class 2	–0.6	–0.3	0.042

The models used here to test and estimate a protective effect of vegetation, employed distance to the sea as the only adjusting factor. In reality, there are further factors, which generally influenced the impacts of the tsunami waves, such as seafloor topography, particularly in near-shore areas (Chatenoux and Peduzzi, 2005; Satheesh Kumar et al., 2008), distance from the origin of the tsunami (Chatenoux and Peduzzi, 2005), and further environmental parameters (Chatenoux and Peduzzi, 2005; Satheesh Kumar et al., 2008; Iverson and Prasad, 2006; Baird et al., 2005). We assumed these factors to be homogenous in the study area and they were therefore not included in our model. However, the generalization of our results is restricted to comparable situations. Apart from the inlet, coastal topography was not included, as the mapped area did not show any relevant topographical differences. A special situation was observed along the inlet connecting the estuary with the sea just south of the vegetation survey. Figure 10 shows the inlet up to the island of Pathamulla, including the surveyed houses with the water level together with the results of the land-cover classification. It shows that people living further inland along canals or other types of water bodies connected to the sea were also exposed to the tsunami, as these water bodies have the potential to channel the energy of the waves inland over a fairly long distance. The travel distance up to the village of Owilana at the southern end of Pathamulla along the inlet is approximately 1.7 km. Nevertheless, the tsunami caused severe damage in this village. Furthermore it is surrounded by a mangrove belt consisting only of Rhizophora apiculata

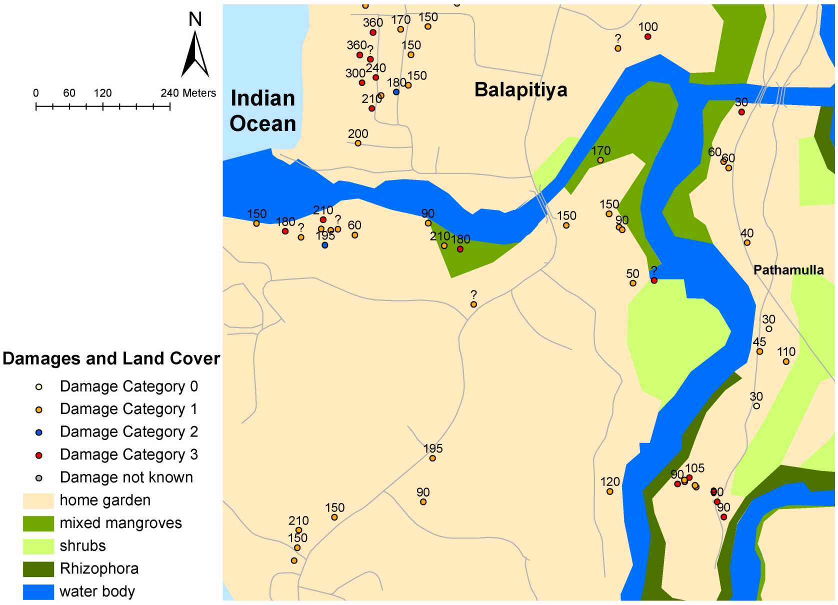

Fig. 10. Overview of Impacts of the tsunami along the canal; numbers give the flow depth at the house during the tsunami (in cm).

with its extensive stilt roots. Although it is one of the few places in the study area with remaining undisturbed vegetation, it was not possible to detect any protective effect from the vegetation belt. For the other small strips of vegetation along the inlet, no protection could be observed either. It is suggested that the existing patches of vegetation were too small to outweigh the increase in energy generated by the narrowing of the inlet.

