Ecology and Development Series No. 77, 2011

Marcus Kaplan

Agent-based modeling of land-use changes and vulnerability assessment in a coupled socio-ecological system in the coastal zone of Sri Lanka

ABSTRACT

In recent decades, the different impacts of global change have led to an increased exposure and vulnerability of coupled socio-ecological systems (SES) to various disturbances and stressors. Human-induced land-use and land-cover changes (LUCC) are an important factor contributing to the vulnerability of such systems. It is therefore reasonable to analyse vulnerability and LUCC in a combined effort. In this study, projections for future LUCC around an estuary in southwestern Sri Lanka were developed. In a subsequent step, the vulnerability of the coupled coastal system to natural hazards was analyzed based on the effects of the tsunami in December 2004.

Changes in land use and land cover are the most important impacts of human activities on the earth system, with mostly negative consequences for both ecosystems and social systems. Awareness has grown about the complexity of the driving forces of LUCC, and various modeling approaches have been developed for generating scenarios on different spatial scales. Agent-based models (ABMs) with their focus on the simulation of human decision making and the interdependencies between humans and their environment are seen as a promising and flexible approach. They are best capable of capturing the complexity of coupled SES and of providing a natural description of the systems under consideration.

This study employed the Land-Use Dynamics Simulator (LUDAS), an ABM consisting of four modules, which was developed in 2005 for an upland watershed in central Vietnam. In addition to the household and the landscape modules, the policy component captures land-use related policies and other external parameters that impact decision making with respect to land use. The decision-making sub-module as the core of the model simulates the decision-making processes of the household agents. First, LUDAS was modified according to different biophysical and socio-economic circumstances in the coastal study region. Current land use was analyzed with high-resolution satellite images (Ikonos), while socio-economic information was based on extensive household surveys and field visits to agricultural plots, complemented by expert interviews on the local, regional, and national level. Principal Component Analysis and Cluster Analysis were used to classify the sampled population into five different livelihood groups. In a next step, binary logistic regression was employed to evaluate decision making with regard to land-use choices of the households within the different livelihood groups.

Access of households to agricultural extension services and agricultural subsidies were identified as the most important external parameters assumed to have an impact on land use and economic patterns in the study region. Notwithstanding the impact of the policy factors, all 20-year simulations revealed slight decreases in the share of income from farming activities, while the overall income of the households of all groups remains more or less constant. Furthermore, landholdings of all households decrease in size, which is mainly due to decreases in homestead area, while agricultural land uses remain on the same level or show slight increases. Access to subsidies has a stronger effect on land use and livelihoods than access to extension services. It increases the share of income from farming activities, and modifies the development of the mixed cinnamon and paddy area. Changes in access to extension services only result in minor LUCC with large uncertainties for all scenarios.

Comprehensive vulnerability approaches attempt to capture the exposure, sensitivity, and resilience of coupled SES. This study employed a guiding multi-level vulnerability framework with a specific focus on the linkages and feedbacks between social and environmental components of the system and their implications for the vulnerability of the SES. Data for the vulnerability assessment were collected through household surveys, expert interviews, analysis of secondary material, statistical analysis, and field and vegetation surveys. The assessment revealed the high vulnerability of households depending on fishery and labor. The vulnerability of the fishery households was due to a higher exposure and to failures in individual and institutional coping after the tsunami. The vegetation survey with the subsequent statistical analysis identified the varying impact of coastal vegetation on the energy of the tsunami waves.

KURZFASSUNG

Agenten-basierte Modellierung von Landnutzungsänderungen und Verwundbarkeits-Analyse in einem gekoppelten sozio-ökologischen System in der Küstenzone Sri Lankas

In den letzten Jahrzehnten haben die verschiedenen Auswirkungen des globalen Wandels zu einer zunehmenden Exposition und Verwundbarkeit von gekoppelten sozio-ökologischen Systemen (SES) geführt. Von Menschen verursachte Veränderungen der Landnutzung und Landbedeckung (LUCC) sind ein wichtiger Aspekt hinsichtlich der Verwundbarkeit solcher Systeme. Es ist daher sinnvoll, Verwundbarkeit und LUCC in einer kombinierten Analyse gemeinsam zu untersuchen. In der vorliegenden Studie wurden Szenarien zur zukünftigen LUCC im Umland einer Lagune im Südwesten Sri Lankas entwickelt. Im darauf folgenden Schritt wurde die Verwundbarkeit des gekoppelten Küsten-Systems gegenüber Naturkatastrophen auf Grundlage des Tsunamis 2004 analysiert.

Änderungen der Landnutzung und der Landbedeckung sind die wichtigsten Auswirkungen von menschlichen Aktivitäten auf das Erdsystem. Sie haben meistens negative Konsequenzen sowohl für Ökosysteme als auch für soziale Systeme. Das Bewusstsein über die Komplexität der Einflussfaktoren für LUCC hat zugenommen, und es wurden verschiedene Modellierungs-Ansätze zur Generierung von Szenarien auf verschiedenen räumlichen Ebenen entwickelt. Agenten-basierte Modelle (ABMs) mit ihrem Fokus auf der Simulation von menschlichen Entscheidungsfindungsprozessen und gegenseitigen Abhängigkeiten zwischen Menschen und ihrer Umwelt sind ein viel versprechender und flexibler Ansatz. Sie sind am besten in der Lage, die Komplexität von gekoppelten SES darzustellen, und eine naturgetreue Abbildung der betrachteten Systeme zu liefern.

Die vorliegende Studie nutzte den „Land-Use Dynamics Simulator“ (LUDAS), ein ABM, das 2005 zur Anwendung in einem Hochland-Einzugsgebiet an der Zentralküste von Vietnam entwickelt wurde und aus vier Modulen besteht. In Ergänzung zu den Modulen „Haushalte“ und „Landschaft“ beinhaltet das „Politik“-Modul landnutzungsbezogene Politiken sowie andere externe Parameter, die einen Einfluss auf Entscheidungsprozesse zu Landnutzung haben. Das Unter-Modul „Entscheidungsfindung“ als zentrales Element des Modells simuliert die Entscheidungsfindungsprozesse der Haushalte (Agenten). Als erstes wurde LUDAS an die veränderten biophysikalischen und sozioökonomischen Rahmenbedingungen in der küstennahen Studienregion angepasst. Die aktuelle Landnutzung wurde anhand hochauflösender Satellitenbilder (Ikonos) analysiert. Die sozioökonomischen Informationen basierten auf ausführlichen Haushaltsbefragungen und Feldstudien der landwirtschaftlichen Flächen, ergänzt durch Experten-Interviews auf der lokalen, regionalen und nationalen Ebene. Die Stichproben der Haushalte wurden mit Hauptkomponenten- und Clusteranalyse in fünf verschiedene Erwerbsgruppen eingeteilt. Mit einer binären logistischen Regression wurde die Entscheidungsfindung im Hinblick auf Landnutzung der Haushalte im Rahmen der Gruppen ermittelt.

Der Zugang der Haushalte zu landwirtschaftlichen Beratungsdiensten und zu landwirtschaftlichen Subventionen wurden als die wichtigsten externen Parameter identifiziert, von denen angenommen wird, dass sie einen Einfluss auf die Landnutzung und ökonomische Muster in der Studienregion haben. Unabhängig von den Auswirkungen der Politikfaktoren zeigten die Simulationen über einen Zeitraum von 20 Jahren leichte Abnahmen des Einkommensanteils aus landwirtschaftlichen Aktivitäten, während sich das gesamte Einkommen der Haushalte in allen Gruppen kaum verändert. Die Größe des Grundbesitzes aller Haushalte nimmt ab, hauptsächlich wegen der Reduzierung des Landes zur vorwiegenden Wohnnutzung, während landwirtschaftlich genutztes Land auf dem gleichen Level bleibt oder einen leichten Anstieg verzeichnet. Der Zugang zu Subventionen hat einen stärkeren Effekt auf Landnutzung und Lebensstrategien als der Zugang zu Beratungsdiensten. Er erhöht den Anteil

des Einkommens aus landwirtschaftlichen Tätigkeiten und beeinflusst die Entwicklung der gemischten Zimt-Plantagen und Reisfelder. Der Zugang zu Beratungsdiensten führt nur zu geringen LUCC mit hohen Unsicherheiten in allen Szenarien.

Umfassende Verwundbarkeitsansätze haben zum Ziel, die Exposition, Anfälligkeit und Resilienz von gekoppelten SES zu ermitteln. Die vorliegende Studie verwendete ein Mehrebenen-Konzept mit einem besonderen Fokus auf den Verknüpfungen und Rückkoppelungen zwischen den sozialen und ökologischen Komponenten des Systems und deren Implikationen für die Verwundbarkeit des SES. Die Daten für die Verwundbarkeits-Analyse basierten auf Haushaltbefragungen, Experten-Interviews, Analyse von Sekundärmaterial, statistischen Untersuchungen sowie Feld- und Vegetations-Erhebungen. Die Analyse zeigte die hohe Verwundbarkeit der Haushalte, die ihr Einkommen durch Fischerei und einfache Erwerbstätigkeiten erzielen. Die Verwundbarkeit der Fischerei-Haushalte entstand durch eine höhere Exposition sowie Fehlentwicklungen in der individuellen und institutionellen Bewältigung nach dem Tsunami. Die Vegetations-Erhebung und die anschließenden statistischen Analysen verdeutlichten die unterschiedlichen Auswirkungen von Küstenvegetation auf die Energie der Tsunami-Wellen.

TABLE OF CONTENTS

LIST OF ACRONYMS

ABM	Agent-based Model
ANOVA	Analysis of Variance
CCC	Community Coordinating Committee
CCD	Coast Conservation Department
CZMP	Coastal Zone Management Plan
DS	Divisional Secretariat
DSS	Decision Support System
GDP	Gross Domestic Product
GIS	Geographic Information System
GN	Grama Niladhari
GPS	Global Positioning System
LKR	Sri Lankan Rupees
LSD	Fisher's Least Square Difference
LUC	Land Use and Land Cover
LUCC	Land-Use and Land-Cover Change
LUDAS	Land-Use Dynamics Simulator
NGO	Non-Governmental Organization
PCA	Principal Component Analysis
RRA	Rapid Rural Appraisal
SAM	Special Area Management
SRL-LUDAS	Sri Lanka-Land-Use Dynamics Simulator
VN-LUDAS	Vietnam-Land-Use Dynamics Simulator

1 INTRODUCTION

1.1 Land-use and land-cover changes, vulnerability, and the complexity of coupled socio-ecological systems

In recent decades, awareness of the numerous impacts of global change on the earth system and on human communities has increased considerably. Global social change can be summarized as global population growth and the intensification and acceleration of world-wide interconnectedness, which are manifested in trends such as economic growth, urbanization, growing dependence and pressure on scarce natural resources, and economic inequalities (Young et al. 2006; Steffen et al. 2005; Crutzen 2006). These trends trigger global environmental change with continuous increases in atmospheric concentrations of greenhouse gases and the resulting changes in the global climate as the most important consequence. Further aspects of environmental change are changes in land use and land cover, increasing nitrogen fixation, pollution of freshwater, degradation of ecosystems, and decreases in biological diversity (Young et al. 2006; Steffen et al. 2005; Crutzen 2006). The impacts of climate change as well as other aspects of global change cause a rise in external disturbances with respect to people and the biophysical environment. It is now widely accepted that climate change will affect the intensity, frequency, and distribution of natural hazards, such as storm surges, flooding, and droughts (Parry et al 2007). Together with tsunamis, earthquakes, volcanic eruptions, and further geological, but also biological or technological hazards they threaten the lives and livelihoods of an increasing number of people. The impacts of some of these hazards are often caused or intensified by unsustainable land management practices. Supplementary to these threats, people also have to cope with economic shocks, epidemic diseases, and other external disturbances that may again be caused or intensified by various impacts of globalization.

In addition to the greater number of natural hazards, further factors contribute to an increased exposure of many communities. People in developing countries who are forced by environmental degradation, ethnic conflicts or other factors to abandon their livelihoods and move into big cities in search for work may serve as an example for this development. They often have to settle in hazard-prone areas and depend heavily on the performance of the national economy for their livelihoods. Other people particularly in rural areas have to settle in places that are subject to regular flooding because they depend on the fertile soils in these regions. Furthermore, they often live in comparably low-cost houses with little protection from the impacts of different types of hazardous events.

This increased exposure contributes to higher human and economic damages from natural hazards. In addition, the internal structure of a system or a society, its various livelihoods, and the access to different types of assets also influence the short- and long-term damages. These characteristics of a community are summarized under the term sensitivity. It also shapes the capacity of people to recover after an event and to adapt to any changes, which is known as the resilience of the system. The importance of both sensitivity and resilience were mostly neglected until the beginning of the 1970s, while the focus was only on technical measures to reduce the impacts of hazards. With the growing awareness of the importance of the structure of the society and the capabilities of people to withstand and cope with the impacts of disturbances, the concept of vulnerability emerged. Vulnerability is seen as a mixture of the three components exposure, sensitivity, and resilience (see Chapter 3).

Vulnerability takes into account the complexity of the systems under consideration, which is caused by the multitude of driving factors and the numerous interlinkages and feedbacks between the different parts of the system. Therefore, vulnerability assessments should not concentrate on individual components, but rather have to consider the complete coupled socio-ecological system with all its interlinkages and feedbacks (Gallopin 2006; Adger 2006; Cutter et al. 2008).

The modification of existing land cover or the conversion into another land cover and land use is one of the most serious human manipulations in the earth system (Vitousek et al. 1997). In this study, these manipulations are summarized under the term “land-use and land-cover change” (LUCC). In the long run, LUCC mostly have negative consequences for ecosystems and for the people living within these ecosystems who depend on their services. Ecosystem services comprise all the benefits people derive from ecosystems, represented by goods as well as by different types of services (MA 2005; Costanza et al. 1997). They serve as the main connecting link between the human and the environmental subcomponents of a system (see section 3.4). Due to their negative impacts on ecosystems, LUCC also have a decisive effect on the abilities of socio-ecological systems to cope with any disturbances and thus on their vulnerability. This linkage between LUCC and vulnerability makes it appropriate to analyze these two issues in a combined effort, particularly when dealing with land-dependent livelihoods.

1.1.1 Socio-ecological systems as complex adaptive systems

The existence and interconnectedness of the various drivers of biophysical, social, political, economic and cultural origin is a decisive feature of both LUCC and vulnerability of socio-ecological systems. These are complex adaptive systems, with both the human as well as the environmental subsystem already being defined as complex. When analyzing them comprehensively, the connections and feedbacks between the two subsystems enhance this complexity. The first step in defining complex systems is to distinguish them from simple systems. The properties of simple systems are merely a combination of the properties of its different components, thus these systems can be captured with disciplinary analytical models (Berkes et al. 2003; Lenton and van Oijen 2002). Complex systems in contrast are defined through the interactions and feedbacks between their various components, which result in properties that are seen as typical for complex systems. These properties make the analysis of such systems and the prediction of their behavior an extremely challenging task (Limburg et al. 2002; Walker et al. 2002).

Hierarchy as one of the most important properties of complex systems explains their organization on different analytical levels, which are separated by different turnover times of processes (Limburg et al. 2002). Higher levels generally consist of larger entities with slower processes, while on lower levels entities are smaller and processes faster. In nested hierarchies, lower level entities completely combine into new units with new organizational structure, functions, and new emergent properties. Emergence describes the fact that higher-level structures differ qualitatively from the mere aggregation of the lower-level components, i.e., the higher level may show a new collective behavior, which is completely different from the characteristics of the individual entities (Parker et al. 2003; Gibson et al. 2000; Rotmans 2002; Wu and David 2002; Manson and O'Sullivan 2006). This is due to the dynamic interactions with the multiple feedbacks of the different parts of socio-ecological systems (Lambin et al. 2003; Bonabeau 2002). Thus, outcomes of processes in such complex systems cannot be predicted by looking at the different elements in isolation (Parker et al. 2003; Lambin et al. 2003; Manson 2001), but rather have to be derived from comprehensive analyses on all analytical levels. Scale dependency has been intensively debated in both land-use related studies (Lambin et al. 2003; Verburg et al. 2003) and the resilience community (Young et al. 2006; Berkes et al. 2003; Folke et al. 2004; Walker et al. 2004). The complex interlinkages and feedbacks together with emergent properties result in strong nonlinearities in the behavior of complex systems, which again causes uncertainty regarding the behavior of the system (Berkes et al. 2003; Crawford et al. 2005; Malanson 1999).

Complex systems are open systems, which can be affected by external forces. They have the ability to react to these impacts and to adapt to changing conditions (Manson 2001), thus they are also called complex adaptive systems (Wu and Marceau 2002). This ability for self-organization results from the emergent properties of the system (Wu and Marceau 2002; Lenton and van Oijen 2002; Malanson 1999). The degree to which the system is capable of learning and adapting to changes determines its resilience to external disturbances (Folke et al. 2004). Resilience with regard to socio-ecological systems can be defined as consisting of two aspects, the robustness against disturbances and the just mentioned ability to learn from changes and to adapt to new conditions (Folke 2006; Walker et al. 2002). After a disturbance, the system organizes around a new equilibrium or stable state. Thus, there is never one steady state, but the system is continuously subject to changes and has several possible dynamic equilibrium states (Berkes et al. 2003; Limburg et al. 2002). Once the disturbances pass a certain level or threshold, the system may no longer be able to cope with them, and a regime shift takes place, i.e., the system changes into a radically different state (Folke et al. 2004; Adger 2006; Liu et al. 2007; Carpenter et al. 2006; Walsh et al. 2008). This shift may also take place when the resilience of the system is weakened through internal disturbances that cause the destruction of internal connections between components of the system (Manson 2001).

In coupled socio-ecological systems resilience is strongly linked to the structure of the biophysical system and the provision of ecosystem services. This fact links resilience to sustainability, as ecosystems weakened by unsustainable management practices tend to be more susceptible to disturbances (Cutter et al. 2008; Berkes et al. 2003; Folke et al. 2004; Adger 2000; Carpenter et al. 2001).

1.2 Research challenges

Based on the statements in the previous section on the complexity of land use and vulnerability and the linkages between these two issues, three main scientific challenges emerge:

- Integrated modeling of land-use and land-cover changes that takes into account and simulates emergent phenomena of the socio-ecological system as well as external influences on the system;
- Integrated assessment of vulnerability to natural hazards that considers the complexity of the socio-ecological system as well as external influences on the system;
- Identification of important linkages and feedbacks between land use and vulnerability and analysis of conceptual and methodological similarities and differences between the above two areas of research.

1.2.1 Integrated modeling of LUCC

Different modeling approaches have been developed for building scenarios of future development of land use and land cover. Most of these approaches face shortcomings when attempting to capture the multiplicity of influencing factors and particularly the complexity of human decision making as one of the decisive factors of LUCC. In recent years, agent-based models (ABMs) have emerged as a new tool for tackling the multiple and complex challenges of developing integrated scenarios of LUCC. Through using simulation rather than deduction or induction, they are able to cover the complexity of the socio-ecological system with all its interlinkages. The flexible design of the agent as the main influencing element forms the core of the approach and enables ABMs to capture the complex processes of human decision making in a realistic way (see Chapter 2).

However, development of ABMs for simulation of LUCC is still in its infancy, and many challenges remain to be solved. As ABMs are designed for the particular conditions in a certain case-study region, they cannot be easily transferred to other areas without major modifications. The model itself and the collection and processing of the empirical data have to be adapted to the new situation. The Land-Use Dynamics Simulator (LUDAS), which has been applied in this study, was originally developed for an upland watershed in Vietnam, where the human and environmental components of the system show completely different conditions compared to the region under consideration in this study. As a rather new approach, LUDAS still awaits implementation in further case studies.

1.2.2 Integrated assessment of vulnerability to natural hazards

The above-described complexity also has to be considered when trying to capture the vulnerability of coupled socio-ecological systems to natural hazards. It requires the application of a comprehensive conceptual framework, which captures all relevant aspects of vulnerability (see Chapter 3). Furthermore, the framework and the assessment have to take into account the influences from levels other than the level of analysis as well as linkages and feedbacks between the human and environmental components of the system. In addition, the application of appropriate tools for data collection and processing is an important aspect that strongly influences the completeness of the results.

While the concept of vulnerability has become more prominent in recent years, analysis of its different facets has mainly concentrated on theoretical or descriptive work (Adger 2006; Alwang et al. 2001; Bohle 2001; Cardona 2003; Gallopin 2006). The implementation of integrated vulnerability assessments on the other hand has only rarely been attempted (Turner et al. 2003b). Simple approaches that focus on only one aspect of vulnerability have their own merits, as this concentration keeps the analysis comparably simple and can provide quick results with comparatively less effort. However, these approaches do not consider all relevant interlinkages and feedbacks and thus cannot provide a comprehensive vulnerability assessment of coupled systems.

The quantitative analysis of indicators according to the categories provided by an integrated vulnerability framework has been identified as an appropriate way to capture the multidimensionality of vulnerability and to detect underlying vulnerabilities beyond the direct impact of the hazard. Vulnerability assessments measure the potential impacts from hazards that might affect the system in the future, thus it is a forward-looking approach. However, the occurrence of a hazard may be used as a supporting means by analyzing the damages and from this analysis deduce the vulnerability to subsequent events. Although the assessment comes too late for this one particular event, the post-hazard approach increases the accuracy and the reliability of the results.

1.2.3 Linkages and feedbacks between LUCC and vulnerability

There are close linkages between land use and vulnerability (see section 3.4). In addition to direct connections, they both base upon the behavior of complex adaptive systems. It is thus a reasonable task to identify the linkages between land use and vulnerability and to show how they influence each other. However, due to the inherent complexity, a comprehensive analysis of both aspects is a challenging task, which is beyond the scope of most studies. They can only highlight the most important connections and thus outline directions for future specific research activities.