4 Discussion and conclusions

Referring to the ongoing discussion on the protective effects of coastal vegetation, one part of this study tried to find evidence as to whether this effect could be observed within the study area in a tsunami-affected area in southwestern Sri Lanka. As the region was homogeneous with respect to important factors such as coastal topography, we could apply simple models to test and estimate the protective effect of vegetation. We found significant differences between the three analyzed vegetation classes with regard to their effects on water height at the surveyed houses and damages to the houses: the water level was significantly higher at houses behind the third vegetation class compared to the other two classes, and the decrease of the water level with increasing distance from the sea was also slower behind this vegetation class. It consisted mainly of coconut trees with only few Pandanus in the forefront but with denser undergrowth of shrubs than the first class and a width of 100 to 220 m. However, due to the given homogeneity in the study region, the results cannot be used as a general argument in favor of coastal vegetation to serve as a protective shield against tsunami waves. Each location has to be analyzed independently, in order to consider particular conditions of the ecosystems under consideration and other aspects such as coastal bathymetry and topography, as well as different aspects of exposure (distance from the sea, construction material of houses, etc.). Nevertheless, the results of this study hint to potential protective effects of coastal ecosystems under specific conditions. Additional, more extensive analyses should be conducted to find more evidence on this important issue for different locations, which could have the potential of saving lives and properties, but which could also lead to a false sense of security, if an ecosystem does not provide the expected protection in the event of a destructive natural hazard.

The use of the multi-dimensional vulnerability framework in combination with the Sustainable Livelihoods Framework proved to be useful for analyzing particular vulnerabilities of households within the study area. It is extremely difficult to include all aspects of vulnerability when dealing with such a complex framework (Turner et al., 2003b). However, the frameworks provide valuable support when the assessment is intended to go beyond the conservative categories of physical impact and physical and financial damage. The combination of the two frameworks ensured that most relevant external and internal aspects were considered. In addition to vulnerability at the local level, the framework by Turner et al. (2003a) pointed to external socioeconomic as well as biophysical influences on different scales, which have an impact on vulnerability of people on the local level. The use of the five different asset categories of the Sustainable Livelihoods framework ensured that all relevant capitals of a household were considered when analyzing sensitivity and resilience in a holistic way.

The results indicated that fishermen show a higher exposure than the other occupational groups as they are living closer to the coast and also their working equipment is highly exposed to sea-related hazards. The distance of homesteads from the sea or the inlet proved to be a major factor with regard to exposure to events like the tsunami. This corroborates findings from other studies conducted after the tsunami (Birkmann and Fernando, 2008; Iverson and Prasad, 2006). Households living closer to the water bodies faced higher water levels, higher damages to their houses, and higher overall financial damages, as expected.

According to the Turner Framework sensitivity is mainly formed by endowments and human capital as well as by external factors such as institutions. While the latter aspect was omitted from this analysis, the available data did not show any significant differences between the different groups under consideration for the former categories.

One of the major benefits of the Turner framework is its broad approach to resilience, which includes impacts and coping immediately after the event, but also long-term recovery and adaptation to changing conditions. Using the framework with its three separate categories (exposure, sensitivity, resilience) it was possible to identify labour households and particularly fishermen as the most severely affected groups, although their sensitivity profile did not mark them as particularly vulnerable. These groups now also face higher vulnerabilities with regard to any upcoming disturbances because of their increased sensitivity. The specific vulnerability of fishermen is due to a combination of increased exposure and difficulties in coping on the individual as well as on the institutional level (provision of too many and inadequate boats). Labour households faced difficulties in recovering after the tsunami due to a lack of appropriate employment. In addition, the assessment found significant differences with regard to the impact on the two major sources of water supply (wells, taps) and their recovery after the event: taps faced much less damage and were restored faster than wells. More people who had depended on wells before had to switch permanently to alternate sources of water supply after the event. In many cases this was a change for the worse, as they lost their private well and now depend on a public water source, either tap, well or a bowser.

The focus of the Turner framework is on coupled human-environment systems as the element of analysis. The emphasis on the interlinkages between social and biophysical components led to focusing particularly on the analysis of coastal ecosystems and their influence on damage to households and their assets. However, one important aspect of the framework was omitted in this analysis: as the study focused on the analysis at the local level, external effects from other scales were not considered, with the exception of the buffer zone as a political measure taken at the national level.