1.3 Objectives and Outline of Thesis

Based on the previous considerations, the overall goal of this study is to analyze land management and vulnerability to natural hazards of the coupled socio-ecological system around Balapitiya and Maduganga estuary, Sri Lanka, in an integrated manner by applying an agent-based model and conducting a comprehensive vulnerability assessment.

To achieve this goal, the specific objectives of the study are:

- To categorize livelihood groups and analyze human decision making with respect to land use, based on empirical data;
- To develop scenarios for sustainable land management and livelihoods by applying LUDAS as an integrated approach;
- To analyze vulnerability of the coupled socio-ecological system after the tsunami 2004 and to evaluate protective effects of coastal vegetation;
- To reveal and describe linkages between land use, ecosystem services, and the vulnerability of coupled socio-ecological systems.

Chapter 2 introduces the significance of human-induced land-use and land-cover changes and the need for an integrated research approach. It also gives an overview of challenges for LUCC modeling and of approaches to deal with these challenges with a special focus on agent-based approaches. Chapter 3 presents the concept of vulnerability and again discusses the necessity of integrated assessments. It also describes the vulnerability framework used in this study and highlights the particular vulnerability of poor people and of coastal systems. It also elaborates on the close linkages and feedbacks between vulnerability and LUCC. Chapter 4 gives an overview of the study site and the impacts of the tsunami on the area. Chapter 5 deals with LUDAS – it explains the conceptual framework of the model and differences between the original (VN-LUDAS) and the modified version applied in this study (SRL-LUDAS). It describes the collecting and processing of the socio-economic and the biophysical data that served as input for SRL-LUDAS. Chapter 6 presents the selected policy factors that can be changed by the model user. It also explains the interface of SRL-LUDAS and presents the results of the simulation process. Chapter 7 is dedicated to the vulnerability assessment in Balapitiya and the analysis of the protective effects of coastal vegetation. It is based on information concerning the impacts of the tsunami in 2004. Finally, Chapter 8 presents the conclusions, highlights linkages between land-use practices, ecosystem services, and the vulnerability of coupled socio-ecological systems, and provides recommendations for further research work.

1.4 Selection of study site

The tsunami that hit the coasts of several Asian and African countries on 26 December 2004 revealed the inherent and so far undetected vulnerability of many coastal communities with respect to this type of hazard. In addition to roughly 226,000 fatalities (EM-DAT 2010), the tsunami caused severe damage to houses and other assets, to infrastructure and to economic sectors such as tourism or fisheries. Even four years after the event, some people had not managed to recover completely. It is assumed that there are further aspects apart from the direct impacts of the waves that influenced the damage to humans and assets as well as the potential for recovery and subsequent vulnerabilities of the affected people. The intensive discussion in the aftermath of the tsunami on the protective effects of coastal vegetation serves as a good example for the interconnectedness between different components and the dependence of communities on ecosystem services. While provisioning services are relatively easy to analyze and to measure, the discussion revealed the difficulty of tracking the value of such regulating services.

After Indonesia, Sri Lanka was most severely affected by the impacts of the tsunami. Balapitiya on the southwestern coast of the island was chosen as study site for several reasons. Although there were only few fatalities in this area, the tsunami caused severe damages to houses, assets and infrastructure. Population density along the whole western and southern coast of Sri Lanka is very high, thus there is a strong pressure on ecosystems. Nevertheless, there are still some patches of degraded coastal vegetation in the study area, which might have the potential for providing protection during a natural hazard. Apart from the flat topography, the geography around Balapitiya is challenging due to the existence of an estuary in the hinterland of Balapitiya town. It is connected to the sea via an inlet, with a small island inside that inlet. The impact of the tsunami on the inlet as a special coastal feature was included in the analysis.

Maduganga estuary is of high ecologic importance and provides a large amount of ecosystem services to the communities living around it. It is one of the few places in Sri Lanka with intact mangrove stands, which are situated in small strips along the inlet and the estuary. Mangroves are known to provide various services to coastal communities, one of which is the protection against storm surges and cyclones (Dahdouh-Guebas et al. 2005; Das and Vincent 2009). This aspect makes mangroves an important feature for the resilience of socio-ecological systems.

The western and southern parts of Maduganga around Balapitiya show an urban setting, while the northern and eastern areas are more rural, and people there depend more on land resources for their livelihoods. This difference results in a diversity of livelihoods, which is a challenge for advanced land-use modeling that aims at simulating the decision making of all relevant agents.

The study areas for the simulation of LUCC and for the vulnerability assessment of this study only overlap in some areas. The vulnerability assessment focused on areas close to the sea, where the impacts of the tsunami were more severe. The land-use modeling concentrated on the region around the estuary, as urban livelihoods around Balapitiya are not land-driven. In spite of these discrepancies, the comprehensive empirical data collection for the modeling process provided important insights into the livelihoods of the communities in that area, which also proved to be helpful for the vulnerability assessment. Furthermore, direct conclusions concerning land use, the dependence on ecosystem services, and the vulnerability of the coupled system for the overlapping areas, which were mainly located along the inlet, could be drawn.

2 MODELING OF LAND-USE AND LAND-COVER CHANGES

2.1 Land-use and land-cover changes

Changes in land use and land cover (LUCC) are the most important impacts of human activities on the earth system (Vitousek et al. 1997). This human imprint on the earth's surface is steadily increasing, and through numerous interlinkages and feedbacks, affects the functioning of ecosystems and people's livelihoods, with the majority of these impacts being negative. While the term "land cover" summarizes the biophysical conditions on the earth's surface, "land use" describes the arrangements, activities and inputs of people in a certain land-cover type to produce, change or maintain it (GLP 2005).

Since man has learnt to control fire, humans have been changing the earth's surface to make use of natural resources and to increase their well-being (Vlek 2005). While modification of land merely took place on a comparably low level for a long time, human influence has increased significantly since the exponentially growing utilization of fossil fuels for energy production and the exponential rise in the world's population with its increasing demand for agricultural products began some 300 years ago (Ramankutty et al. 2006).

From 1700 to 1990, the global cropland area increased by a factor of 4.5 (from 3-4 to 15-18 million km^2), while at the same time the area under pasture increased around 6 fold (from 5 to 31 million km^2). This expansion took place to a large extent at the expense of forests, natural grasslands, steppes, and savannas. The forest area decreased from 50-62 million km^2 in 1700 to 43-53 million km^2 in 1990 (Lambin et al. 2003).

In the second half of the 20th century, the speed of LUCC has increased considerably and is unprecedented in human history (MA 2005; Lambin et al. 2001), so that, e.g., today roughly 40-50 % of the land areas are occupied by cropland or pastures (Ramankutty et al. 2005; Vitousek et al. 1997; Foley et al. 2005). According to estimations, more forests were converted to other land uses and agricultural expansion was greater between 1950 and 1980 than during the 150 years between 1700 and 1850, although there are also significant regional differences (Richards 1990). Most of the decrease in forest cover today takes place in tropical regions (Lambin et al. 2003). In other regions of the world, there has been stabilization or even a decrease in cropland area; this land has either been reforested or converted to urban or infrastructure use (Ramankutty et al. 2006). In tropical Asia, a decline in forest and woodland areas of 47 % between 1880 and 1980 was detected, while in the same period cultivated and urban areas increased significantly (Flint and Richards 1991). According to the Millennium Ecosystem Assessment, 24 % of the terrestrial surface consists of cultivated systems, which in addition to all kinds of cropping systems also include confined livestock systems as well as aquaculture (MA 2005).

Most scenarios predict a further increase in agricultural land of up to 40 % until the year 2100 (Alcamo and Busch 2005). The trend for future global development of forested areas is less clear due to uncertainties in fundamental drivers such as population and economic growth, whereas it seems evident that urban areas will continue to grow until 2025 or even beyond 2050 (Alcamo et al. 2006).

The effects of LUCC are not necessarily negative for people's livelihoods, as they often result in continuing increases in food production and in resource efficiency. Through these pathways, LUCC may contribute to a higher wealth and well-being of people (Lambin et al. 2003). Notwithstanding these local benefits, many LUCC have serious negative environmental impacts on a regional and global scale (Chhabra et al. 2005; Verburg et al. 2003; Lambin et al. 2001; Manson 2005; Huigen 2003; Metzger et al. 2006; Renaud 2006; MA 2005). They alter biogeochemical cycles (e.g., through the excessive input of nitrogen), have a direct impact on biodiversity and soil degradation, change water and radiation budgets, and contribute to regional climate changes as well as to global warming (Chhabra et al. 2005; Verburg et al. 2003; Lambin et al. 2001). Any kind of impact can be differentiated into small-scale drivers, which only affect the local environment, and impacts that extend far beyond their place of origin (Mustard et al. 2004). A particular threat for coastal zones comes from the excessive use of nitrogen, which eventually ends up in coastal waters and has severe impacts on water quality, damaging both fauna and flora (Foley et al. 2005; MA 2005).

Several decades ago, scientists started to work on LUCC issues when it was recognized that through modifications in surface albedo LUCC have an influence on the regional climate (Lambin et al. 2003). In the early 1980ies, the impact on global carbon budgets and consequently on global climate was highlighted and later, further impacts of LUCC such as changes in the water cycle, loss of biological species, as well as changes in soil structure and nutrient cycling were observed and analyzed (Lambin et al. 2003).

While it used to be reported that LUCC were caused by a limited number of explaining factors with population density being the most important aspect, this view has changed significantly. It is now widely accepted that LUCC are formed by a complex suite of underlying and proximate factors of biophysical as well as socio-economic origin. These rarely operate isolated from other factors and are always linked together, with numerous interactions and feedbacks between the different forces (Haggith et al. 2003; Lambin et al. 2003; Lambin et al. 2006; Liu et al. 2007).

More than 200 years ago, Malthus (1798) was the first to see a linkage between the need for food, and thus for agricultural land, and population growth. His main finding suggested that a geometrically growing population would result in food shortages and emigration, as agricultural land and thus subsistence can only grow arithmetically, until eventually all land is under cultivation. From today's point of view, the increase in population and the resulting need for additional space and food together with growing economic activity are still seen as some of the most important drivers on a global level (Huigen 2004; MA 2005; Geist et al. 2006). Some studies, however, conclude that population growth is not of major importance when looking at the regional level, and that flawed data distort analysis results and conclude a strong impact of population growth on LUCC (Angelsen and Kaimowitz 1999). With analytical tools becoming more sophisticated, it has become evident that not only population growth or density influence LUCC, but also additional aspects such as population composition and distribution as well as linkages to other factors such as agricultural intensification, access to resources, and land-related policies (Geist et al. 2006; Carr 2004; Rindfuss et al. 2004a).

The multiple causes for LUCC can generally be divided into two main categories: proximate and underlying causes. Proximate or direct causes are physical actions with a direct effect on the land. They are usually limited to activities related to agriculture, forestry, or infrastructure construction (Geist et al. 2006). They are mostly implemented at the local level by people having direct access to the land under investigation. Proximate causes are often shaped by underlying or root causes. These are much less tangible, because they operate more diffusely and on different levels of organization. Furthermore, they are multifaceted, as they may be of social, political, economic, demographic, technological, cultural, or biophysical origin. In contrast to proximate causes, underlying factors are out of the control of local land managers, but constitute the structural conditions in which they have to take decisions on land use (Geist et al. 2006; Mather 2006). They result from complex interactions and feedbacks between economic, political, and transnational institutions as well as social processes and are thus difficult to predict (Brown et al. 2004).

Some authors argue that globalization, i.e., “the worldwide interconnectedness of places and people through global markets, information, capital flows and international conventions, for example” (Geist et al. 2006, p.64), is a major factor influencing LUCC, although it is not a cause by itself. The impacts of globalization may be either positive or negative for people and ecosystems (Lambin et al. 2006; Young et al. 2006), although negative impacts surely prevail, especially in particularly fragile ecosystems, which are more vulnerable to any kind of external disturbances.

Many authors emphasize the complexity of drivers and causes of LUCC, which is intensified through the numerous interactions and feedbacks between the different relevant factors in the human and biophysical systems (Geoghegan et al. 1998; Rindfuss et al. 2004b; Lambin et al. 2003; Verburg et al. 2004; Geist et al. 2006; Walsh and Crews-Meyer 2002). Further complications arise from the different factors operating on different temporal and spatial scales that influence the dynamics of the coupled socio-ecological system (see Chapter 3) and that ideally all have to be integrated for comprehensive analyses (Huigen 2003; Verburg et al. 2003; Lambin et al. 2003). These multiple interactions and feedbacks also complicate any predictions on future LUCC. As nearly all global ecosystems are influenced by humans in one way or another, the importance of human decision making as one of the main aspects influencing the development of land has been increasingly recognized and has thus become a focus of analysis (Lambin et al. 2003; Verburg et al. 2003; see also section 2.2).

In addition to the impacts of LUCC already mentioned, the modification of land may also influence the vulnerability of people and places to different kinds of biophysical, economic, or socio-political perturbations (Lambin et al. 2006). This effect results from the close connection between the provision of ecosystem services and livelihood strategies especially in rural areas (see section 3.4). Due to several reasons, coastal systems are particularly vulnerable to the impacts of different hazards (see section 3.5).

2.2 Land-change science as an integrated concept

First attempts to model LUCC mainly focused on biophysical attributes due to the good availability of such data (Veldkamp and Lambin 2001). But the above-described complexity of LUCC and its multiple driving forces call for new multidisciplinary approaches (Agarwal et al. 2002; Veldkamp and Lambin 2001), which are sometimes summarized under the term “land-change science” (Geoghegan et al. 1998; Rindfuss et al. 2004b; Lambin et al. 2001; Manson 2005; Turner et al. 2007). The level of integration varies between the different approaches, with the most interdisciplinary effort being a joining of human and environmental science, complemented by geographical information approaches (Turner et al. 2007).

Most analyses on LUCC are conducted in form of place-based case studies, which seem to be most appropriate to link the different types of information and to not only describe LUCC, but also to increase understanding of the forces leading to these changes (Rindfuss et al. 2007).

The impacts of humans on ecosystems are a central aspect of LUCC, and therefore it is crucial to understand how people make land-use decisions, and what are the interactions of the various factors influencing their decisions (Lambin et al. 2003; Rindfuss et al. 2007). Thus, ideas and methodologies from social and economic sciences that can provide more insights into decision making as the main factor influencing land-use systems have become more important in recent years and are also increasingly integrated into modeling approaches (see sections 2.3 and 2.4).

Results from studies on LUCC are influenced by the temporal and spatial scales chosen, although literature mainly focuses on spatial scales that have a major impact on LUCC studies. Attempts to analyze LUCC – especially when they are rooted in the social sciences – often face difficulties, as the multiple influencing factors operate on various temporal and spatial scales (Parker et al. 2003; Gibson et al. 2000). Proximate factors acting on a local level are comparably easy to analyze, whereas the impacts of underlying factors often operating on a higher level are rather difficult to assess due to the multiple interlinkages and feedbacks involved (Turner et al. 2007; Brown et al. 2004). The factors have different impacts on different scales, thus studies carried out on a local scale might come up with completely different drivers for LUCC than a study on the regional or national scale (Verburg et al. 2004; Laney 2004; Park et al. 2003). Population growth may serve as an example, as it has significant effects on deforestation when looking at the national level, while it mainly serves as a proxy for other factors such as governmental policies or distance to markets on the local or regional level (Angelsen and Kaimowitz 1999). Furthermore, due to scale issues some factors are not considered when studies with a coarse resolution are not able to detect impacts on a local level. For example, a Landsat 7 ETM+ image with a resolution of 30 m x 30 m might miss some important land-cover information on the sub-pixel level. On the other hand, small-scale studies might overlook external forces that have an influence on land-use decisions on the local level (Verburg et al. 2004).

The hierarchy theory states that processes at one level are always influenced by the next higher and the next lower level, which thus form a so-called "constraint envelope". This envelope has to be taken into account during analysis when attempting to understand processes leading to LUCC (O'Neill et al. 1989; Gibson et al. 2000; Verburg et al. 2004).

Finally, it is important to consider that interactions between different forces are complex and rarely linear and are therefore even more difficult to analyze. This non-linearity results from the emergent properties of such complex systems (see section 1.1). These properties call for approaches that can deal with non-linear behavior of people, heterogeneous interactions, as well as learning and adaptation (Bonabeau 2002). The next sections present an approach that follows new ways of dealing with these issues.

2.3 Modeling land-use and land-cover changes

A model is a simplifying description of reality. The model developer has to decide if the model should be designed in a more complex manner and thus turned into a better description of reality, or whether the degree of simplification/abstraction should be enhanced in order to simplify the model and to advance its manageability.

Models from different disciplines tend to address the issue of LUCC at different levels of organization, varying from the household to the national or even global level. In general, there are two different approaches for dealing with this issue. While social and econometric approaches traditionally focus on individual behavior on the micro-level, natural scientists generally operate on the macro-level with a particular focus on spatial explicitness (Verburg et al. 2004).

Projections of future development of land use and land cover are the basis for proactive land management and sustainable use of natural resources (Dent et al. 1995), and they may help to identify vulnerable people and places with respect to the increasing influences of global change (Verburg et al. 2004). Spatially explicit modeling approaches can also support the communication of results of different developments to local stakeholders and thus stimulate discussions about different options for natural resource management (Verburg et al. 2004).

Future scenarios of land use and land cover call for an in-depth understanding of the proximate and underlying driving forces of observed historical LUCC. Spatially explicit models are to a certain extent able to fulfill these tasks and may thus also serve as scientific tools to support decision making.

Different methodological approaches have evolved for analyzing the driving factors of LUCC and for deriving scenarios for future development. There are several criteria for distinguishing between different types of LUCC models (Briassoulis 2000; Verburg et al. 2006). A first distinction can be made between spatial and non-spatial models. While non-spatial models focus on the rate and magnitude of LUCC, spatially explicit models also analyze where changes take place at a certain level of detail (Verburg et al. 2006). Other criteria for distinction are purpose of the modeling exercise, type of land use analyzed, temporal dimension of the model (i.e., if it is static or dynamic), spatial dimension, and the methodology used, with the latter two criteria being the most important (Briassoulis 2000; Verburg et al. 2003).

Most models mainly rely on statistical tools like regression analysis and other multivariate techniques for revealing the driving forces of LUCC. These approaches face shortcomings in capturing the complexity of the interconnected drivers for LUCC and particularly of the importance of human decision making (Parker et al. 2003; Laney 2004; Verburg et al. 2006). Most conventional approaches assume that local decision makers have perfect rationality and always opt for the utility that provides the highest returns. This implies that everybody is fully informed about outcomes and alternatives, and that decision making of all actors is homogeneous (Brown 2006; Manson 2004). Although the assumption of perfect rationality has some explanatory power, experiments have provided contradicting evidence, and thus alternative approaches have been developed (Parker et al. 2003). People face limits with respect to information and computational capacity, and tend to satisfice, i.e. they tend not to make optimal, but rather acceptable decisions by using simple heuristics. This will result in an outcome that is not perfect but good enough. Furthermore, people are able to learn from experience and adapt their decision-making mechanisms to new upcoming situations (Manson 2006; Manson and Evans 2007). Therefore, the paradigm of bounded rationality serves as the main tool for analyzing agent behavior in agent-based models on land use.

Other approaches include expert models, which rely on expert knowledge in combination with probability techniques or artificial intelligence (Parker et al. 2003). Cellular automata are another option for modeling LUCC. They are based on a grid of congruent cells, which change their state in the course of the modeling process due to "transition rules based on a local spatiotemporal neighborhood" (Parker et al. 2003, p.316). Like statistical approaches, cellular automata face difficulties when dealing with complex behavior and decision-making strategies that cannot be explained satisfactorily by transition rules (Parker et al. 2003).

From this brief review, it becomes clear that the complexity of coupled socio-ecological systems with their interlinkages and feedbacks and particularly the complexity of human decision making are the main challenges in developing a tool that can reproduce reality and derive accurate assessments of future LUCC and at the same time be understandable and manageable. Therefore, agent-based models have been developed that attempt to capture this complexity by using a new approach.

2.4 Agent-based modeling of LUCC

As mentioned above, some significant difficulties arise when modeling LUCC in complex socio-ecological systems. These are heterogeneity of agents, emergence, complexity of decision making, and interactions and feedbacks between different human and biophysical elements of coupled socio-ecological systems. Agent-based models (ABMs) tackle these challenges by using simulation, which is in contrast to the traditional approaches that follow inductive or deductive methodologies (Axelrod 2003; Castle and Crooks 2006). For simulating decision making, ABMs also apply elements of deduction and induction, e.g., when starting with a set of assumptions concerning human behavior and interactions, but which are not used to prove theorems. Instead, the model generates data that are analyzed in an inductive manner. In contrast to typical induction, which relies on the measurement of empirical data, simulated data are produced by specified set of rules (Castle and Crooks 2006). Based on this new approach, simulation can be seen as a third way of doing science in addition to induction and deduction (Axelrod 2003).

Analyzing human decision making forms the core of an ABM. The actors, who make decisions on land use in their respective environment, are called agents. An agent is "a real or abstract entity that is able to act on itself and on its environment; which can, in a multi-agent universe, communicate with other agents; and whose behavior is the result of its observations, its knowledge and its interactions with other agents" (Verburg et al. 2004, p.311). The characteristics of agents, as outlined in this definition, enable the modeler to capture the complex behavior of agents and inter-agent relationships as well as relationships of agents with their environment in a coupled socio-ecological system (Bonabeau 2002; Ligtenberg et al. 2004; Macal and North 2006; Castle and Crooks 2006). Autonomy as one of the key characteristics of agents describes their ability to achieve goals, as they have control over their actions. This ability is based on a certain degree of cognition with varying specifications (Rindfuss et al. 2007). Thus, simulations have to use approaches that are able to deal with the complexity of human decision making with its interconnections, feedback processes, the ability to learn and to adapt, heterogeneities, and lack of information. To solve this issue, a range of models of human decision making exist, from simple heuristics to bounded or full rationality (Verburg et al. 2005).

Other modeling approaches such as System Dynamics predefine the relationship between human and environmental components via equations. The discussion so far showed that this procedure does not provide a realistic description of real decision-making processes. In contrast to ABMs it also does not account for the ability of agents to learn and to adapt to new situations. Compared to traditional modeling approaches, ABMs have three major advantages: (1) they capture complexity, particularly emergent phenomena as a major property of complexity, (2) they provide a natural description of socio-ecological systems, and (3) they are highly flexible (Bonabeau 2002; Castle and Crooks 2006).

Together with nested hierarchies, non-linearity, interactions between system components, openness of the system, and path dependence, emergence is an important characteristic of complex land-use systems (Parker et al. 2003; Brown et al. 2004; Huigen 2003; Castle and Crooks 2006; Henrickson and McKelvey 2002; Batty and Torrens 2001). The system behavior depends on its current condition, but also on its history, which is expressed by the term path dependence (Brown 2006). ABMs follow bottom-up approaches when modeling human decision making, as behavior and interactions develop during the simulation process, while in traditional approaches human behavior is predefined in the form of differential equations (Castle and Crooks 2006; Huigen 2003).

A complex system is defined as an open system, which is in contact and exchange with its environment. This implies the impossibility to reach an equilibrium, which is a prerequisite in many traditional, static models and also in systems theory, which was the main theoretical paradigm before complexity theory entered the scene (Matthews et al. 2005; Batty and Torrens 2001). ABMs provide a natural description of complex systems in general and socio-ecological systems in particular, as it is easier to describe and simulate the complex behavior of agents than attempting to model it with equations, which are not suitable for capturing the exponentially rising complexity of a system and thus the aggregate properties of the system under investigation (Bonabeau 2002; Castle and Crooks 2006).

Finally, ABMs offer multiple dimensions of flexibility. It is possible to add more agents to the simulation process if necessary, and all these agents are mobile, which is of particular importance for geospatial modeling. Furthermore, the framework of ABMs provides greater flexibility for tuning the complexity of agent behavior with its degree of rationality, its ability to learn and to adapt to new situations, and its rules for interactions. There are also different possibilities for aggregating agents, from single agents up to larger groups on higher levels of organization (Bonabeau 2002; Castle and Crooks 2006; Parker et al. 2003).

ABMs are able to operate on different temporal and spatial scales, which is necessary to capture all relevant aspects influencing LUCC (Huigen 2004). This indicates one of the major difficulties when dealing with ABMs. This multidimensionality and the complexity of socio-ecological systems and human decision making require a large amount of data at multiple organizational scales, which sometimes might be difficult or expensive to obtain or to generate (Verburg et al. 2005; Manson and Evans 2007).

In conclusion, ABMs are a still young but promising approach in the field of LUCC analysis due to their numerous advantages, and therefore are receiving increasing attention within the land-change science community (Alcamo et al. 2006; Rindfuss et al. 2007).

3 VULNERABILITY OF COUPLED SOCIO-ECOLOGICAL SYSTEMS

3.1 Vulnerability as a comprehensive approach

The world is undergoing rapid environmental and socio-economic changes. Processes such as population growth, urbanization, and poverty but also environmental degradation, climate change, and the increasing occurrence of natural disasters affect the social and economic development in many parts of the world. These growing influences of humankind on the earth are summarized under the term “global change” (Steffen et al. 2005; Vitousek 1994), and have led some scientists to declaring a new geological era, the “Anthropocene” (Crutzen and Stoermer 2000; Steffen et al. 2005). Although this development also generates positive outcomes such as increases in food production and resource-use efficiency (Lambin et al. 2006), most of them have multiple adverse consequences for people and ecosystems (Chhabra et al. 2005; Lambin et al. 2001; Renaud 2006).

The increase in the frequency and magnitude of certain natural hazards such as windstorms, floods, or droughts in recent decades is one of the negative impacts of global change (Figure 3.1). This increase is mainly due to the rise in weather-related events. Some types of natural hazards are indirectly triggered by anthropogenic activities such as land degradation or the combustion of fossil fuels. Global environmental change and especially the anthropogenic interference of the earth’s climate system lead to the warming of the atmosphere, which in turn is expected to have an increasingly severe impact on climate patterns in general and on the frequency and magnitude of extreme climate events in particular (UN/ISDR 2004).

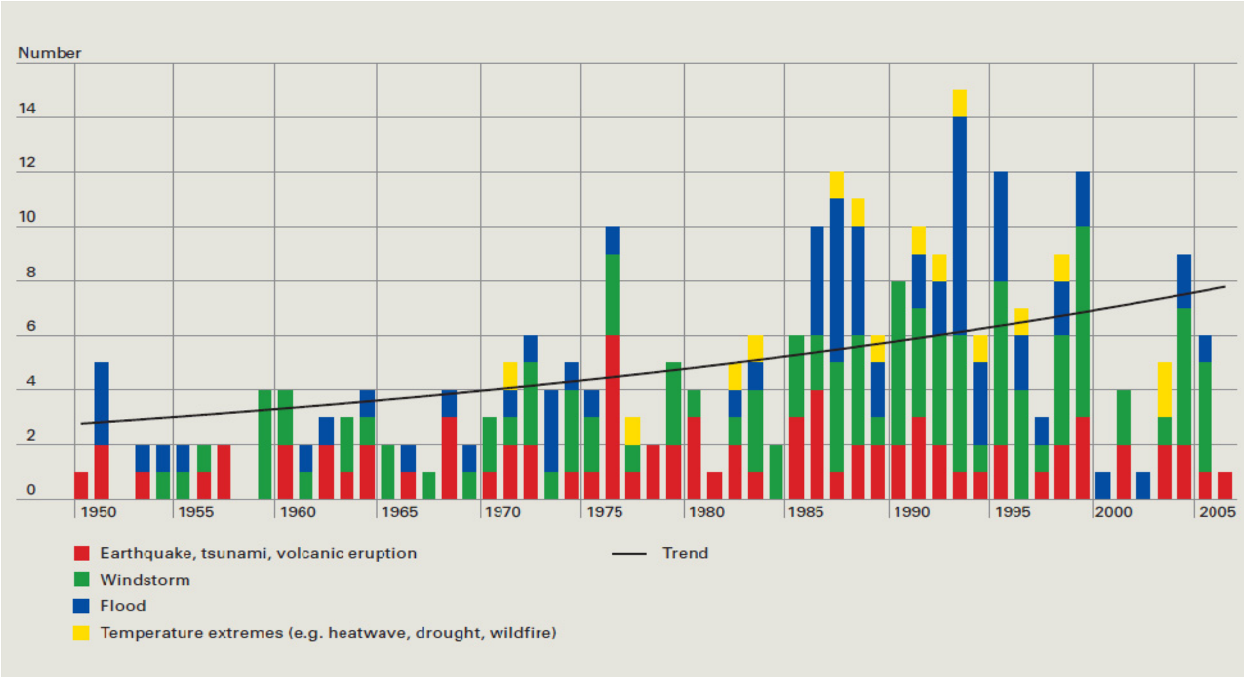

Figure 3.1: Number of great natural catastrophes for the period 1950 to 2006. Natural catastrophes are classified as "great" when "the affected region's ability to help itself is clearly overstretched and supraregional or international assistance is required". Source: Munich Re 2007.

Natural hazards such as hurricanes, earthquakes, droughts or storm floods cause immense human and economic damages. Due to the observed and predicted increases in hazards and damages, attempts to analyze the impacts of hazards and related vulnerabilities have been intensified in recent decades. It has been recognized that natural hazards are not catastrophes by themselves, but only turn into such when they affect human lives and assets. This notion has been emphasized by the former secretary general of the United Nations, Kofi Annan: "Natural hazards are a part of life. But hazards only become disasters when people's lives and livelihoods are swept away." (Annan 2003). This aspect has led to a shift of focus, from the hazard itself and technical measures to minimize the impacts of hazards, to the interplay of the damaging event and the vulnerability of a society and of its infrastructure, economy and environment (Birkmann 2006). People are no longer only seen as victims of disturbances, but it is acknowledged that they have certain means to cope with risks and adapt to changes (UNEP 2007). This process of focusing on humans and their livelihoods started in the 1970's (Villagrán De León 2006). It has also been described as a paradigm shift, not only with regard to vulnerability but also to human security in general as well as to poverty issues (Thywissen 2006).

The concept of vulnerability is approached from different disciplines and domains such as academia, disaster management agencies, the climate change community and development agencies (Villagrán De León 2006). This results in a multitude of definitions for vulnerability and related terms like exposure, risk, and resilience, depending on the approach adopted (Schneiderbauer and Ehrlich 2004; Gallopin 2006). A comprehensive review of various approaches was conducted by Thywissen (2006), who collected 35 different definitions for the term vulnerability alone. Two common definitions give a first idea about the different features of the concept.

- 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, p.16)
- For the United Nations Development Programme (UNDP) vulnerability is “A human condition or process resulting from physical, social, economic and environmental factors, which determine the likelihood and scale of damage from the impact of a given hazard.” (UNDP 2004, p.11)

Both definitions underline the multidimensionality of the concept and, particularly in the case of UNDP, stress the focus on humans as the center of the approach.

Notwithstanding the different notions of the concept, there are a few criteria that are commonly agreed to be important aspects of vulnerability. First, 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).

Exposure identifies the parts of a system (people, ecosystems, houses, infrastructure, etc.) that are at risk of being affected by a natural hazard or another disturbance, and it also quantifies this risk (Thywissen 2006). Its focus is more on the impact of a hazard, while the other two aspects highlight the internal structure of the affected society. Thus, there is a general tendency to divide the concept of vulnerability into two main parts. Bohle (2001) was one of the first to bring these two aspects into a framework in which he distinguished between "exposure" as the external side of vulnerability and "coping" as the internal side. Cardona (2003) calls it "physical fragility" (exposure) in contrast to socio-economic fragility, and Adger et al. (2004) use the terms "biophysical" and "social vulnerability". In this approach, the socio-economic factor combines the aspects sensitivity/susceptibility and resilience.

Sensitivity or susceptibility describes 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. Influencing aspects are generally the access to different kinds of assets such as income, land, occupation, type of house, or political power (Cannon et al. 2003; Alwang et al. 2001; Cutter et al. 2003). Sensitivity is also particularly related to human assets, which comprise factors such as age, gender, or health. In addition to properties of the households, this aspect explicitly also covers the sensitivity of infrastructure and ecosystems, as it directly influences the sensitivity of people living around them (Adger et al. 2005; UNEP 2007; Villagrán De León 2008).

The third category has been given several names with slightly different meanings, although the terms resilience, adaptive capacity, and coping capacity tend to show strong overlapping (Thywissen 2006). Resilience is a concept originating in ecology, where it "determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist" (Holling 1973, p.17). Later, the concept was transferred to 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). As for vulnerability, the utilization of the term "resilience" is not consistent (Carpenter et al. 2001). Thywissen (2006) provides 14 different definitions for resilience and resiliency. There is a tendency to view resilience as an all-encompassing term, where coping capacity includes strategies immediately after an event as well as longer-term recovery (Thywissen 2006; Schneiderbauer and Ehrlich 2004). One common definition describes social resilience as "the ability of groups or communities to cope with external stresses and disturbances as a result of social, political and environmental change" (Adger 2000, p.347). In all disciplines, resilience describes the magnitude of disturbance that can be absorbed before a system changes its structure (Adger 2000; Carpenter et al. 2001). Another relevant term in this regard is adaptive capacity, which describes the learning component of a system, i.e., the capability to adapt to new circumstances (Carpenter et al. 2001; Gallopin 2006). Adaptation and adaptive capacity have become particularly prominent in the discussion on the impacts of climate change, which force societies to adapt to changes such as sea-level rise and changes in precipitation and temperature patterns.

Another commonly agreed characteristic 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). The concept of vulnerability extended the traditional impact-focused view by moving the human into the center of analysis. In order to cover all aspects that impact on the vulnerability of coupled 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 any analysis (Thywissen 2006; UNEP 2007; Few 2003). This integrated approach has to be complemented by the multi-scale properties of potential disturbances and how they impact on the system (Gallopin 2006).

The complexity of vulnerability is further enhanced by its site-, level- and hazard-specific nature. Communities might show different vulnerabilities to different hazards, thus one of the first questions to be asked is "vulnerability to what?" (Cardona 2003; Birkmann and Wisner 2006; Gallopin 2006; Makoka and Kaplan 2005). Another important point to be considered before conducting a vulnerability assessment is "vulnerability of what?", as different vulnerabilities may emerge on different levels. A household will definitely show different vulnerabilities to a community or a country (Birkmann and Wisner 2006; Adger et al. 2004; Villagrán De León 2006; Few 2003). This scale dependence also applies to varying geographic scales, which might be influenced by different parameters (Thywissen 2006; Downing and Ziervogel 2004; Adger et al. 2004).

3.2 Frameworks for analyzing vulnerability

Multiple frameworks have been developed from various disciplines to capture the complexity of vulnerability, with different foci on particular elements of vulnerability. A comprehensive summary and comparison of the most important approaches has been conducted by Birkmann (2006). It is the common goal of all approaches to conceptualize the linkages between the impacts of a hazard (exposure) and the inherent vulnerability of the system under consideration, with an emphasis on the latter aspect (Birkmann 2006).

One major difference between the approaches arises from the inclusion of different elements under the term vulnerability (Figure 3.2). Starting from vulnerability as an intrinsic risk factor, the next level includes the particular focus on humans. Further steps also consider the double structure of vulnerability, which consists of susceptibility and coping capacity or, in the case of Bohle (2001), the internal and the external (exposure) aspect. In the last steps, the concept is widened to a multidimensional approach, finally also including the complex interlinkages between physical, economic, social, environmental, and institutional components.

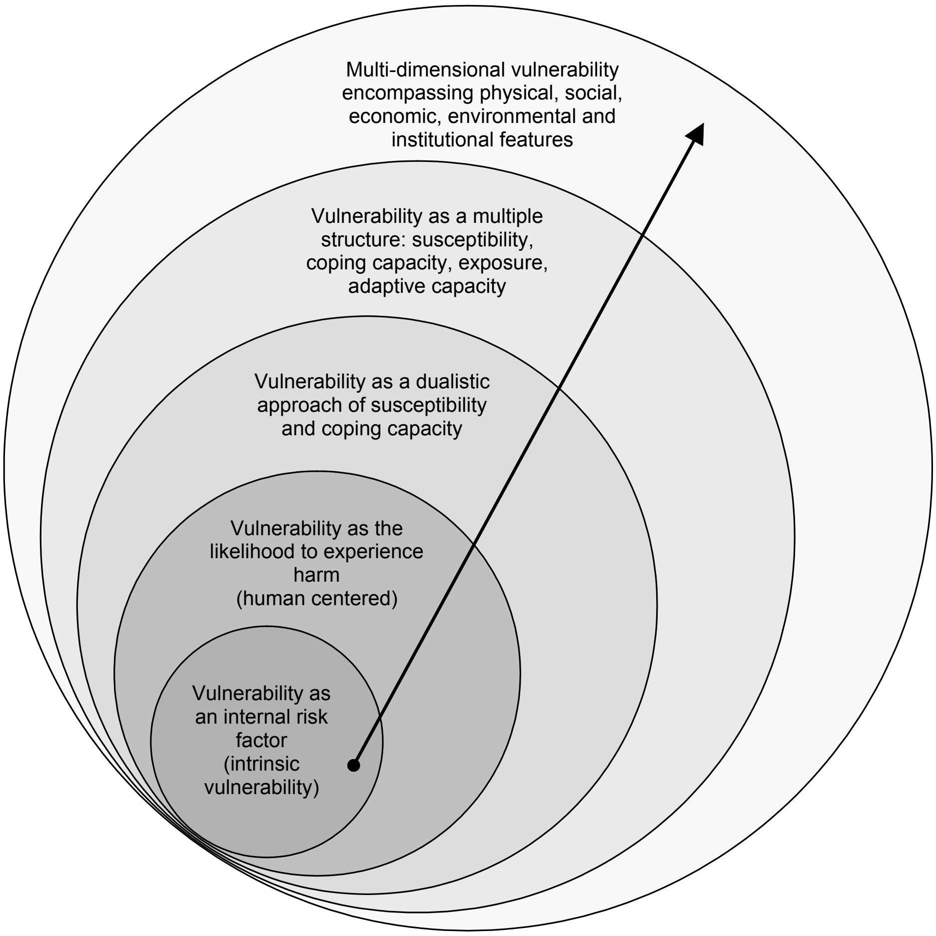

Figure 3.2: Key spheres of the concept of vulnerability. Source: Birkmann 2006.

One of the most comprehensive frameworks has been developed by Turner et al. (2003a). It focuses particularly on the interlinkages and feedbacks between social and ecological components of a system and thus does not restrict analyses to humans but rather looks at the integrated vulnerability of socio-ecological systems. The developers see vulnerability in a wider context of global environmental change and a sustainability science, which aims to understand the functioning and interlinkages of human-environment systems as a reaction to these ongoing global changes (see section 3.4).

In order to capture complexity and its impacts on the vulnerability of coupled socio-ecological systems, the Turner framework operates on multiple levels and emphasizes the importance of the linkages and feedbacks between these levels (Figure 3.3).

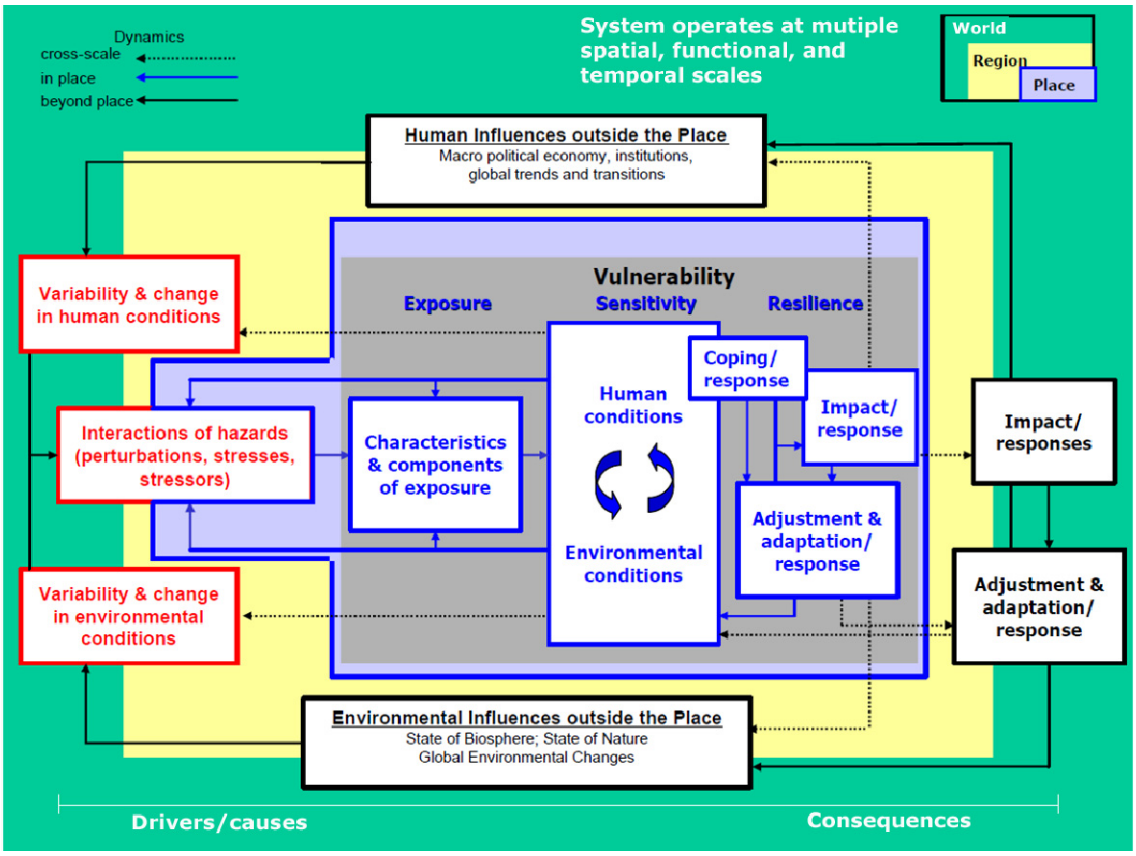

Figure 3.3: Vulnerability framework. Components of vulnerability identified and linked to factors beyond the system of study and operating at various scales. Source: Turner et al. 2003a.

The figure shows the complexity the concept, and the developers themselves state, that a comprehensive vulnerability analysis is unrealistic, but that time and data constraints will lead to a “reduced” assessment (Turner et al. 2003b).

The framework consists of 3 main elements. The local vulnerable system under consideration (1) including its exposure and response to disturbances is at the core of the framework. It is impacted by various perturbations and stressors (2) that emerge from the human and biophysical conditions operating on higher hierarchical levels (3).

The vulnerable system (Figure 3.4) is described by its exposure, sensitivity, and resilience, as well as the interlinkages between the different elements of the system. The framework particularly emphasizes the feedbacks between social and biophysical sub-systems, which imply that changes in one sub-system also influence the state of the other sub-systems.