The declaration and enforcement of this buffer zone immediately after the tsunami has been criticized intensively particularly because of the uniform regulation of 100 m setback, which did not take into account different aspects of exposure such as coastal topography or bathymetry (Ingram et al., 2006; Jayasuria et al., 2005). The results of this study on the rapidly decreasing damages with increasing distance to the sea can, in general, serve as a proof that the reduction of exposure by moving people out of the exposed areas further inland promises to be an adequate measure. Another argument in favor of a 100 m buffer zone is given by our analysis, which proved the considerable reduction of the water level after the first 150 m from the shore (see Table 2). However, the channelling effect of the inlet, proven by the vulnerability assessment as well as by the vegetation survey, shows that it may produce a false sense of security when ignoring particular landscape features and other aspects influencing exposure. This sense of security might be also misleading when the extent of the buffer zone is not large enough. A buffer zone of 35 to 125 m, as is currently in force, will not be sufficient in many parts of the low-elevation coast of Sri Lanka in case of a devastating event such as the 2004 tsunami. Additionally, for livelihood groups depending on living close to the sea such as fishermen, resettlement to inland areas means a disruption of their livelihoods.

Another protective measure, which received much attention after the tsunami and which was under consideration by the Coast Conservation Department as an agency of the Sri Lankan Government (R. A. D. B. Samaranayake, personal communication, 2006), is the establishment of various types of greenbelts along the coasts. Our results, corroborated by other research, hint that a certain width and structure of these belts is necessary to ensure that they have a reliable protective effect. Not respecting this aspect could also lead to a false sense of security. The planting of large vegetation belts might again result in relocation of people and restricted access to beaches and thus contribute to disruptions of livelihoods.

To increase the transferability of this approach, the vulnerability assessment should in a next step be linked to advanced models of land-use and land-cover change in order to be able to analyze in a more detailed manner the condition and structure of the biophysical environment and its effects on vulnerability of households and communities as well as the complex interplay of coupled human-environment systems.

Acknowledgements. The authors thank the Center for Development Research (ZEF) for financial support of this study, the Federal Ministry of Education and Research (BMBF) as well as the Ministry of Science and Research of the State of North Rhine-Westphalia for providing financial support to UNU-EHS, which was used for this research, the International Water Management Institute (IWMI) for technical and organizational support, and the Joint Research Centre of the European Commission (JRC) for providing the satellite images.

Edited by: J. Birkmann
Reviewed by: B. G. McAdoo and S. Fuchs

References

Adger, W. N.: Social and Ecological Resilience: are they Related?, Prog. Hum. Geog., 24(3), 347–364, 2000.

Adger, W. N.: Vulnerability, Global Environ. Chang., 16, 268–281, 2006.

Alwang, J., Siegel, P. B., and Jorgensen, S. L.: Vulnerability: a View from Different Disciplines, Social Protection Discussion Paper Series, The World Bank, Washington, 2001.

Appanah, S.: Assessment of Forestry-related Requirements for Rehabilitation and Reconstruction of Tsunami-affected Areas of Sri Lanka, Mission Report, Food and Agriculture Organization of the United Nations, 10–24 March 2005.

Baird, A. H., Campbell, S. J., Anggoro, A. W., Ardiwijaya, R. L., Fadli, N., Herdiana, Y., Kartawijaya, T., Mahyiddin, D., Mukminin, A., Pardede, S. T., Pratchett, M. S., Rudi, E., and Siregar, A. M.: Acehnese Reefs in the Wake of the Asian Tsunami, Curr. Biol., 15, 1926–1930, 2005.

BBC: Tsunami Fishermen Struggle to Cope, British Broadcasting Corporation, available at: http://news.bbc.co.uk/1/hi/world/south_asia/4534868.stm, access: 3 March 2009, 2005.

Birkmann, J.: Measuring Vulnerability to Promote Disaster-resilient Societies: Conceptual Frameworks and Definitions, in: Measuring Vulnerability to Natural Hazards – Towards Disaster Resilient Societies, edited by: Birkmann, J., United Nations University Press, Tokyo, 9–54, 2006.

Birkmann, J. and Wisner, B.: Measuring the Un-Measurable – The Challenge of Vulnerability, Source 05/2006, United Nations University, Institute for Environment and Human Security, Bonn, 2006.

Birkmann, J. and Fernando, N.: Measuring Revealed and Emergent Vulnerabilities of Coastal Communities to Tsunami in Sri Lanka, Disasters, 32(1), 82–104, 2008.

Cannon, T., Twigg, J., and Rowell, J.: Social Vulnerability, Sustainable Livelihoods and Disasters, Report to DFID, Conflict and Humanitarian Assistance Department (CHAD) and Sustainable Livelihoods Support Office, 2003.

Cardona, O. D.: The Need for Rethinking the Concepts of Vulnerability and Risk from a Holistic Perspective: a Necessary Review and Criticism for Effective Risk Management, in: Mapping Vulnerability: Disasters, Development and People, edited by: Bankoff, G., Frerks, G., and Hilhorst, D., Earthscan Publications Ltd., London, 37–51, 2004.

CCD: Coastal Environmental Profile – Maduganga Special Management Area Sri Lanka, Coast Conservation Department, Colombo, 2004.

Chang, S. E., Eeri, M., Adams, B. J., Alder, J., Berke, P. R., Chuenpagdee, R., Ghosh, S., and Wabnitz, C.: Coastal Ecosystems and Tsunami Protection after the December 2004 Indian Ocean Tsunami, Earthq. Spectra, 22(S3), 863–887, 2006.

Chatenoux, B. and Peduzzi, P.: Analysis on the Role of Bathymetry and other Environmental Parameters in the Impacts from the 2004 Indian Ocean Tsunami, UNEP/GRID-Europe, United Nations Environment Programme, Geneva, 2005.

Cochard, R., Ranamukhaarachchi, S. L., Shivakoti, G. P., Shipin, O. V., Edwards, P. J., and Seeland, K. T.: The 2004 Tsunami in Aceh and Southern Thailand: A Review on Coastal Ecosystems, Wave Hazards and Vulnerability, Perspect. Plant Ecol., 10, 3–40, 2008.

CPA: Reflections on Tsunami one Year on: Lessons to be Learnt, Discussion Paper, The Centre for Policy Alternatives, 2006.

Cutter, S. L., Boruff, B. J., and Shirley, W. L.: Social Vulnerability to Environmental Hazards, Soc. Sci. Quart., 84(2), 242–261, 2003.

Dahdouh-Guebas, F., Jayatissa, L. P., Di Nitto, D., Bosire, J. O., Lo Seen, D., and Koedam, N.: How Effective were Mangroves as a Defence against the Recent Tsunami?, Curr. Biol., 15(12), R443–R447, 2005.

Danielsen, F., Sorensen, M. K., Olwig, M. F., Selvam, V., Parish, F., Burgess, N. D., Hiraishi, T., Karunagaran, V. M., Rasmussen, M. S., Hansen, L. B., Quarto, A., and Suryadiputra, N.: The Asian Tsunami: a Protective Role for Coastal Vegetation, Science, 310, p. 643, 2005.

DCS: Census of Persons, Housing Units and other Buildings affected by Tsunami, 26th December 2004, Department of Census and Statistics, Colombo, 2005a.

DCS: Census of Buildings and Persons Affected by the Tsunami – 2004 – Balapitiya DS Division, Galle District, Department of Census and Statistics, Colombo, 2005b.

DCS: Statistical Abstract 2008, Department of Census and Statistics, Colombo, 2008.

DFID: Sustainable Livelihoods Guidance Sheets, Department for International Development, London, 2001.

Downing, T. and Ziervogel, G.: Toolkit for Vulnerability and Adaptation Training, Stockholm Environment Institute, 2004.

EM-DAT: The OFDA/CRED International Disaster Database – www.em-dat.net – Université catholique de Louvain – Brussels – Belgium.

Few, R.: Flooding, Vulnerability and Coping Strategies: Local Responses to a Global Threat, Progress in Development Studies, 3(1), 43–58, 2003.

Gallopin, G. C.: Linkages between Vulnerability, Resilience, and Adaptive Capacity, Global Environ. Chang., 16, 293–303, 2006.

Garson, G. D.: Bootstrapping and Resampling, Statnotes: Topics in Multivariate Analysis, available at: http://faculty.chass.ncsu.edu/garson/PA765/statnote.htm, 2009.

GTZ: Linking Poverty Reduction and Disaster Risk Management, German Technical Cooperation, Eschborn, 2005.

HIC: Impact of Tsunami on Lives by DS Divisions – Galle District, Humanitarian Information Centre for Sri Lanka, available at: http://www.humanitarianinfo.org/srilanka/catalogue/Files/Map%20Centre/Thematic%20Maps/Sectoral%20Maps/LK0078_galle%20Tunami_Impact_07July.pdf, 2005.