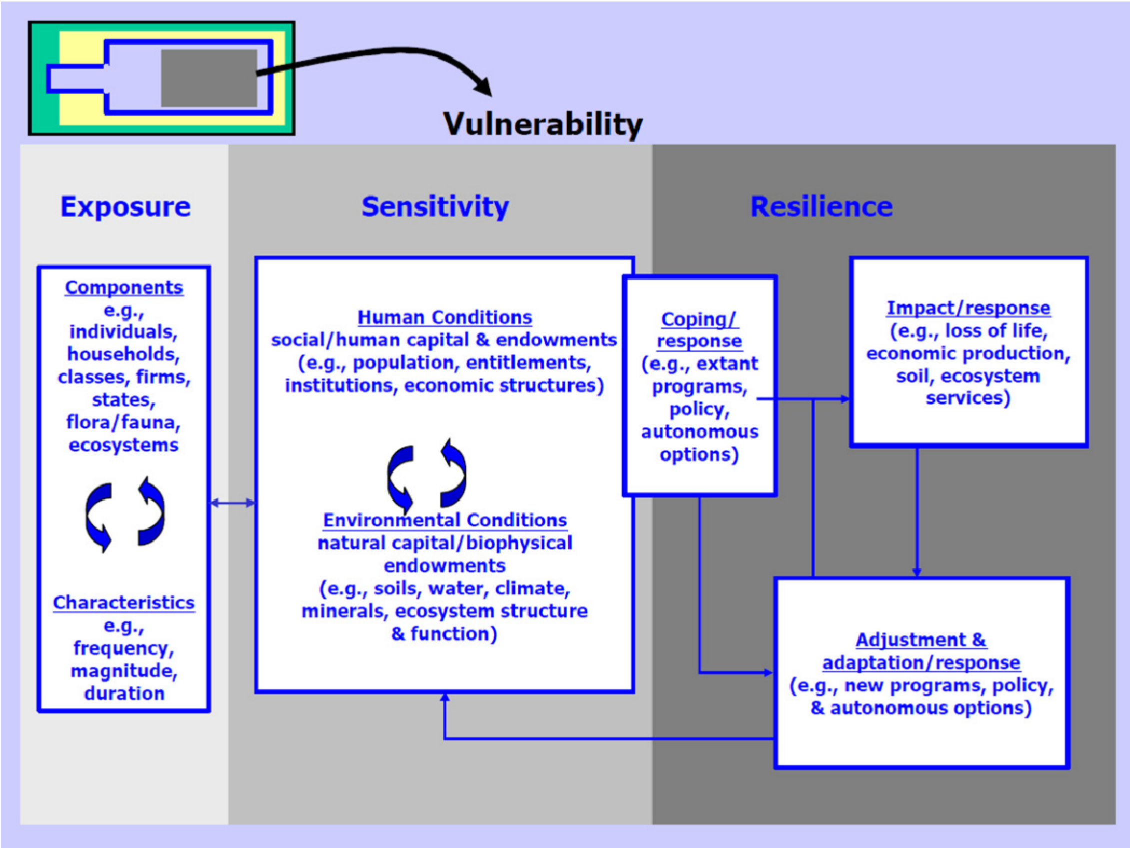

Figure 3.4: Details of the local coupled system of the vulnerability framework. Figure at the top left refers to the full framework illustrated in Figure 3.3. Source: Turner et al. 2003a.

Apart from this broad approach of vulnerability, the consideration of multiple scales and the coupled system as the element of analysis, there are further aspects of particular importance in the Turner framework. It is recognized that within a coupled system there is not only one vulnerability, but that subsystems and components of the coupled system show different vulnerabilities. Another aspect of relevance is the "interactions of hazards" (Figure 3.3), which illustrates that hazards are a combination of different perturbations and stressors, and that they arise from influences on different levels. They can also be affected by the system itself, thus the characteristic of a hazard is always place-specific. The framework particularly emphasizes the complexity and nonlinearity of hazards, which emerge from multiple influences of the interlinked elements on different scales.

3.3 Vulnerability and poverty

Vulnerability is often equated with poverty. However, vulnerability is particularly distinguishable from poverty through its dynamic approach. Poverty only measures the current state, whereas vulnerability has a predictive perspective (Thywissen 2006; Cannon et al. 2003; Alwang et al. 2001; Schneiderbauer and Ehrlich 2004). Notwithstanding these differences, there are strong connections between the two elements. 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 2003; Few 2003; Makoka and Kaplan 2005; GTZ 2005; Prowse 2003). This applies to exposure as well as to sensitivity and resilience. Poor people often live in more exposed areas, as they do not have a choice where to settle and thus have a higher risk of being affected by a hazard (Few 2003). Additionally, they dwell in less resilient houses and have less access to information. Thus, poor people tend to suffer more from the direct impacts of hazards (Figure 3.5). After an event, they have fewer possibilities to recover and to adapt to any changes, as they have less access to various kinds of assets (Alwang et al. 2001; Schneiderbauer and Ehrlich 2004). Poorer people often depend directly on the natural resources surrounding them, which further contributes to their increased vulnerability (see section 3.4).

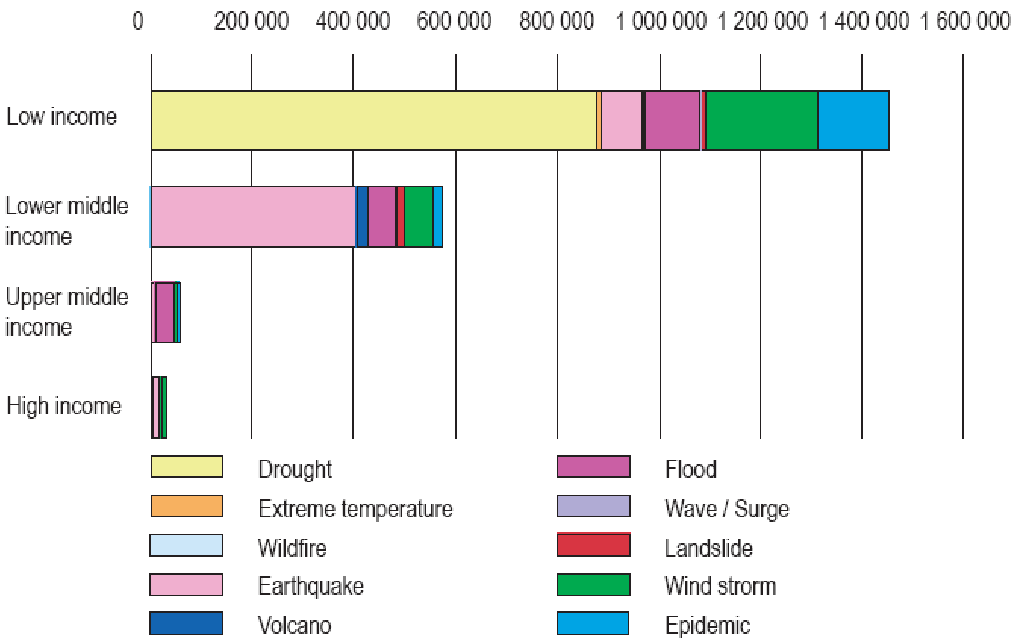

Figure 3.5: Number of people killed (income class/disaster type), world summary 1973-2002. Source: UN/ISDR 2004.

This connection between vulnerability and poverty does not only apply to differences in wealth within a country (Figure 3.5), but also to differences between developed and developing countries. In terms of human losses, developing countries are more severely affected by natural hazards than developed countries. 90 % of all fatalities from natural hazards occur in developing countries (UN/ISDR 2004). The likelihood of death in a disaster is four times higher for poor people in developing countries than for those people living in high-income countries (GTZ 2005). For every person killed in developing countries, around 3,000 more are affected by natural hazards and become severely impoverished through destruction of personal assets, damage to health and education infrastructure, and loss of drinking water and sanitation (GTZ 2005). This aspect also shows that the connection between poverty and vulnerability also works the other way round, i.e., not only that poor people are more vulnerable to disturbances, but also that disturbances and natural hazards can increase the poverty of people affected by these events (Hoogeveen et al. 2004).

In addition to poverty and access to assets, there are further aspects shaping the vulnerability of people. Women may have fewer possibilities to recover after an event due to lower wages or sector-specific employment, and because they also have to take care of the family. People with physical handicaps such as older people, children, and disabled persons have greater difficulty to protect themselves in case of an event. Finally, households with jobs that rely on resource extraction face particular difficulties in recovering after an event when the respective resource has been affected (Cutter et al. 2003; see section 3.4).

Taking the linkages between vulnerability and poverty into account, many authors and organizations have recognized the importance of mainstreaming preventive measures for disaster risk reduction and of reducing underlying risk factors and vulnerabilities to hazards (Birkmann 2006; UN/ISDR 2005; Few 2003; UNEP 2007). The Hyogo Framework for Action states that "there is now international acknowledgement that efforts to reduce disaster risks must be systematically integrated into policies, plans and programs for sustainable development and poverty reduction, and supported through bilateral, regional and international cooperation, including partnerships" (UN/ISDR 2005, p.1).

Due to these linkages between vulnerability and sustainable development, the Sustainable Livelihoods Framework (DFID 2001) plays an important role when analyzing vulnerability. While attempting to analyze people's livelihoods in a comprehensive manner, the vulnerability context is a crucial part of the framework (DFID 2001). It is kept rather general and includes all kinds of shocks, trends, and seasonalities that may affect the assets of a household. The focus of this concept is mainly on a comprehensive analysis of the different asset categories, on transforming structures and processes and the resulting livelihood strategies, thus it is not intended to be used as a framework for analyzing vulnerability. However, with the growing focus on people's livelihoods when analyzing vulnerability, the Sustainable Livelihoods Framework can serve as a valuable tool to capture the livelihoods of the people under consideration.

3.4 Integration of LUCC and vulnerability

The consideration of the interlinkages and feedbacks of the various components of social and biophysical systems is of central importance when attempting to analyze the vulnerability of coupled systems comprehensively. Changes in land use and land cover have a strong impact on the conditions of biophysical sub-systems and are thus most relevant for the vulnerability of coupled systems. Therefore, the link between the social and biophysical components, which is mainly established through the provision of ecosystem services, is of particular relevance for this study and deserves special consideration (Figure 3.6).

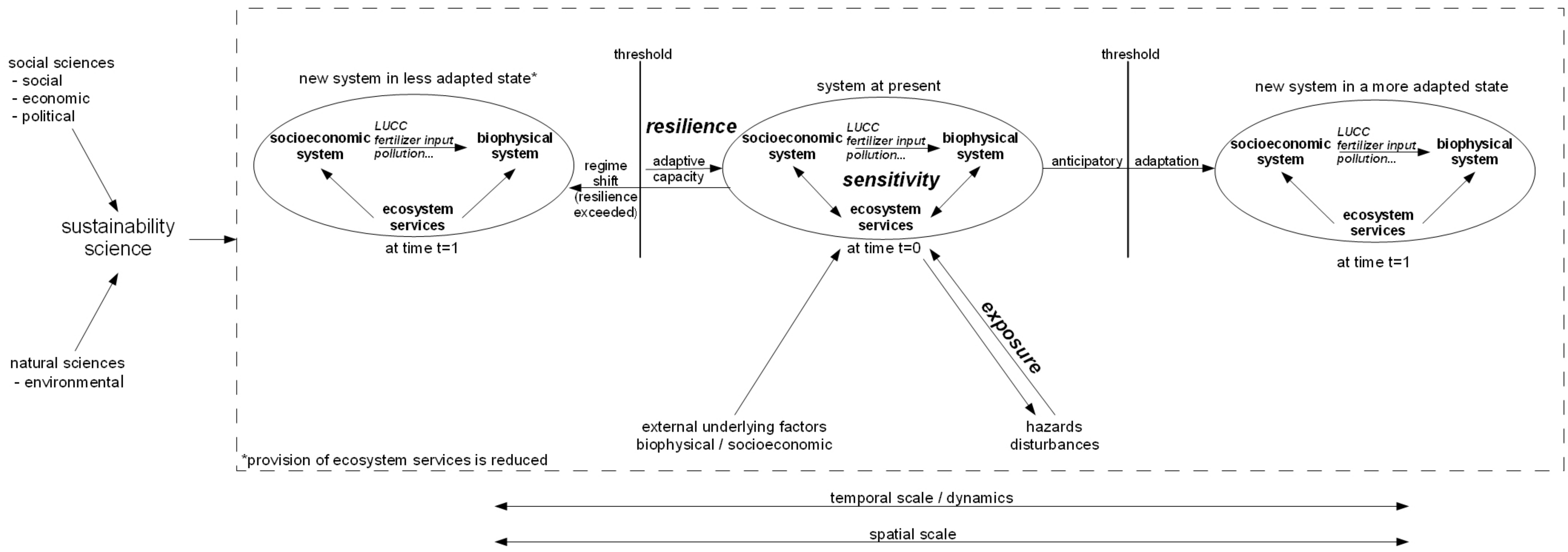

Figure 3.6: Interlinkages between vulnerability/resilience and ecosystem services in coupled socio-ecological systems. Source: own design.

The system in the center is the starting point of the conceptual framework and depicts the coupled socio-ecological system under consideration, which features the properties of complex adaptive systems. The system not only has a certain degree of vulnerability but also a certain resilience to external disturbances. The resilience is formed by the capacity of the system to withstand these disturbances and by its adaptive capacity, which allows the system to adapt to changes in external parameters while at the same time keeping its structure and function. Once a threshold is passed, the system shifts into a less adapted state or regime, in which its capacity to provide ecosystem services is reduced. On the other hand, the awareness and anticipation of potential disturbances may lead to measures strengthening the structure of the subsystems and thus the resilience of the whole system. When such modifications include major changes in variables of the system including how people use and depend on ecosystem services, the system shifts to a new state, in which it is more adapted to different threats. The non-linearity of processes and feedbacks has been particularly described for complex socio-ecological systems (Folke 2006; Berkes et al. 2003; Parker et al. 2008; Young et al. 2006). As a further characteristic, these systems are open and thus subject to external influences of various origins (e.g., Anderies et al. 2004). The dashed outer square in Figure 3.6 frames the system under consideration together with its corresponding influences, and thus defines the object of analysis for any integrated research activities related to vulnerability and resilience assessments.

The main connection between the socio-economic and the biophysical components of the coupled system is established through the provision of various types of ecosystem services (Adger 2000; Adger et al. 2005; Lambin et al. 2001; Renaud 2006), which can be divided into supporting, provisioning, regulating, and cultural services. These services contribute to livelihoods and human well-being through various pathways (Figure 3.7). In contrast to provisioning services, other types of services are more difficult to decipher and to translate into measurable values and are thus often excluded from any analysis, although their contribution to the resilience of a coupled system is often of central importance (Barbier 2007).

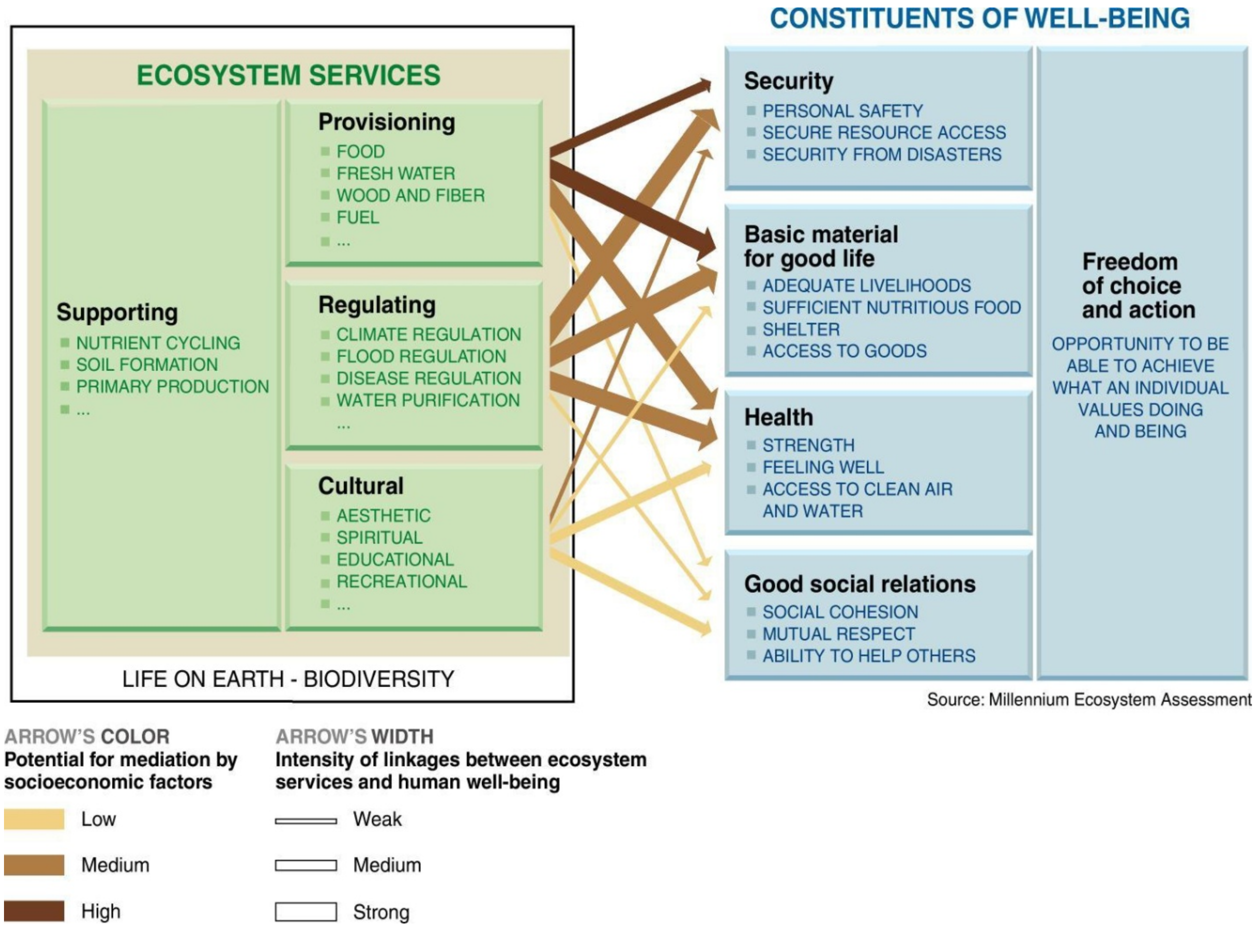

Figure 3.7: Linkages between ecosystem services and human well-being. Source: MA 2005.

The conditions of the three components of the system – the socio-economic and the biophysical subsystem and ecosystem services – and the interactions between them generate the overall sensitivity of the system, which determines its capacity to deal with any disturbances (Verburg et al. 2002). Due to their importance for livelihoods, ecosystem services have to be given particular attention when dealing with vulnerability (Renaud 2006; Metzger et al. 2006; Lambin et al. 2001; Cutter et al. 2008). This refers especially to poorer communities, as their livelihood strategies often depend directly on the ecosystems and the resources surrounding them. In order to secure their livelihoods, communities might tend to increase their dependence on ecosystem services in an unsustainable way and thus overuse them. This leads to a long-term decrease in services and thus affects livelihoods. Through this pathway, the state of ecosystems can significantly influence the vulnerability and resilience of communities (Cutter et al. 2008; UN/ISDR 2004; UNEP 2007; Sudmeier-Rieux and Ash 2009). The dependency on these services and the resulting vulnerability of communities may only become visible in case of a hazard that affects the provision of ecosystem services, and thus people's livelihoods and the structure of the whole system.

People manipulate the environment and thus also the provision of services in various ways, such as through changes in land use and land cover, fertilizer application, and the input of contaminants (Foley et al. 2005; Lambin et al. 2001; Renaud 2006; Metzger et al. 2006). Worldwide, 15 out of the 24 major ecosystem services are being degraded or used unsustainably. While on a global level, most of the benefits from provisioning services such as food, water and timber are still increasing, many cultural and in particular regulating services such as regulation of diseases, natural hazards and climate or water purification have decreased, with human modification of ecosystems being one of the main contributors (MA 2005). Many human activities impacting ecosystems have positive effects for communities in the beginning such as rising yields due to increased fertilizer input. However, in the long run they may show adverse impacts on livelihoods due to unsustainable management practices and the degradation of ecosystems. One of the most prominent examples is deforestation in mountainous regions, which can trigger flash floods after extensive rainfall. Natural forests have the potential to reduce the impacts of small-scale flooding events, while this effect is smaller under plantation forests or other land uses (Calder 2005). Another example can be found in coastal zones, where intact mangroves protected the people during a super cyclone that hit the coast of Orissa, India, in 1999 (Das and Vincent 2009). Furthermore, ecosystem-related activities might not benefit the local communities, who nevertheless have to cope with possible long-term negative effects of a conversion, when these changes are initiated by external investors. In the northwestern part of Sri Lanka, mangroves have been converted into industrial shrimp farms (Karunathilake 2003), which soon suffered from diseases due to overstocking and other unsustainable management practices. Thus, the ponds had to be abandoned after some years. The pond owners left bare and unusable land, and reforestation with natural vegetation is only slowly taking place, while in the meantime the land cannot be used by the local people.

The reduced provision of services again feeds back negatively on livelihoods and the vulnerability of the people in two ways. People are more exposed to natural hazards when they are not protected by specific types of ecosystems such as coastal vegetation. Furthermore, the lack of provisioning services hampers the economic recovery after an event, particularly when the income is mainly generated through, e.g., farming, which directly depends on services provided by soils (Marre and Renaud 2010).

The relationship between the three elements of the core system is further complicated through trade-offs among ecosystem services when, e.g., agricultural productivity is increased at the expense of forest cover, water quality, or biodiversity. People tend to prefer provisioning to regulating services, because they provide direct and measurable benefits (Carpenter et al. 2006; Parker et al. 2008). This feeds back on resilience, as regulating services are of particular importance for the ability of coupled socio-ecological systems to cope with various kinds of external disturbances (Carpenter et al. 2006).

The framework proposed in this study also depicts the shaping of vulnerability of the coupled system through external underlying factors. Referring to the complexity and multidimensionality of vulnerability, these comprise all biophysical, economic, social, cultural, and political aspects, which are not directly part of the system but have a strong impact on its vulnerability, either by influencing livelihoods directly or through manipulating ecosystems within the system. The factors impact on the exposure of a system as well as on its sensitivity and resilience. As they are not directly part of the system and operate more diffusely and on different levels of organization, they are less tangible than proximate factors, which are part of the core system. Underlying factors are out of the control of local people, but constitute the structural conditions in which they have to take decisions on land use and livelihood strategies (Geist et al. 2006; Mather 2006). Due to the complex interactions of economic, political, and transnational institutions and social processes, they are difficult to track and to predict (Brown et al. 2004).

Coupled socio-ecological systems may be severely affected by natural hazards or other disturbances. These impacts can emerge directly by destroying valuable land covers and making it impossible for them to recover, e.g., through the salinization of agricultural soils from sea water. The impact of a hazard may also manifest itself indirectly by affecting livelihoods such that people have to intensify land use and land-use practices in an unsustainable way in order to compensate for losses. Altogether, the occurrence of a hazard may reveal the vulnerability of certain land covers and the services they provide, which might not have been realized by the community before the event. The structure of the coupled system on the other hand may also influence the occurrence or the characteristics of a hazard, e.g., when unsustainable land management triggers desertification in dryland areas.

The consideration of the temporal and spatial scale are two important components in the framework, which impact on the system under consideration. The hierarchical organization of complex systems results in emergent properties and thus uncertainty and non-linearity. Additionally, the influence of different factors on different scales applies to both the spatial and the temporal scale (Huigen 2004; Park et al. 2003; Veldkamp et al. 2001; Laney 2004; Carpenter et al. 2001; Vogel and O'Brien 2004; Downing et al. 2005). Population, for example serves as an important influence on land-use changes at aggregate scales, while at local to regional scales it does not (Geist et al. 2006). Another example is given by Veldkamp and Lambin (2001), who describe the different parameters of importance influencing land use on various levels. While at the farm scale, social and accessibility variables are most important, topography and agro-climatic potential are relevant on the landscape level. Finally, at the regional and national scale, climatic variables as well as macro-economic and demographic factors have the strongest influence on land use. With regard to community resilience, the structure of livelihoods, entitlements, and access to resources are seen as important drivers on the household scale, while at the national scale purely economic indicators such as the Gross Domestic Product are often seen as adequate parameters for measuring resilience (Cutter et al. 2008). Temporal scale also includes the dynamic aspect as an inherent feature of vulnerability and resilience, because vulnerabilities of systems can be subject to substantial change over time due to changes in important influencing factors (Carpenter et al. 2001; Folke 2006; Cutter et al. 2008; Luers et al. 2003).

The overarching goal of all efforts related to alleviating vulnerability and increasing resilience is the sustainable development of the systems under consideration. To achieve this, sustainability science has evolved focusing particularly on the dynamic interactions of nature and society in all its different facets (Kates et al. 2001; Jäger 2006; Clark 2007; Wu 2006; Clark and Dickson 2003). It emerged from the growing awareness of the close connections between human and environmental systems, the deficiency of disciplinary approaches, and as a reply to the multiple challenges of global change (Raven 2002). Sustainability science is an integrated approach for analyzing and understanding the behavior of complex coupled socio-ecological systems (Swart et al. 2004; Clark and Dickson 2003). In contrast to other research fields, it is not driven by the disciplines it is based on, but rather by the problems it addresses, and which shape the toolbox being used for conducting a study (Clark 2007). In order to capture all relevant drivers, sustainability science combines tools, methodologies, frameworks, and theories of different scientific fields from natural and social sciences. This includes quantitative as well as qualitative approaches. Studies related to sustainability science have to refer to those issues brought up by the properties of complex adaptive systems. They have to deal with multiple temporal and spatial scales, and they have to consider complexity of connections between system components as well as uncertainty, thus resulting in a wide range of possible outcomes. Furthermore, these studies should produce knowledge relevant for policy makers and stakeholders, and which has to be fed into decision-making processes (Swart et al. 2004; Kates et al. 2001; Wu 2006). Sustainability science also explicitly creates the link to vulnerability and resilience of coupled socio-ecological systems that have to be analyzed in the course of these integrated types of studies (Wu 2006; Kates et al. 2001).

At this stage, the framework proposed here is not intended to be operationalized through any indicators or other tools, as this study made use of the Turner and the Sustainable Livelihoods Framework as two available operational frameworks. Its objective is rather to depict and emphasize the importance of ecosystems and their services for the resilience of coupled systems within the course of this combined study. Furthermore, it focuses on the adaptive capacity of a system, i.e., its capacity to modify its behavior and properties between certain thresholds beyond which it changes into another regime. The framework is kept simple in order to focus on the most important linkages and feedbacks without sacrificing clarity due to too many details. Summarizing the connections between socio-economic and biophysical systems under ecosystem services illustrates the need to quantify all different types of services. Until now, regulating, cultural, or supporting services have been largely neglected.

These changes in complex adaptive systems have intensified in recent decades. They are increasingly pushed by different aspects of global change, such as deforestation, overuse of natural resources, declining biodiversity, and global as well as regional climate change. Population growth together with a total and per-capita increasing food and energy consumption pushes this development further (Metzger et al. 2006). These linkages contribute to the intensification and complexity of the interconnections between the social and the ecological components (Young et al. 2006), and thus also affect their combined vulnerability to any disturbances. Due to this development, the vulnerability of coupled socio-ecological systems is still increasing in many parts of the world (Metzger et al. 2006; Berkes et al. 2003).

3.5 Coastal vulnerability

Coastal zones produce disproportionately more services than other areas, and people living in coastal areas often experience higher well-being (MA 2005). While coastal zones only cover about 6 % of the earth surface, they provide approximately 38 % of the value of global ecosystem services (Costanza et al. 1997). They provide marketable goods like fish and tourism, but also contribute to nutrient recycling and provide support for terrestrial and estuarine ecosystems, habitats for plants and animals, and the satisfaction people derive from simply knowing that a beach or coral reef exists (Wilson et al. 2005). Many coastal ecosystems serve as filters for upstream nutrients and are thus highly fertile. Some are valuable nursery grounds for fishes and other marine organisms. Fishery is a major food source and economic activity in most coastal zones around the world, and industrial activities tend to concentrate along coasts due to favorable transport conditions. Recreation and tourism are further important economic factors for many countries as well as for livelihoods of local communities (MA 2005). When transferring all coastal services into a monetary value, coastal systems account for approximately 43 % of the estimated total value of global ecosystem services, although they cover only 8 % of the world’s surface (Costanza et al. 1997). Sub-national sociological data report that people living in coastal areas experience higher well-being than those living in inland areas. The world’s wealthiest populations live primarily in coastal areas, and the per capita income is four times higher in coastal areas than inland. Life expectancy is higher in coastal regions, while infant mortality is lower

(MA 2005). Furthermore, they have the potential to provide protection from natural hazards like storm surges or tsunamis (see Chapter 7). All this shows that due to their diversity, coastal systems allow for multiple economic activities and are thus more resilient against shocks than systems benefiting only from a small number of resources (Adger 2000). However, economic marginalization and restricted access to resources imply that many people do not benefit from this potential for increased wealth (MA 2005).

The attractiveness of coastal regions also has severe downsides. Coastal ecosystems are under immense stress due to high population density and the overexploitation of natural resources. The average global population density within 100 km of the shoreline is 112 persons/km^2, which is 2.5 times higher than the average global value (Valiela 2006). Demographic trends show that coastal populations are increasing rapidly, mostly through migration, increased fertility, and tourism. Currently, nearly 40 % of the world's population lives within 100 km of the coast (MA 2005). This value is still 10 % when only considering the high-risk areas with an elevation of up to 10 m, although this area only comprises 2 % of the world's land mass (McGranahan et al. 2007). Particular threats are the overexploitation of natural resources such as fuelwood, timber, and sand through industrial activities or local people, but also eutrophication, waste disposal, shipping, recreation, or aquaculture. All these activities lead to the degradation and loss of habitats and ecosystem services. The global overexploitation of fisheries resources has become a particular threat for the livelihoods of local people, who might loose one of their main food sources as well as an economic activity of major importance. The negative impact of humans on coastal habitats is further aggravated by the fact that people in coastal areas tend to settle close to sensitive ecosystems such as estuaries and mangroves (Affeltranger et al. 2005; MA 2005). 71 % of the global coastal population lives within 50 km of estuaries; in tropical regions settlements are concentrated close to mangroves and coral reefs (MA 2005). Coastal ecosystems are also under further pressure of human activities in remote areas, as many have negative impacts on coastal zones, e.g., excessive use of fertilizers, which eventually end up in coastal waters.

The increased exposure of coastal systems to multiple hazards is another important aspect contributing to their vulnerability. They are exposed to threats such as storm surges, tsunamis, hurricanes, flooding, and sea-level rise and also to technical hazards such as oil spills or industrial accidents.

Coastal zones therefore are particularly vulnerable systems. Furthermore, the large number of different stakeholders results in numerous different interests and objectives and makes the development of sustainable coastal zone management plans a challenging task (McFadden and Green 2007).

3.6 Materials and methods

Issues related to changes in land use and land cover as well as to the vulnerability of coupled socio-ecological systems can only be tackled comprehensively by using a set of different scientific tools from different scientific fields and combining the results in an integrated and interdisciplinary approach (see Chapters 2 and 3). Thus, this research employed different frameworks and methodologies and combined them for a comprehensive analysis of important issues related to sustainable land management and sustainable livelihoods in the study area. The Sustainable Livelihoods Framework and particularly its asset categories were employed for both the data collection for the LUCC modeling and for the vulnerability assessment in order to capture people's livelihoods. The vulnerability assessment was conducted using the Turner framework, which puts particular emphasis on the linkages between the different social and biophysical elements of the system and the influences from various scales. Particular consideration was given to the impact of various ecosystem services on communities along the lines of the framework introduced in section 3.4.

The analysis of changes in land use and land cover as the second major scientific issue of this study was carried out by applying an agent-based model (ABM), as ABMs are particularly strong in simulating the influences of human decision making and the non-linearity of complex systems. The data collection and processing for the simulation employed a variety of different tools such as remote sensing, spatial analysis with Geographic Information Systems (GIS), multivariate statistics to identify livelihood groups and factors influencing decision making as well as differences in vulnerabilities of different livelihood groups, vegetation surveys, extensive household surveys, expert interviews, and the evaluation of secondary data such as scientific literature, governmental reports, and statistics.

4 STUDY SITE

4.1 Sri Lanka

The island of Sri Lanka covers 65,610 km^2 and lies between 6° and 10° N and 79° and 82° E. It has a tropical climate dominated by the monsoonal periods, and the temperature remains between 27 and 28°C in the lowlands throughout the year (CEA and Arcadis Euroconsult 1999). The heavier monsoon from May to August particularly affects the southwestern parts of the country, while the northeastern monsoon from October to January affects the northern and eastern parts of the country.

These climate characteristics lead to a subdivision of the island into three different rainfall zones (Figure 4.1):

- The dry zone occupies most areas of the north, east, and southeastern part of the island; annual average rainfall is below 1,000 mm;
- The wet zone is in the southwestern part of the country, where rainfall is higher than 2,500 mm;
- Between the dry and the wet zone lies the intermediate zone with 1,500 to 2,500 mm annual rainfall.

These zones are further divided into agro-ecological zones.

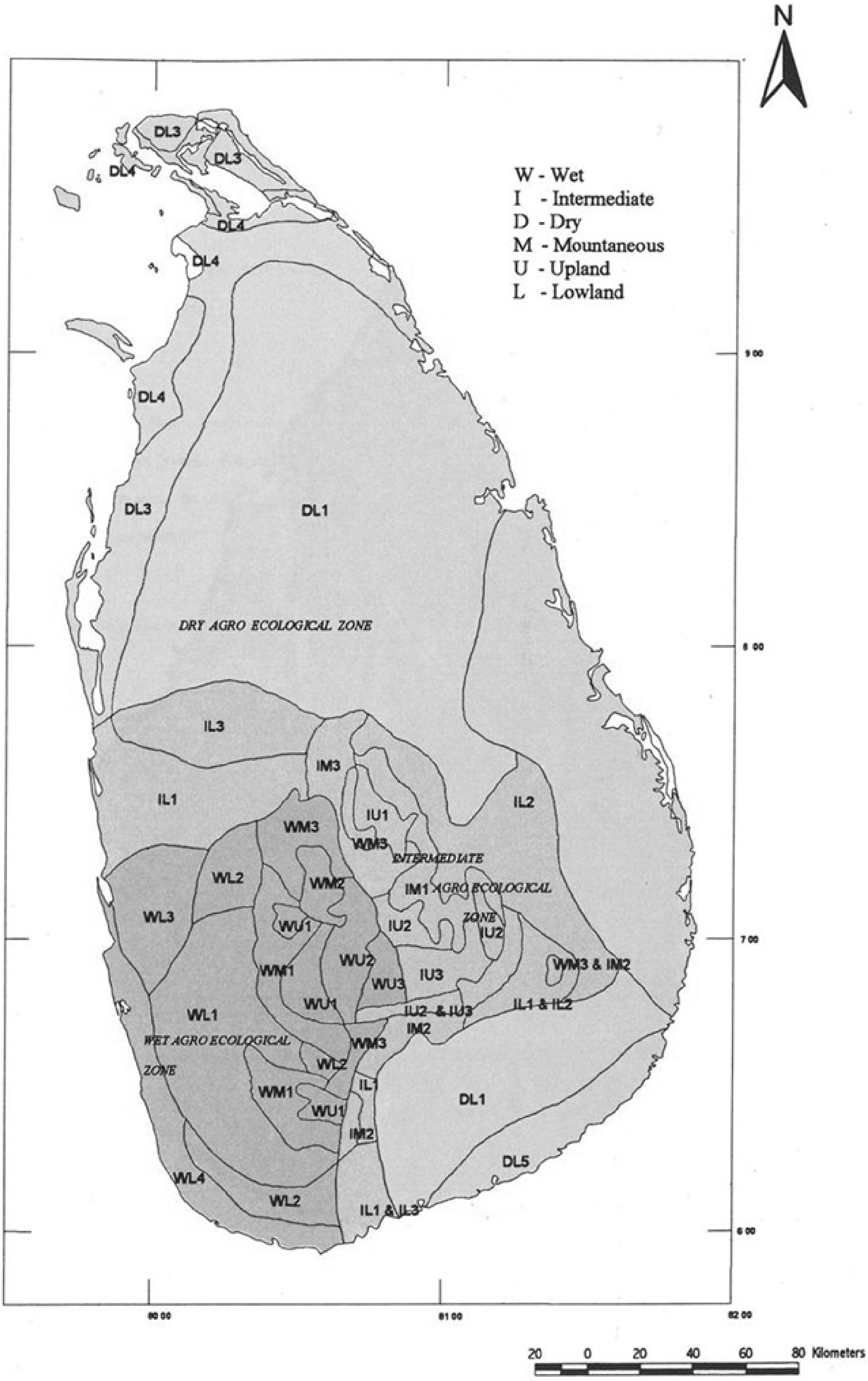

Figure 4.1: Agro-ecological zones of Sri Lanka. Source: CEA and Arcadis Euroconsult 1999.

Sri Lanka has a population of 19.9 to 21.1 million people (DCS 2007; CIA 2008) with an annual growth rate of 1.1 % from 1975 to 2005 (UNDP 2007a). This rate is expected to drop to 0.4 % between 2005 and 2015 (UNDP 2007a). With a share of

82 % of the population, the Sinhalese are the main ethnic group in the country. The other groups are Moors (7.9 %), Indian Tamils (5.1 %), and Sri Lankan Tamils (4.3 %) (DCS 2007). The country has one of the highest population densities in the world (300 people per km^2) with most people living in the southwestern coastal areas and particularly around Colombo, the capital city (DCS 2007; CEA 2005). Most Sri Lankans are Buddhists (69.3 %), while Muslims make up 7.6 % of the population, Hindus 15.5 %, and Christians 7.6 % (DCS 2007).

The GDP is US$ 4,100 per capita at purchasing power parity (US$ 4,595 according to UNDP 2007) with 16.5 % coming from agriculture, 26.9 % from industries, and the remaining 56.5 % from services (CIA 2008). The annual growth rate of the GDP is 7.7 % (DCS 2007). In addition to the ethnic conflict, the high inflation rate (19.7 %; CIA 2008) has been a major obstacle for Sri Lanka's economic development.

The Human Development Report (UNDP 2007a) ranks Sri Lanka 99 (out of 177) with a Human Development Index of 0.743. The educational standard of the population is relatively high with a literacy rate of 90.7 % of all inhabitants over 15 years of age and nearly all children finishing primary and most of them also secondary school. However, poverty is a widespread phenomenon: 41.6 % of the population has to live on less than US$ 2 per day and 5.6 % on less than US$ 1. One quarter of the population lives below the national poverty line. The poverty line is derived from a nutrition-based anchor and the "cost of basic needs" method and calculated on a district level (DCS 2004). It is readjusted every month.

4.2 Coastal ecosystems and the impacts of the tsunami in Sri Lanka

The length of the Sri Lankan coastline is 1,620 km (CCD 2004a). The coastal zone (Table 4.1) is defined as the area within 300 m landward of the mean high water line and a limit of 2 km seaward of the mean low water line. In the areas around rivers, streams, lagoons, or any other body of water connected to the sea either permanently or periodically, the landward boundary of the coastal zone extends to a limit of 2 km landward (CCD 2004a).

The coastal zone contains some highly valuable ecosystems with rich biodiversity (Table 4.1). However, it also comprises 65 % of the country's urbanized areas, and is of utmost importance for the economic development of Sri Lanka. 40 % of the GDP comes from this region with 70 % of the total industrial output with an increasing tendency. Furthermore, it is by far the most important area for tourism-related activities with 80 % of the tourist infrastructure located in the coastal zone (UNEP 2001). It thus has a dense network of transport infrastructure (Samaranayake 2006). In addition to industry and tourism, fishing is the major economic activity along the Sri Lankan coast and also a very important source of protein for the local people. Before the tsunami in 2003, fishing contributed 3 % to the GDP and employed 300,000 people with about 1 million people depending directly and indirectly on the fisheries sector (Samaranayake 2006). Agriculture on the other hand is much less important and is mainly relevant in form of small-scale subsistence farming for poorer people (Samaranayake 2006). Most of these activities require healthy ecosystems as sources for provisioning and cultural services. Additionally, some coastal ecosystems such as coral reefs, mangroves or dunes also have a regulating function by stabilizing coastlines, trapping sediments and reducing coastal erosion (CCD 2004a).

Table 4.1: Most important coastal habitats in Sri Lanka. Source: Samaranayake 2006.

Habitat	***Area (ha)***
Estuaries and lagoons	158,017
Mangroves	8,687
Salt marshes	23,819
Sand dunes	7,606
Beaches, spits	11,800
Marshes	9,754
Other water bodies	18,839

But like many coastal areas worldwide, the Sri Lankan coasts are also subject to various threats, which are due to a combination of population growth with its consequent intense utilization of coastal resources and a particular vulnerability of the affected ecosystems to disturbances (CCD 2004a). The main threats are coastal erosion, sand and coral mining, the overexploitation, degradation, and transformation of habitats, as well as the degradation of water quality (Samaranayake 2006).

The Sri Lankan government has recognized these threats. In addition to management of coastal erosion, controlling coastal water pollution, and integration of coastal fisheries and aquaculture, the conservation of coastal habitats is one of the main issues of the coastal zone management plan (CZMP), which serves as the overall guidance for all coastal development issues in Sri Lanka (CCD 2004a). These conservation efforts shall be conducted in a way that also considers the livelihoods of the local people and their needs for the utilization of coastal resources.

The tsunami in December 2004 affected the whole eastern coastline of the island, as well as the southern and the western coasts up to Negombo, slightly north of Colombo. The impact of the waves on coastal ecosystems varied significantly, as it was subject to various influences such as the location but also local features like bathymetry, coastal topography, as well as structure and composition of the respective ecosystem. The structure of an ecosystem depends to a large extent on its modification by humans, and the impacts of the tsunami revealed a general trend that disturbed ecosystems showed less resistance to the impacts of the tsunami (Appanah 2005; Cochard et al. 2008; Lacambra et al. 2008). The major impacts were erosion of beaches, increased salinity, modification of coastal structures, and destruction of coastal vegetation and coral reefs (UNEP 2005; UNEP and MENR 2005; Appanah 2005). While some coastal species such as *Casuarina*, *Borassus* (Palmyrah Palm), *Eucalyptus*, *Oleander*, and *Ipomoea* were either uprooted by the waves or suffered from later increased salinity, other species proved to be more resistant. In addition to *Cocos nucifera* (coconut palm), which managed to resist comparably well, mangroves were often reported to have withstood the tsunami waves (UNEP 2005; UNEP and MENR 2005; Appanah 2005). Another study reported the remarkably high resistance of *Casuarina* and *cocos nucifera* to the waves on the southern coast of India (Mascarenhas and Jayakumar 2008). There, only the first line of trees close to the shore was affected, while the other stands remained more or less intact and recovered quickly.