Holling, C. S.: Resilience and Stability of Ecological Systems, Annu. Rev. Ecol. Syst., 4, 1–23, 1973.

IMF: World Economic Outlook Database, International Monetary Fund, available at: http://www.imf.org/external/pubs/ft/weo/2008/01/weodata/index.aspx, 2008.

Ingram, J. C., Franco, G., Rumbaitis-del Rio, C., and Khazai, B.: Post-disaster Recovery Dilemmas: Challenges in Balancing Short-term and Long-term needs for Vulnerability Reduction, Environ. Sci. Policy, 9, 607–613, 2006.

IRIN: Sri Lanka: Fishing Industry still Lacks Large Tonnage Boats, Integrated Regional Information Networks, UN Office for the Coordination of Humanitarian Affairs, available at: http://www.

irinnews.org/Report.aspx?ReportId=72857, access: 15 February 2009, 2007.

Iverson, L. R. and Prasad, A. M.: Using Landscape Analysis to Assess and Model Tsunami Damage in Aceh Province, Sumatra, Landscape Ecol., 22(3), 323–331, 2007.

Jayasuriya, S., Steele, P., Weerakoon, D., Knight-John, M., and Arunatilake, N.: Post-Tsunami Recovery : Issues and Challenges in Sri Lanka, Institute of Policy Studies of Sri Lanka, Asian Development Bank, Asian Economics Centre/University of Melbourne, 2005.

Kathiresan, K. and Rajendran, N.: Coastal Mangrove Forests Mitigated Tsunami, Estuar. Coast. Shelf S., 65(3), 601–606, 2005.

Kerr, A. M., Baird, A. H., and Campbell, S. J.: Comments on "Coastal Mangrove Forests Mitigated Tsunami" by K. Kathiresan and N. Rajendran [Estuar. Coast. Shelf Sci., 65, 601–606, 2005], Estuar. Coast. Shelf S., 67(3), 539–541, 2006.

Kerr, A. M. and Baird, A. H.: Natural Barriers to Natural Disasters, BioScience, 57(2), 102–103, 2007.

Lacambra, C., Spencer, T., and Moeller, I.: Tropical Coastal Ecosytems as Coastal Defences, in: The Role of Environmental Management in Disaster Risk Reduction and Climate Change Adaptation, ProAct Network, 2008.

Latief, H. and Hadi, S.: Thematic paper: The role of forests and trees in protecting coastal areas against tsunamis, in: Proceedings of the Regional Technical Workshop on Coastal protection in the aftermath of the Indian Ocean tsunami: what role for forests and trees?, Khao Lak, Thailand, 28–31 August 2006, 5–32, 2006.

Liu, P. L. F., Lynett, P., Fernando, H., Jaffe, B. E., Fritz, H., Higman, B., Morton, R., Goff, J., and Synolakis, C.: Observations by the International Tsunami Survey Team in Sri Lanka, Science, 308, p. 1595, 2005.

MA: Ecosystems and Human Well-Being: Current State and Trends, Findings of the Condition and Trends Working Group, Millennium Ecosystem Assessment, Island Press, Washington, 2005.

Moore, D. S. and McCabe, G. P.: Introduction to the Practice of Statistics, Palgrave Macmillan, Hampshire, 2005.

O'Brien, K., Leichenko, R., Kelkar, U., Venema, H., Aandahl, G., Tompkins, H., Javed, A., Bhadwal, S., Barg, S., Nygaard, L., and West, J.: Mapping Vulnerability to Multiple Stressors: Climate Change and Globalization in India, Global Environ. Chang., 14, 303–313, 2004.

Polsky, C., Schröter, D., Patt, A., Gaffin, S., Martello, M. L., Neff, R., Pulsipher, A., and Selin, H.: Assessing Vulnerabilities to the Effects of Global Change: An Eight-Step Approach, Research and Assessment Systems for Sustainability Program Discussion Paper 2003-05, Cambridge, MA: Environment and Natural Resources Program, Belfer Center for Science and International Affairs, Kennedy School of Government, Harvard University, 2003.