Many reports after the tsunami stated that mangroves not only resisted the waves, but also dissipated wave energy and thus protected lives and assets behind the vegetation belts (Appanah 2005; UNEP and MENR 2005; IUCN 2005; Mamiit and Wijayaweera 2006). Since then, this topic has been subject to intense debate and, in addition to mainly anecdotal reports, scientific studies tried to find evidence of a protective function of mangroves or other types of coastal vegetation (Chang et al. 2006; Chatenoux and Peduzzi 2005; Cochard et al. 2008; Dahdouh-Guebas et al. 2005; Danielsen et al. 2005; Iverson and Prasad 2007; Kathiresan and Rajendran 2005; Kumar et al. 2008; Lacambra et al. 2008; Latief and Hadi 2006). Most studies saw coastal vegetation as one factor reducing the destructive force of the tsunami waves in addition to other aspects such as coastal topography, bathymetry, and distance from the origin of the event. Most of them also emphasized the importance of the composition and structure of the vegetation belt, such as species composition, density, age, height, and width of the forest. Chatenoux and Peduzzi (2005) published the only study that did not report any protective effect of mangroves at all, as mangroves are only found in sheltered areas such as estuaries and protected bays. Thus, they conclude that areas with mangroves were naturally less affected due to their sheltered location. Other authors generally negate any buffering effects of mangroves and question some of the results on this issue (Baird 2006; Baird and Kerr 2008; Kerr et al. 2006; De Silva 2005).

The complexity of the discussion on this topic can be best shown using the study by Kathiresan and Rajendran (2005). They compared the tsunami death tolls of 18 coastal hamlets in southern India. By applying linear regression, they found distance to the sea, elevation of the hamlets, and coastal vegetation in and around the hamlets as the main factors causing the different death tolls. This study was followed by an intense scientific discussion, published in the same journal, on the correctness and applicability of the methodologies applied in the study (Kerr et al. 2006; Kathiresan and Rajendran 2006; Vermaat and Thampanya 2006; Vermaat and Thampanya 2007). This discussion, which did not come to a final solution, shows how difficult it is to find the solution for such a complex issue, which is subject to various influencing factors, depending on the location of the analysis. There is also no generally agreed rule on which statistical or other methodologies should be used for analyzing the protective effect of coastal vegetation with regard to natural hazards.

Most of the mentioned studies applied different statistical methodologies, sometimes supported by remote sensing, to determine factors influencing water height and tsunami damage including the protection of coastal vegetation (Danielsen et al. 2005; Kathiresan and Rajendran 2005; Iverson and Prasad 2007; Chatenoux and Peduzzi 2005). Other studies relied on field observation and comparison of pre- and post-tsunami conditions (Dahdouh-Guebas et al. 2005), literature reviews (Cochard et al. 2008; Lacambra et al. 2008; Latief and Hadi 2006), and remote sensing together with inundation mapping (Kumar et al. 2008).

Furthermore, there have been several attempts to analyze the hydrodynamics in mangrove forests via numerical simulation modeling (Massel et al. 1999; Mazda et al. 1997; see also Cochard et al. 2008), some of them with special regard to tsunami waves (Yanagisawa et al. 2009; Harada and Kawata 2004). These studies highlight the various influencing parameters such as forest density, stem diameter, tree height, species composition, wave period, and wave height. These multiple parameters make it nearly impossible to determine composition and width of a mangrove forest necessary to give partial or complete protection to people living behind it.

4.3 Mangroves in Sri Lanka

Pressure on ecosystems in Sri Lanka mainly results from high population density, together with unsustainable land management practices, expansion of industries, and urbanization (UNEP 2001). The extent of the various forest types decreased steadily from an overall 80 % of the land area in 1881 to about 24 % in 1992 (UNEP 2001). About one third of the land is being used for agricultural purposes today. Agricultural land use is heavily influenced by shifts during the colonial past of Sri Lanka from traditional subsistence farming systems to commercial cash crop plantations (Samaratunga and Marawila 2006). However, the conversion of agricultural land for settlement and industrial purposes is still ongoing (Samaratunga and Marawila 2006). These developments create a strong pressure on ecosystems and natural resources, which is particularly relevant in coastal zones due to their high population density, exploitation of natural resources, and a concentration of industrial and tourism activities (UNEP 2001).

Mangroves are woody plants growing in the interface between land and sea in the tropics and sub-tropics between approximately 25°N and 30°S (Valiela et al. 2001). The warm and humid tropics provide them with the best conditions for maximum production and growth (Schwamborn and Saint-Paul 1996). They prefer sheltered, inter-tidal areas with low wave energy (Alongi 2002). The environment is characterized by high salinity, tides, strong winds, and muddy, anaerobic soils. Thus, the mangroves developed mechanisms to deal with these conditions such as excreting salt through specialized glands in the leaves. Morphological specializations include lateral roots to anchor the trees in the loose sediment, or exposed aerial roots that ensure gas exchange when partly submerged (Kathiresan and Bingham 2001). Other characteristics are viviparous embryos and the tidal dispersal of propagules in order to ensure reproduction (Alongi 2002).

Mangroves are highly productive ecosystems providing multiple services. They trap sediments and thus stabilize coastlines and reduce erosion, and provide people with various products such as timber, fuelwood, fruits, honey, or medicines. During the survey around Maduganga many respondents also mentioned the utilization of mangrove bark for the dyeing of fishing nets. Mangroves also protect the coastline from hurricanes and storm floods and are of high value for fishery, as they serve as nurseries for various types of marine organisms such as fishes and shrimps (Kathiresan and Bingham 2001). Finally, they provide habitats for birds and other valuable fauna and have a potential for generating income for local people through tourism activities (Manassrisuksi et al. 2001; UNEP-WCMC 2006).

Due to the specialization mentioned above, mangroves are particularly prone to human- or natural-induced disturbance. The conversion of mangroves into ponds for shrimp aquaculture is the biggest threat to mangroves worldwide and accounts for approximately 50 % of their losses (Valiela et al. 2001). Further threats result from the overexploitation of mangrove resources and from agricultural, industrial, and urban development (Valiela et al. 2001; UNEP-WCMC 2006; Alongi 2002).

While mangroves in Sri Lanka covered around 12,000 ha during the 1980ies, this area has decreased to an extent between 8,700 ha (Samaranayake 2006; WRI 2003) and 9,500 ha (FAO 2005). Other sources even mention an area of only 6,000 ha (CCD 2004a). It is assumed that the island lost roughly 50% of its mangrove cover from 1986 to 2002 (CCD 2004a). The mangroves in Sri Lanka are comprised of around 20 to 25 true mangrove species and 18 mangrove associates (Amarasinghe 2004; Jayatissa et al. 2002). As the area inundated by tides is rather low in Sri Lanka and restricted to a narrow belt along the coast, the extent of mangroves is proportionately low (Amarasinghe 2004; CCD 2004a). Mangroves are particularly found in less populated regions and also in the areas affected by war in the northern and northeastern part of the island, while in the south and southeast they are restricted to small patches around estuaries, lagoons, and river mouths (Figure 4.2).

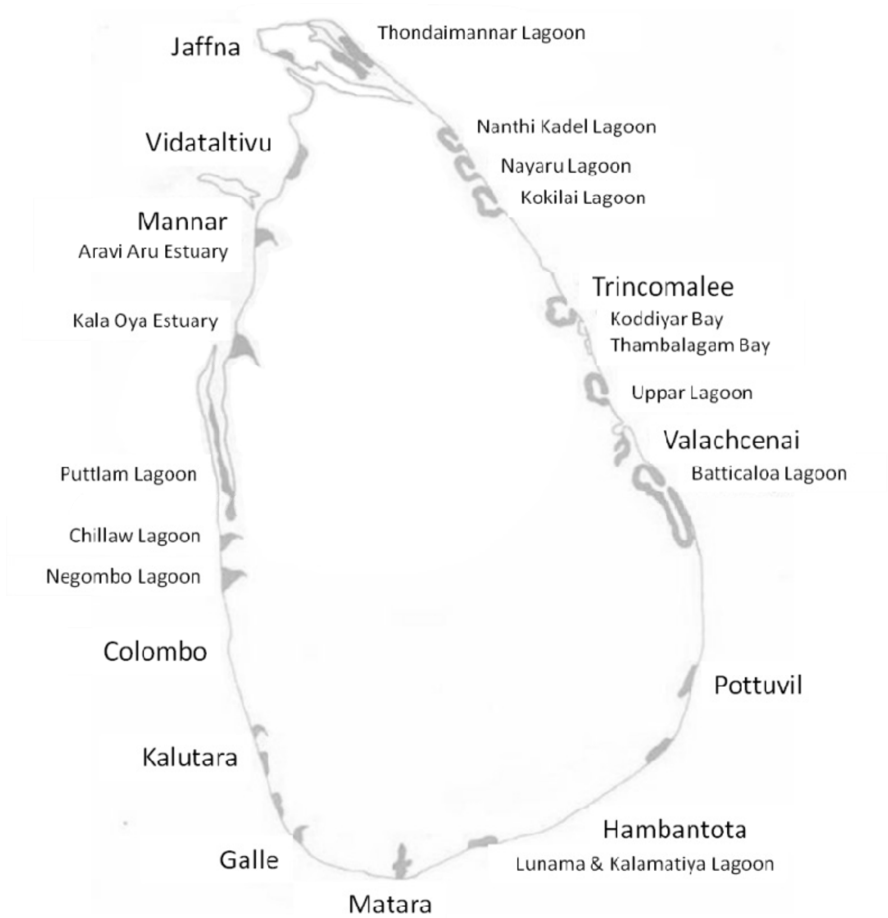

Figure 4.2: Mangroves in Sri Lanka. Source: CCD (no year).

Particularly in the northwestern part of Sri Lanka, mangroves have been destroyed through the establishment of shrimp farms. In other areas they are threatened by local utilization of wood, landfilling, extension of settlements, pollution, and illicit breweries in mangrove hideouts (UNEP 2001; IUCN 2000).

One of the objectives of the CZMP is the protection and monitoring of mangroves, together with a sustainable use of mangrove resources (CCD 2004a). However, mangroves in Sri Lanka not only fall under the jurisdiction of the CZMP, but are also subject to other regulations such as the Forest Ordinance and the Fauna and Flora Protection Ordinance (CCD 2005). Although they generally contain protection rules for mangroves, these numerous regulations and different responsible agencies nevertheless lead to confusion, which can result in a lack of enforcement of existing protection rules.

4.4 Maduganga estuary

4.4.1 Biophysical overview

Maduganga is situated in the wet zone and in the agro-ecological region WL4 (Figure 4.1). This region is defined as an area with a 75 % expectancy of annual rainfall exceeding 1,525 mm (CCD 2004b). The average annual rainfall around Maduganga between 1986 and 2002 was 2,217 mm with peaks from April to July and from October to November. Temperatures are fairly constant, ranging from 26.8 to 28.5°C with an annual mean of 27.2°C (1986-2002).

Maduganga is an estuary with an inlet connecting the main water body with the sea and with several rivers flowing into the estuary. There are 15 permanent islands of which Maduwa is the largest (39 ha). Although the smaller Randombe Lake in the south of Maduganga is connected to the estuary through two narrow canals, it has been excluded from this study in order to keep the study area smaller. The estuary is rather flat with an average depth of 1.9 m and a maximum of 3 m. Tidal influence is low with a maximum difference of about 1 m close to the sea. Salinity varies with the tides and the inflow from the different streams, and whether the estuary mouth is blocked or not. Close to the sea, salinity ranges between 6.7 and 20.8 ppt and decreases with increasing distance (Ramsar 2003).

A large part of the study area is dominated by poorly drained bog and half-bog soils (Histosols) with a surface layer rich in organic matter. Furthermore, waterlogged muddy soils can be found in the marshes. Towards the coast, large areas are also dominated by alluvial soils of variable drainage, which are often saline and are suitable for coconut cultivation. Cinnamon plantations in the northern and eastern parts of Maduganga are mostly located on red and yellow podzolic soils in different stages of weathering (CCD 2004b; Panabokke 1996).

Homesteads with surrounding gardens are the predominant land use in the western and southern part of the study area. When gardens around the houses are large enough, they might also include a small coconut plantation where the nuts are mainly for own use. The northern and particularly the eastern areas are more rural, and land use is a mixture of scattered homesteads and cinnamon, coconut and paddy plantations. Patches of natural or semi-natural vegetation are mainly found along the shores of the estuary, inflowing streams, and the inlet. Altogether there are 302 plant species belonging to 95 families; 121 species are woody plants. Most of the species are native, 19 are endemic, while 8 are nationally threatened, and 9 are invasive alien species (Bambaradeniya et al. 2002).

Maduganga is one of the few areas in Sri Lanka with remaining intact mangrove stands. Mangroves in this area have been degraded mainly due to local use of the trees as fuelwood and illegal construction. A total of 14 species of true mangroves and mangrove associates are to be found around the estuary. Their occurrence depends on distance to the sea, i.e. differences in salinity and tidal influence (Bambaradeniya et al. 2002).

The existence of the mangrove patches around Maduganga was one criterion for declaring the area as one of three Sri Lankan wetlands of international importance under the Ramsar Convention on Wetlands in 2003. Other important aspects for this nomination were the rich biodiversity of the region, the importance of the estuary for the lifecycle of different shrimps and prawns species as well as the high number of commercially important anadromous fish species (Ramsar 2003).

The "Special Area Management" (SAM) process in Maduganga started in 2003 and was finished by the end of 2007 (see section 6.1.1). It identified several major resource-management issues that have adverse effects on the ecosystems and livelihoods around Maduganga. One of them is the increasing pollution of the estuary, which has several sources. The main factor is the excessive input of fertilizers and pesticides from surrounding cinnamon plantations. This leads to eutrophication of the water body, which is already documented by the spread of *Najas marinas*, an aquatic weed. It is an indicator plant for high nutrient content and has negative impacts on fishery and for boat operators. The process of eutrophication is intensified by the lack of sanitary facilities for some households, the continual blocking of the estuary mouth through sand, which hinders water exchange with the sea, as well as the uncontrolled disposal of waste.

Around 90 % of the people living around Maduganga use wood as fuel (CCD 2004b). Although most of this wood comes from cinnamon plantations, some people also use the mangrove resources. Additional threats to the mangroves are illegal encroachment and the disturbance from tourist motorboats. This also contains tension between tour boat operators and estuary fishermen.

The paddy area decreased significantly by 44 % between 1994 and 2003 (CCD 2004b) due to insufficient maintenance of the irrigation channels and the gates at the main water body, which leads to increased salinity and waterlogging. As a consequence, the paddy fields have to be abandoned and left fallow. This process could be affirmed during the field survey and the interviews.

4.4.2 Socio-economic overview

Maduganga is located in the southern Province in Galle district. It spreads out over two Divisional Secretariats (DS), namely Balapitiya in the west close to the coast, and Karandeniya, which covers the more rural areas in the eastern part of Maduganga. Each DS is further divided into Grama Niladhari (GN) Divisions, which are the smallest administrative units in Sri Lanka. The borders of the GN divisions were the main tool for outlining the area under consideration for this study. The study area covers 20 GN divisions in Balapitiya and 4 in Karandeniya fully or in parts.

The main water body of the estuary is only a few hundred meters east of Galle Road, which is the main road connecting Colombo with the south of Sri Lanka. Balapitiya as the main dwelling in this area is spread along Galle Road (Figure 4.3). It is the economic as well as the administrative center, as it accommodates the government of Balapitiya DS. Buses from Colombo to the south and vice versa stop here, and most buses from places further inland head to Balapitiya. Thus, it is also the transport center of the region. Karandeniya is the administrative capital of Karandeniya DS, but it is much smaller and less important than Balapitiya.

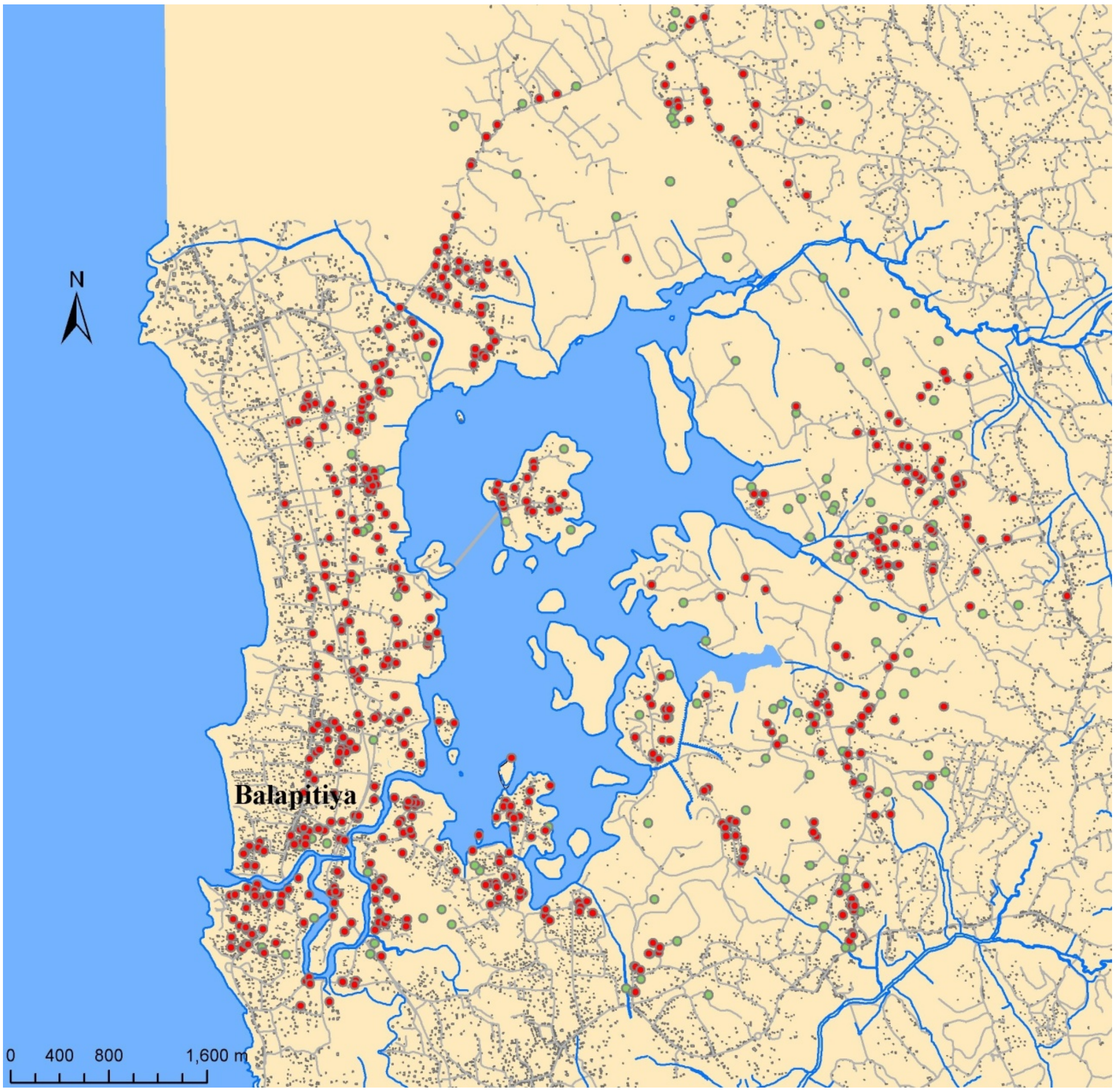

Figure 4.3: Map of Maduganga estuary. Red dots show surveyed households, green dots surveyed plots.

Generally, the transport system in the whole area is quite good. Most roads are in good condition, while some of the smaller roads in the rural areas are poorly maintained and may be impassable after heavy rainfall. Most areas can be reached with public transport on a regular basis.

There are about 26,500 people living in the study area, distributed over approximately 6,080 households. The annual population growth rate is 0.97 % on the district level. There is no information available about the ethnic distribution on the DS level, but in Galle District nearly all people are Sinhalese (94.5 %) with few Tamils (2.3 %) and Sri Lankan Moors (3,2 %) (DCS 2007). The study for the SAM planning (see section 6.1.1) showed a similar picture with an even higher Sinhalese share (98.2 %).

Religious affiliation in the district is associated with the ethnicity: 94.2 % are Buddhists, 1.9 % Hindus, 3.2 % Muslims, and 0.6 % Christians. In the SAM area, the Buddhist share is 97.1 %, while most of the remaining population are Muslims (CCD 2004b).

About 8 % of the population in Balapitiya and 1 % in Karandeniya do not have access to any kind of toilet. All people have access to drinking water, either in form of a common or private well or tap. Only very few people have to rely on tank trucks for their water supply, although this number increased after the tsunami. 72 % in Balapitiya and 56 % in Karandeniya have access to electricity, while more than 90 % use wood for cooking.

The numbers of the different occupations of the population in the respective GN divisions of Balapitiya and Karandeniya were taken from the last census on population and housing in 2001 (Figures 4.4 and 4.5), which were the latest available data on GN division level at the time of the study.

While the people in Balapitiya depend more on different kinds of non-agricultural work, nearly 50 % of the working people in Karandeniya earn their income through agricultural activities; fishery is only of marginal importance in these areas.

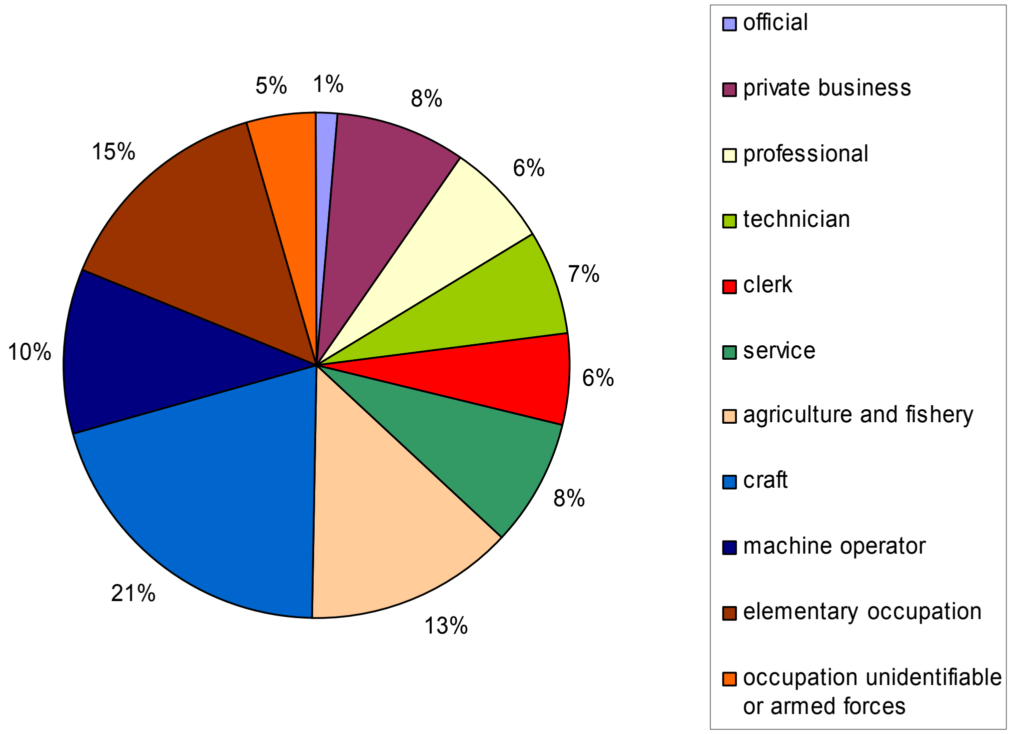

Figure 4.4: Sources of income in the 20 relevant GN divisions in Balapitiya DS. Source: DCS 2001.

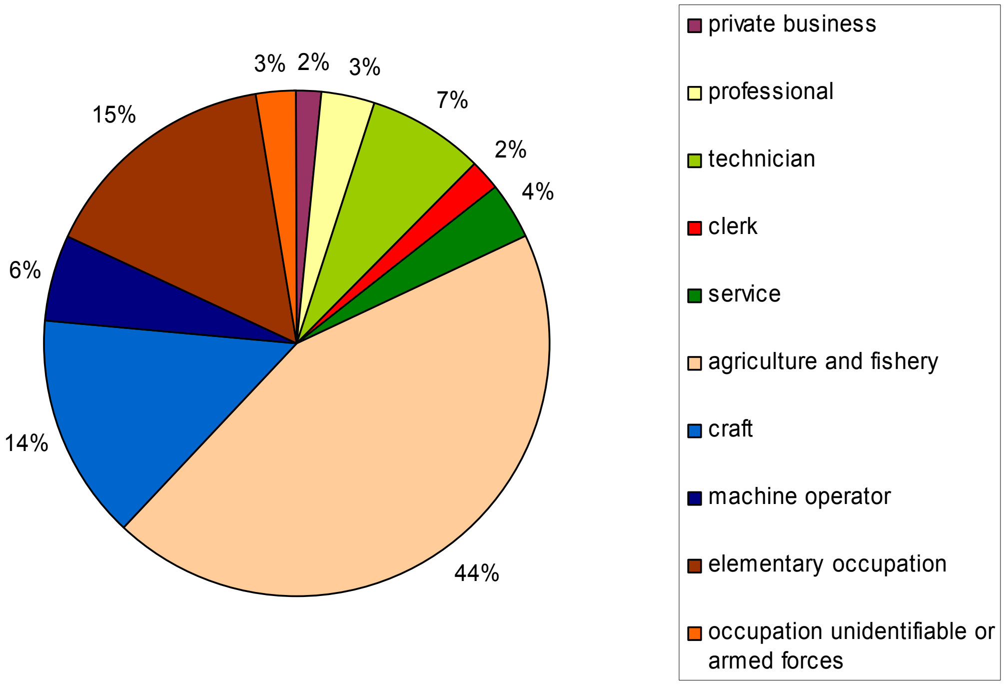

Figure 4.5: Sources of income in the 4 relevant GN divisions in Karandeniya DS. Source: DCS 2001.

The rather low percentages for private business must be viewed with caution, as the survey informed on different types of informal self-employment, which might have been ignored by the census, e.g., women producing and selling food in small stalls.

There is a general tendency that households very rarely depend on one source of income, but rather tend to diversify. This also includes households with a strong focus on agriculture or fishery, particularly as most agriculture-related activities in this area are not very time consuming, so that there is enough workforce available for additional off-farm activities.

4.4.3 Impacts of the tsunami

The southwestern part of Sri Lanka was severely affected by the tsunami in December 2004. In an environmental impact assessment after the tsunami, UNEP and the Sri Lankan government only found minor impacts on the estuary system of Maduganga (UNEP and MENR 2005). Apart from mentioning a slight uprooting of mangroves the report stated: "The physical structure of the mouth of Maduganga lagoon has not changed, but the sandbar blocking the lagoon from the sea was swept away and the southern bank was slightly damaged in places. A large amount of debris is still inside the lagoon, including several sunken boats. Due to the opening of the lagoon mouth, salinity inside the lagoon has increased, which could cause salt-water intrusion into paddy fields. In several places the coastal vegetation has been damaged." (UNEP and MENR 2005, p. 44). Due to the distance of the estuary from the sea, which varies between 1.3 and 1.6 km, the physical impact on the main water body was negligible. The inlet connecting the estuary with the sea showed signs of tsunami damage (uprooted trees, sunken boats, debris in the water, etc.), an observation that was confirmed by people living along the inlet, whose houses were moderately or severely damaged by the waves (for details, see sections 7.3 and 7.4). With increasing distance from the sea, damages were less, but even on Pathamulla Island, which is about 800 m away from the beach (linear distance) and which is surrounded by the inlet, houses and gardens suffered severe damage.

In Balapitiya between the sea and the estuary, damages were much more severe. Several houses west of Galle Road were severely damaged or completely destroyed and some people lost their lives. During the field survey, damages were observed up to 1.2 km distance from the sea (see Chapter 7).

5 LAND-USE DECISIONS BY HOUSEHOLD AGENTS AND BIOPHYSICAL DYNAMICS OF LANDSCAPE AGENTS

The advantages of agent-based modeling compared to conventional modeling approaches for simulating land-use and land-cover changes (LUCC) are mainly the capture of socio-ecological complexity, the provision of a natural description of systems consisting of entities with a certain behavior, and their high degree of flexibility (see section 2.4). Despite these benefits of ABMs, there are still some major challenges for the application of this approach for simulating LUCC in the context of coupled socio-ecological systems (Le et al. 2008). These challenges mainly result from the heterogeneity of landscapes and human communities. Landscapes have different environmental properties, provide different types of services to human communities, and show different responses to human interventions. The challenge concerning human communities results from the existence of heterogeneous livelihoods within the landscape under investigation. They result in varying decision-making mechanisms between different livelihood groups, which also includes the parameters influencing these mechanisms. Another difficulty relates to the formulation of a comprehensive and realistic decision-making mechanism, as the frequently applied optimization approach is not a reasonable representation of reality.

5.1 Introduction to LUDAS

Simulations of future LUCC in this study were conducted with the “Land Use Dynamics Simulator” (LUDAS) (Le et al. 2008; Le 2005). LUDAS was developed in 2005 and first applied to an upland watershed of about 90 km^2 in central Vietnam. The site was chosen for the heterogeneity of its biophysical conditions and the diversity of livelihoods. Furthermore, LUCC is a major concern of many stakeholders in the management of the watershed resources in that area.

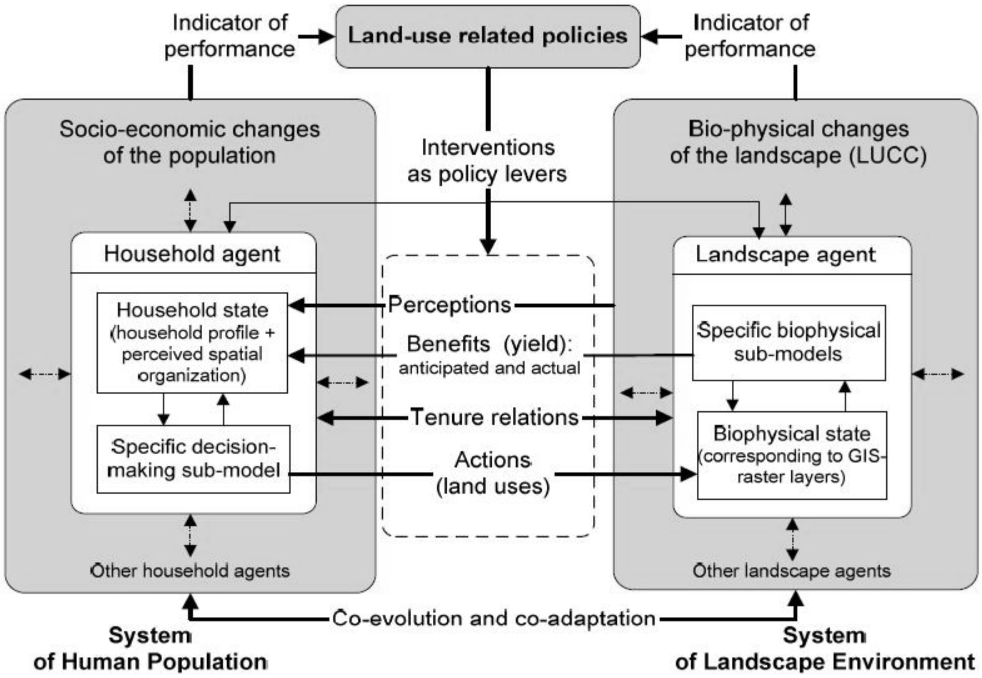

Figure 5.1: Conceptual LUDAS framework. Source: Le 2005; Le et al. 2008.

Four modules serve as the main features of the model: the environment, human population, land-use related policies, and the decision-making procedure (Figure 5.1).

(1) The environment is represented by landscape agents, i.e., land patches with equal size, specific socio-ecological attributes, and ecological response mechanisms with respect to external environmental changes and human interventions. From a spatial standpoint, landscape agents correspond to pixels in GIS and/or remote sensing databases used by the model. The pixel size depends on the nature of land use and data availability in the study area, as well as the purpose of the investigation. For the case study in Vietnam, the selected pixel size was 30 m x 30 m, as this resolution corresponded to land-use data classified from Landsat TM/ETM data, thus the agricultural plots could be visualized at this spatial resolution. Variables representing the landscape agents correspond to GIS raster layers. The landscape agents are captured with a diversity of variables such as biophysically spatial variables (e.g., terrain condition, land cover, accessibility to rivers/streams), economically spatial variables (e.g., proximate distance to roads), institutionally spatial variables (e.g., owner, village territory, protection zoning class), and histories of particular patch properties.

For the representation of the ecological response mechanisms, LUDAS contains internal sub-models of agricultural and forest productivity dynamics. Through a cellular automata sub-model of land-cover transition implemented in every landscape agent, environmental features are allowed to change also without human intervention, e.g., through vegetation growth or succession.

The landscape system in the model is organized in form of a hierarchy of three spatial scales: the landscape agents as self-controlled land, the landscape vision, which describes the limited landscape space perceived by a household agent, and the entire study landscape. While changes take place on the landscape agent level, either through human impact or through natural modification, the results of this process feed back on the other two scales. The entire landscape is a collection of all individual pixels. Through the aggregation of the interactive behavior of the landscape agents over time and space, the landscape dynamics as a whole are evolutionary. The landscape vision is connected to the household agent and his decision-making process. It is an aggregation of the landscape patches within the vision of the respective household agent, which are arranged as circular neighborhoods around the plots of the respective agent. The spatial extent of landscape vision is household specific. In addition to the spatial information attributed to all landscape patches, the patches within the vision contain further attributes that are specific for the agent. The landscape vision serves as the basis for the land-use related decision-making processes of the agents.

(2) The human system represents the households in the study area as the smallest unit of this system. Households of different livelihood typology have different livelihood strategies, including different decision-making mechanisms with regard to land use. The profile of a household agent consists of two basic components. The first one is the household profile, which is comprised of numerous socio-economic variables and variables measuring the households' access to certain institutions. The second component is the individual perception of the landscape by the households. This landscape vision of the households serves as the main link between the biophysical and the human system. The dynamics of the household agents include three types of changes. While natural changes such as age occur without any actions, other changes are triggered by external influences such as policies that impact on farmers' livelihoods. Finally, some changes occur on an annual basis as effects of the simulation process,

such as annual income and land endowment. Household agents are equipped with a decision-making mechanism as an internal sub-model, which will be described below.

Like the landscape system, the human module is also self-organized on three organization levels: the household agent, groups of household agents, and the population. As it is not possible to define the behavior for every household individually, the empirical data are used to divide the sample into more or less homogeneous livelihood groups based on the Sustainable Livelihoods Framework (see section 5.3). The categorization is not fixed, but can change every year as a result of the simulation process. In this case, the household completely adopts the decision-making mechanisms of the new group. Finally, the population is the aggregation of all individual households, with the patterns emerging from the processes at the lowest organizational level.

The main link between the human and the environmental part of the system is given by the perception-response loop, which comprises tenure relations and the flow of information and services between the two components. Perception refers to the way how human agents perceive the environment within their vision, which eventually results in decisions and activities related to land use. These activities generate a biophysical response at the level of the landscape agent.

(3) The policy module refers to land-use related policies and other external parameters, which affect all household and landscape agents. This is why they are also called global parameters. They can be tuned by the user in order to derive scenarios of the impacts of different interventions on land use and land cover in the area under consideration. The policies to be included are based upon the field surveys and the expert knowledge concerning any external parameters that might be of importance for land use and land cover in the area. Expert knowledge also decides through which pathways these policies impact on the system and thus also which parameters are useful to describe the impacts of the policies.

(4) Household agents are equipped with a decision-making mechanism as an internal sub-model (Figure 5.1), which follows the same logical procedure for all household agents. However, due to different input parameters, outcomes of decision processes are extremely diverse. The sub-model integrates household characteristics, perceived environmental conditions, as well as policy and institutional information into household decision making on land use. Therefore, it serves as the core engine of the

modeled socio-ecological system. Because of the disadvantages of assuming perfect rationality, when simulating complex human decision making, LUDAS models decision making as a logical procedure, which reflects both bounded-rational as well as reflex behavior.

The selection of locations for cultivation as the main activity with regard to LUCC is assumed to be a rational decision with the goal of maximizing utility. Household collection of forest products is modeled as a reflexive activity in response to different conditions of resource availability (forest status) and accessibility (closeness to forest and institutional constraints).

The decision procedure starts with the division of the labor pool of the household into different labor budgets according to their livelihood typology. In VN-LUDAS, households follow two main processes: The claims and uses of landholdings for cultivation and the collection of forest products, with the former following the bounded rationality approach, while the latter is simulated by assuming reflective behavior. Given particular land-use options (M possible land-use types) and possible location alternatives within the household's landscape vision (N possible locations), the household agent will evaluate the multi-attribute utility of every possible combination of land-use type and location of the decision space M x N. He will tend to select the combination with the maximal utility. As the utility function is expressed as a probability term (P), there is some chance (1-P) that the household does not select the optimal option when comparing his choice with the option leading to the maximum utility. This is relevant in a way that farmers may face specific constraints to identify and adopt the most profitable land use that was not captured by the decision-making sub-model, or he may have his own preferences on land-use practices that are not rational.

The identification and conversion of new patches to farmland is constrained by the labor budget of the household agent. If the labor budget is not depleted completely after finishing work on his current plots (static phase), the agent will start looking for new plots (moving phase). This process will repeat until the labor budget is finished.

After setting up the initial state of the household and landscape agents and setting of the external parameters, LUDAS enters the annual simulation cycle (Figure 5.2). In step 2, the preference coefficients and the labor allocation lists are adopted, both according to the membership of the household to a particular livelihood group. Steps 3 to 5 contain the decision processes for the three different production lines, with step 3 being divided into the static and the moving phase. Income from non-farm activities (step 5) is not endogenously modeled, but is simply calculated based on the cost (empirical cost norms) of labor allocated to such activities. The proportion of labor budget allocated to activities of this type is also the empirical value, which is assumed not to change during the simulation period. However, as this empirical value is household-type specific, the value will change if the typology of the household changes.

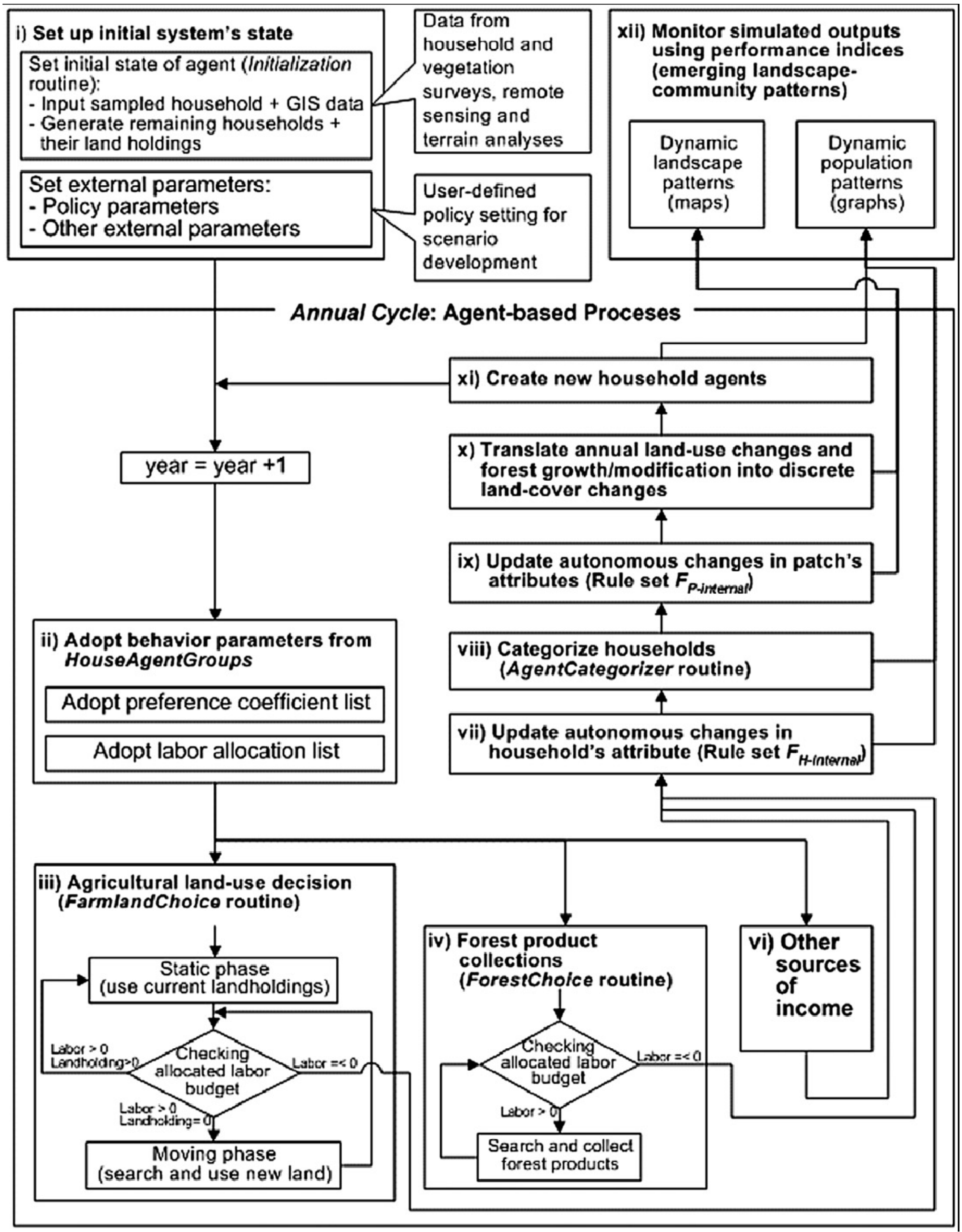

Figure 5.2: Main steps of the simulation program in LUDAS. Source: Le et al. 2008.

Next steps are the modification of the households' attributes, which might result in a re-categorization of a household into another group. Then, attributes of landscape patches are updated and translated into land-use changes. Finally, new household agents are created to simulate population growth, and annual changes of the human and the biophysical system are displayed before the model enters the annual cycle again.

VN-LUDAS identified forest protection zoning, access to agricultural extension, and access to agrochemical subsidies as the main external factors influencing decision making of household agents in the study area with regard to land use and land cover. Data were extracted from governmental reports and other secondary literature and interviews with local experts and households. In order to include policy factors into the simulation process for LUDAS, data had to be represented by quantitative global parameters. Forest protection zoning is represented by the score threshold, which is based on the watershed protection scoring system introduced by the Vietnamese government, and by the enforcement coefficient. The percentage of farming households having access to agricultural extension services is the parameter for the second policy factor. Finally, access to agrochemical subsidies is again represented by the percentage of households with access, and also by the amount of subsidies.