Prowse, M.: Towards a clearer understanding of "vulnerability" in relation to chronic poverty, CPRC Working Paper No 24, Chronic Poverty Research Centre, Manchester, 2003.

Rothman, K. J., Greenland, S., and Lash, T. L.: Modern Epidemiology, Lippincott Williams & Wilkins, Philadelphia, 2008.

Satheesh Kumar, C., Arul Murugan, P., Krishnamurthy, R. R., Prabhu Doss Batvari, B., Ramanamurthy, M. V., Usha, T., and Pari, Y.: Inundation mapping - a study based on December 2004 Tsunami Hazard along Chennai coast, Southeast India, Nat. Hazards Earth Syst. Sci., 8, 617–626, 2008, http://www.nat-hazards-earth-syst-sci.net/8/617/2008/.

Schneiderbauer, S. and Ehrlich, D.: Risk, Hazard and People's Vulnerability to Natural Hazards – A Review of Definitions, Concepts and Data, Joint Research Centre, European Commission, Luxembourg, 2004.

Smit, B. and Wandel, J.: Adaptation, Adaptive Capacity and Vulnerability, Global Environ. Chang., 16, 282–292, 2006.

Sonvisen, S. A., Pajot, G., and Anmarkrud, T.: Survey of Fisheries Rehabilitation in Sri Lanka, Norwegian College of Fishery Science, Food and Agriculture Organization of the United Nations, 2006.

Thywissen, K.: Components of Risk – A Comparative Glossary, Source 02/2006, United Nations University, Institute for Environment and Human Security, Bonn, 2006.

Turner II, B. L., Kasperson, R. E., Matsone, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, L., Kasperson, J. X., Luerse, A., Martello, M. L., Polsky, C., Pulsipher, A., and Schiller, A.: A Framework for Vulnerability Analysis in Sustainability Science, PNAS, 100(14), 8074–8079, 2003a.

Turner II, B. L., Matson, P. A., McCarthy, J. J., Corell, R. W., Christensen, L., Eckley, N., Hovelsrud-Broda, G. K., Kasperson, J. X., Kasperson, R. E., Luers, A., Martello, M. L., Mathiesen, S., Naylor, R., Polsky, C., Pulsipher, A., Schiller, A., Selin, H., and Tyler, N.: Illustrating the Coupled Human-Environment System for Vulnerability Analysis: Three Case Studies, PNAS, 100(14), 8080–8085, 2003b.

Twigg, J.: Sustainable Livelihoods and Vulnerability to Disasters, Disaster Management Working Paper 2/2001, Benfield Greig Hazard Research Centre, 2001.

UNDP: Measuring Human Development – a Primer, United Nations Development Programme, New York, 2007.

UNEP: After the Tsunami – Rapid Environmental Assessment, United Nations Environment Programme, 2005.

UNEP, MENR: Sri Lanka – Post-Tsunami Environmental Assessment, United Nations Environment Programme, Ministry of Environment and Natural Resources of Sri Lanka, Geneva, Battaramulla, 2005.

UNEP: Global Environment Outlook GEO 4 – Environment for Development, United Nations Environment Programme, Nairobi, 2007.

UN/ISDR: Living with Risk, A Global Review of Disaster Reduction Initiatives, United Nations/International Strategy for Disaster Reduction, Geneva, 2004.

Vermaat, J. E. and Thampanya, U.: Mangroves Mitigate Tsunami Damage: a Further Response, Estuar. Coast. Shelf S., 69(1–2), 1–3, 2006.

Villagrán De León, J. C.: Vulnerability – A Conceptual and Methodological Review, Source 04/2006, United Nations University, Institute for Environment and Human Security, Bonn, 2006.

Vogel, C. and O'Brien, K.: Vulnerability and Global Environmental Change: Rhetoric and Reality, Aviso – An Information Bulletin on Global Environmental Change and Human Security, Issue No. 13, Global Environmental Change and Human Security (GECHS), Oslo, 2004.

Wijetunge, J. J.: Tsunami on 26 December 2004: Spatial Distribution of Tsunami Height and the Extent of Inundation in Sri Lanka, Science of Tsunami Hazards, 24(3), 225–239, 2006.