First simulations with VN-LUDAS revealed the differences in significance of the selected policy factors. A decrease in forest protection level or a lower enforcement of protection rules led to a higher degradation of dense natural forest to open natural forest, particularly in areas close to roads or settlements. Variations in the access to agricultural extension services on the other hand had almost no impact on land use and land cover. Finally, an increase in the access to agrochemical subsidies led to a decrease in agricultural land and an increase in productivity on existing land. However, this trend is not very pronounced when compared to the amount of additional subsidies. As a result of these simulations, an “ideal” scenario was generated, which suggested a reduction of protected area from 90 to 50 %, while at the same time paying more attention to enforcement of protection rules (enforcement degree of 80 %). By setting the percentage of the population reached by agricultural extension to 75 % and the percentage of the population reached by agrochemical subsidies to 5 %, this combined scenario results in a significantly reduced forest degradation compared to the current policy settings. At the same time, gross income per capita increases by 15 %.

5.2 Differences between VN-LUDAS and SRL-LUDAS

The differences between the original version of LUDAS (VN-LUDAS) and the version modified for this study result from the different environmental and socio-economic conditions in the study areas. VN-LUDAS was developed for a mountainous watershed of about 90 km^2 in central Vietnam. Population density in this area is low (approximately 13 people/km^2 in 2003), and the region still contains a considerable amount of primary and secondary forests (about 50 to 60 % of the area). Livelihoods of the local communities largely depend on agricultural activities and forest products. This dependence on agriculture is also reflected by the classification in different livelihood groups for the modeling process, as all three groups rely on agricultural activities (Le 2005) in addition to the collection of forest products, livestock production, off-farm activities (e.g., in public services) and governmental subsidies. Upland crops (mainly paddy rice, sometimes replaced by Cassava), fruit-based agroforestry, and forest plantations are the main land uses, with the upland crops being managed through shifting cultivation.

In SRL-LUDAS, the classification of livelihood groups (section 5.3.4) shows that the share of agricultural activities for income generation is much lower around Maduganga than in the study area in Vietnam. One of the five livelihood groups receives a high share of income from cinnamon and coconut plantations (58 %), but apart from this group, people mainly depend on off-farm activities for income generation. Some households, particularly in the northern part of the study region, have small paddy plots for subsistence, but only very few households produce rice for sale on the market. Livestock production is of no significance in the study area. As there are only very few forests, the collection of forest products was only reported by few respondents living close to the estuary who use firewood from mangroves and other trees close to the shore. Due to the large number of cinnamon plantations, most people use cinnamon branches after harvesting as firewood. The differences in livelihoods also imply differences in labor allocation of households for the various activities, particularly as cinnamon and coconuts as the main crops are not very time consuming.

Cinnamon and coconuts as the major crops around Maduganga are perennial in contrast to annual food crops such as paddy rice, maize, and cassava, and short-term fruit crops such as pineapple or bananas, which are the main crops in the Vietnamese study. Annual crops lead to higher land-use dynamics. These dynamics are much steadier over time for a cinnamon plantation, where a tree can be harvested after 4 years for the first time, and the harvesting period is about 40 to 45 years. The same applies to coconut plantations. The dominance of perennial crops in combination with the high population density, which does not leave much space for large-scale changes, produces the relatively stable land-use patterns in the study area. Landscape and livelihood characterization reveal that livelihoods around Maduganga are less land-driven than in rural areas of developing countries. However, modifications in land-use related policies might change decision-making procedures of households and could thus lead to an increase in one land use at the expense of other uses. As cinnamon is the dominant cash crop in the study area and is likely to be subsidized by the government, it can be expected that it could continue to replace other land uses. This development could also lead to changes in livelihoods with a stronger reliance on agricultural activities, which might further push agricultural land uses.

The basic structure of the model and the main steps of the simulation process (Figures 5.1 and 5.2) are very similar in both versions of LUDAS. SRL-LUDAS also consists of the four main modules: human, landscape, decision making, and policies. Decisions on land use and production strategy are taken on an annual basis like in VN-LUDAS. However, the decision-making process is not divided into two different phases as for VN-LUDAS, but only consists of the static phase. The mobile phase in VN-LUDAS is used for acquiring new land, if

- after the static phase the household still has available labor,
- there are viable plots of unused land in the study area, and
- this unused land is accessible at a low price or even free.

This step was omitted in SRL-LUDAS due to the non-availability of additional land for opening new plots. New land cannot simply be occupied by the household, but has to be purchased on the market. The incorporation of this activity would require an additional modeling procedure that defines the mechanisms of the local land market, i.e., how different household agents interact through land bidding processes under changing political and economic conditions. When households still have labor resources available after the static phase, these resources are used for non-agricultural activities. Additional land is only allocated to new emerging households, sprouted during the simulation process.

In both approaches, landscape agents are represented as pixels, whose characteristics are described through internal state variables. The pixel size in SRL-LUDAS is 15 m x 15 m, while it was 30 m x 30 m for the study site in Vietnam. VN-LUDAS introduced ecological sub-models for simulating agricultural yield responses, forest yield functions, and natural transition among different land-cover types, which were omitted in the Sri Lankan version. The perennial nature of the major agricultural land-use systems around Maduganga complicates the development of an agricultural yield-dynamic sub-model. The lack of long-term monitoring data does not permit to estimate the growth dynamics of the tree-based agricultural system. As such a sophisticated yield simulation sub-model is not expected to generate significant additional information for the achievement of the modeling objective, it was decided to use a less data-intensive approach to capture major responses of agricultural production to management interventions. A simple rule set of discrete yield responses to different levels of fertilizer application was specified, based on empirical data collected during the household and farm surveys. The surveys produced potential yield ranges depending on variations in natural conditions and particularly in management practices. VN-LUDAS also contains a sub-model on the dynamics of forest yields, which was not adopted for SRL-LUDAS, as the area around Maduganga hardly contains any forest stands apart from the strips around the estuary and the inlet. Finally, the absence of natural vegetation and the unlikelihood of a re-conversion of land to natural vegetation through fallowing due to the pressure on the land led to the decision not to incorporate the sub-model on vegetation succession.

The design of the human and the decision-making modules is very similar for both approaches, with the main exception that the additional labor budget was only used for non-agricultural activities in SRL-LUDAS, as described above. VN-LUDAS introduced a so-called decision matrix, which depicts the anticipated choice possibilities for (1) all possible land uses, and for (2) all locations within the landscape vision of the respective household. The decision matrix, which is calculated as part of the decision-making module, supports agents in finding the best solution for land-use choices with the goal of maximizing utility. As it is not possible for existing households in SRL-LUDAS to acquire new land, the choice probability is not computed within a two-dimensional matrix (land-use type x location) as a decision space, but as a vector (land-use type), which depicts probabilities of different land uses for existing patches within the landscape vision of the agent.

Finally, there are slight differences in the procedure for determining household decision making of the different livelihood groups. VN-LUDAS used multi-nominal logistic functions for the land-use choice model where annual upland crops, paddy rice, fruit-based agroforestry, and forest plantation were the four land-use alternatives for the dependent variable. Due to various reasons (see section 5.3.5), it was decided to apply a binary logistic function for SRL-LUDAS with the probability of the respective land use being tested against the probability of all other land uses. Apart from paddy rice, the other crops of significance in the study area are perennial, thus it does not make sense to specify the choice probabilities calculated by the bi-logit functions for the probability of annual land-use changes. However, the choice probability would be relevant to account for the possibility of land-use changes after a period that is consistent with the basic time cycle of production for cinnamon and coconut as the most important perennial crops in the study area. Field observations and discussions with local farmers resulted in the assumption of a time horizon of 9 to 11 years after establishment of the plantation for implementing any changes. Thus, it was decided to calculate the annual possibility of land-use changes by dividing the choice probability by 10 years.

Different legislation rules for protecting terrestrial ecosystems in general and mangroves in particular exist, and also scenarios for a protection zoning of the land around Maduganga estuary (see section 6.1.1). However, the implementation of the zoning plan and measures for its enforcement are still vague. The same applies to further protective measures for Maduganga, such as its declaration as a sanctuary under the Fauna and Flora Protection Ordinance in 2006, which does not include any activities for enforcement of the protective rules (Ratnayake, Department of Wildlife Conservation, 2006 pers. comm.). Although protection of ecosystems will surely have positive impacts on the condition of the vegetation along the shore of the estuary and its inlet, the area affected by these protection rules will be comparably small and will not have a significant effect on land use in the study area. Particularly the latter aspect led to the decision not to include any protection rules as part of the model code.

5.3 Socio-economic input to SRL-LUDAS

5.3.1 Household survey

In order to comprehensively capture people's livelihoods in the study area, the asset approach of the sustainable livelihoods (SL) framework was used for structuring and conducting the household survey. The framework was developed by the UK Department for International Development (DFID), based on the work by Chambers and Conway (1991) and by Scoones (1998). It is used for analyzing and describing particularly the livelihoods of poor people in developing countries. It has become a popular tool for conducting multidimensional analyses of livelihoods even though it has been criticized for the lack of certain aspects such as gender and culture or for its complexity (Cahn 2002; Parkinson and Ramírez 2006). Due to its multidimensional approach it helps to avoid bias selection of indicators from one particular discipline (Campbell et al. 2001). The framework consists of three major components: The vulnerability context, livelihood assets, and transforming structures and processes (Figure 5.3). These components shape the development of livelihood strategies of households and eventually their livelihood outcomes, i.e., the results of these livelihood strategies. In addition to increases in income, these outcomes also comprise less tangible factors like well-being or reduced vulnerability. The term well-being summarizes aspects such as health, political enfranchisement, or maintenance of cultural heritage (DFID 2001).

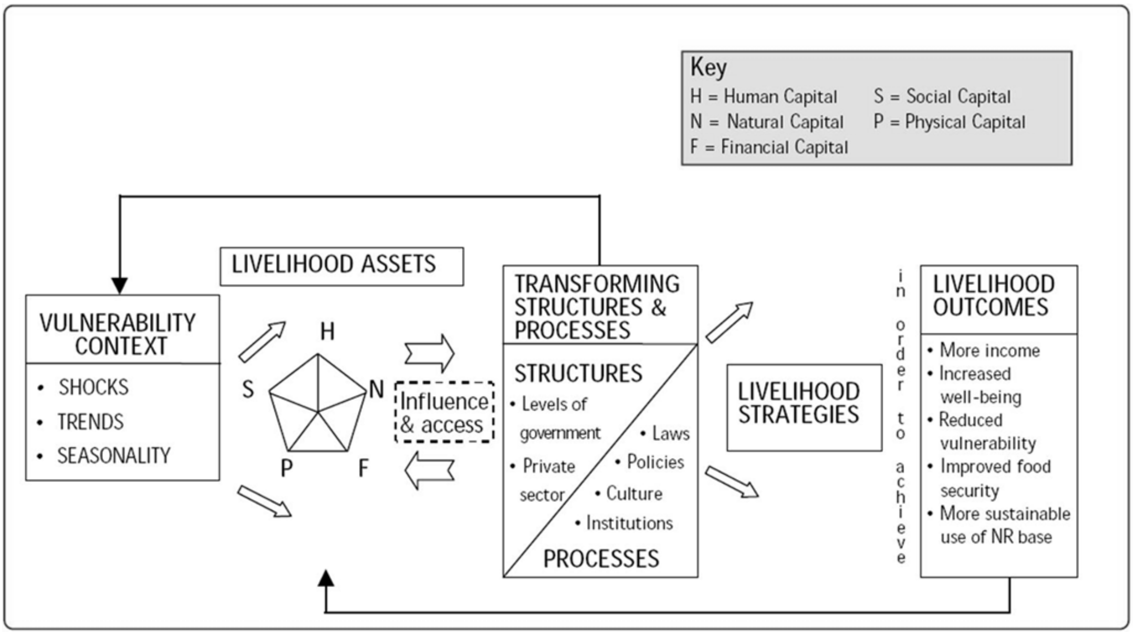

Figure 5.3: Sustainable Livelihoods Framework. Source: DFID 2001.

Vulnerability as part of the SL framework is a description of the environment in which people build their livelihoods (DFID 2001). It is kept more general than in the frameworks on vulnerability (see Chapter 3). The term describes all kinds of disturbances, divided into shocks, trends, and seasonality, which can affect livelihoods, most of them negatively, and which mostly cannot be controlled by the people (DFID 2001).

Transforming structures and processes is another major component of the framework. These capture all institutions, organizations, policies, and legislation that shape livelihoods by influencing people's access to assets and hence their livelihood strategies. These structures and processes operate on all levels, from local to global.

Finally, the livelihood assets form the core of the concept. They determine the opportunities of households to develop livelihood strategies. When dealing with livelihoods, there is still a major focus on income as the most important livelihood factor, which in addition is comparably easy to quantify. However, it is now widely acknowledged that there are other important aspects that shape people's livelihoods, although these might be more difficult to analyze or measure.

The asset approach is based on the idea that people "require a range of assets to achieve positive livelihood outcomes; no single category of assets on its own is sufficient to yield all the many and varied livelihood outcomes that people seek" (DFID

2001). The assets are divided into 5 different categories or capitals to cover the entirety of people's livelihoods: 1) human capital, which comprises the skills, knowledge, ability to work and health of the people under consideration, 2) social capital, which includes all kinds of social resources like informal networks and membership in formalized groups, 3) natural capital, which contains all natural resource stocks such as land, water, air quality, and biodiversity. There is a particularly close connection between natural resources and vulnerability, as "many of the shocks that devastate livelihoods of the poor are themselves natural processes that destroy natural capital (…) and seasonality is largely due to changes in the value or productivity of natural capital over the year" (DFID 2001) (see also section 3.5). 4) physical capital, which includes all kinds of basic infrastructure (transport, shelter, water supply, energy, information) as well as producer goods, and 5) financial capital, which includes all types of available stocks and regular inflows of money. By applying the asset approach, it was ensured that the survey took into account all relevant aspects that influence livelihoods and decision making of the households in the study area.

The household survey was conducted from August to November 2006 with the support of Sri Lankan students. The data collection was designed as a mixture of a formal survey and tools from the Rapid Rural Appraisal (RRA) approach (Townsley 1996; Crawford 1997). Most of the household-related quantitative information was collected through questionnaires. This information was enriched with secondary data from statistics, interviews with national and local decision makers and representatives from relevant non-governmental organizations, maps, transect walks, and general observations.

The questionnaire mainly captured information on access and ownership of assets with a special section on agricultural practices where applicable. Further sections dealt with the households' perception of mangroves and their role during the tsunami, and the households' recovery from the impacts of the tsunami if they had been affected. These sections did not form part of the categorization into livelihood groups, but were used for the vulnerability assessment (see Chapter 7).

The survey covered 538 households around the estuary that were selected via stratified random sampling from election lists received from the local administration. Stratification describes the process of dividing the population into non-overlapping groups due to certain characteristics, which results in a more even distribution. The samples were stratified according to the population in the different GN divisions and covered about 8 % of the population living in the study area.

Information was collected in face-to-face interviews with the household head, if possible, or with one or more other adult household members. If they had any additional land apart from the plots around their house, these plots were also visited together with a household member and additional information about land-use practices was collected in the field. Location of the homesteads and all plots were taken with a hand-held GPS device and afterwards entered into the GIS.

5.3.2 Principal Component Analysis

Based on the survey and knowledge of the study area, 15 variables extracted from the questionnaire served as input for the Principal Component Analysis (PCA). Other potentially important parameters like available means of transport, percentage of different types of household land, or percentage of male and female workers did not show a clear statistical response with regard to separating different principal components. The selected variables (Table 5.1) cover the different asset categories of the SL framework and are relevant for livelihoods in the study area in general as well as for separation of different types of livelihoods:

- Natural capital: total land of household, land per capita, percentage of cinnamon land of all landholdings;
- Physical capital: distance from house to nearest main road;
- Human capital: educational level of household head, % of household members, who passed secondary school (grade 11; all household members over 15 years are taken into account), number of household members, number of potential workers (all employable persons between 15 and 64 years), dependency ratio (ratio of potential dependents to potential workers, with dependents being persons under 15 or over 64 years);
- Financial capital: total monthly income of household, monthly income per capita, % income from agriculture, % income from fishery, % income from remittances, % income from other activities (this variable captures all activities that do not fall under the previous variables);

- Social capital: leadership of household (leading position of a household member in any kind of governmental or non-governmental organization). As this variable is in nominal scale (1=yes, 0=no), it was not included in the PCA, but was taken into account later in the models of land-use choices.

PCA is a well-recognized multivariate statistical methodology for reducing a high number of variables to a lower number of factors while still explaining most of the variance of the original data (Campbell et al 2001; Lesschen et al. 2005). The resulting factors are called principal components. PCA is defined as an orthogonal linear transformation that transforms the data to a new coordinate system such that the greatest variance by any projection of the data comes to lie on the first, the second greatest variance on the second coordinate, and so on. Thus, the first principal component (PC1) is a linear combination of the original variables, i.e., PC1 = aX1 + bX2 + cX3….with X1, X2, X3… being the standardized original variables, while a, b, c…are the fitted coefficients (Campbell et al. 2001). The goal of PCA is to reduce dimensionality and thus complexity while keeping accuracy of the data.

Table 5.1: Independent input variables for PCA.

Variable	*Definition*
H_{land}	total land of household (in perches)
$H_{land/cap}$	land per capita (in perches)
H_{cin}	amount of cinnamon land (percentage of all landholdings of household)
H_{road}	distance of house from nearest main road
$H_{edu/head}$	educational level of household head
$H_{edu/members}$	% household members, who finished secondary school (level 11)
H_{size}	household size (number of household members)
$H_{workers}$	number of potential workers
H_{dep}	dependency ratio
H_{income}	total monthly income of households (in LKR)
$H_{income/cap}$	monthly income per capita (in LKR)
$H_{in/agr}$	% income from agriculture
$H_{in/fish}$	% income from fishery
$H_{in/rem}$	% income from remittances
$H_{in/other}$	% income from other activities
H_{leader}	leadership of household*

* in nominal scale, therefore not used in PCA, but included later on for analysis of land-use choices

Like all statistical procedures in this study, the PCA was carried out using SPSS 14. It was run with Varimax rotation and Kaiser normalization. The common procedure is to extract only components with eigenvalues over 1.0. However, it was decided to include the 6th component with an eigenvalue of 0.99, since it still contains a significant additional explanatory value (6.5 %) with its eigenvalue very close to 1.0. The results of the PCA served as input for the subsequent Cluster Analysis.

5.3.3 Cluster Analysis

Cluster Analysis is an explorative statistical tool for classifying a number of unsorted cases into smaller groups (clusters) with similar characteristics by the measure of distance between the cases in a vector space with the parameter values representing the dimensions. The aim is to divide the cases into clusters such that similarity within the clusters is as high as possible, while the cases of different clusters should be as different as possible from each other. Cluster Analysis is divided into hierarchical and partitional (e.g., K-means) approaches. Furthermore, there are different methods for measuring the distances between the cases and for clustering the cases.

The values of the 6 components that had been extracted in the previous step of the PCA were used as input for the analysis. In a first step, the hierarchical approach with a single-linkage clustering and squared Euclidean distance measure was applied in order to eliminate outliers from the dataset, as this clustering method has proven to be useful for identifying outliers (Backhaus et al. 2006). Using the revised data set, several methodologies were tested to find the best clustering approach for the purposes of this study. It was seen that K-means as a partitional clustering approach, which is particularly useful for larger samples, gave the best results. When applying the hierarchical approach using the Ward method and squared Euclidean distance measure, this approach produced very similar clusters.

5.3.4 Results

Principal Component Analysis

The PCA extracted 6 principal components with 5 of them having eigenvalues over 1.0. It reduced the number of 15 input variables down to 6 components while still explaining 79.3 % of the variance of the original data (Table 5.2). The rotated component matrix

(Table 5.3) displays the correlation of the independent variables with the resulting components.

Table 5.2: Total variance explained by the extracted components of the PCA.

Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	3.603	24.017	24.017	3.603	24.017	24.017
2	2.706	18.041	42.058	2.706	18.041	42.058
3	1.796	11.976	54.035	1.796	11.976	54.035
4	1.512	10.077	64.111	1.512	10.077	64.111
5	1.290	8.602	72.714	1.290	8.602	72.714
6	0.989	6.592	79.306	0.989	6.592	79.306
7	0.886	5.910	85.216			
8	0.634	4.227	89.443			
9	0.512	3.416	92.859			
10	0.433	2.887	95.746			
11	0.312	2.080	97.825			
12	0.202	1.349	99.175			
13	0.093	0.617	99.792			
14	0.020	0.131	99.922			
15	0.012	0.078	100.000			

PC 1, which explains 24 % of the variance, is highly correlated with income and land-related variables, with loadings between 0.842 and 0.924. The loading values describe the correlation between the components and the variables. Therefore, this component was labeled “income and land”. Due to their high loadings and their explanatory power, monthly income per capita and land per capita were selected as the main explanatory variables for the first PC.

PC 2 was labeled “income from agriculture”, as the respective variable has the highest loading (0.825) and the highest economic importance. The amount of cinnamon land with a loading of 0.772 as the by far most important agricultural land cover also fits into this component. Furthermore, it is also likely that in comparison to households without agricultural activities they are located further away from main roads, which explains the assignment of the third variable to this component.

PC 3 is highly correlated with two variables representing human capital, namely the number of household members (0.949), and the number of potential workers, which contains all employable people between 15 and 64 years (0.82). Due to the economic importance of the second variable this component was labeled "labor availability".

The education-related variables are summarized under PC 4. It was therefore labeled "education" and explains 10.1 % of the total variance of the original data.

PC 5 collected all income from non-agricultural activities, with income from other activities being negatively correlated (-0.892) plus income from remittances (0.682) and from fishery (0.578). It was summarized under "non-farming income". Finally, PC 6 is only correlated with dependency ratio. Thus, the PC was given the name of this variable.

Table 5.3: Rotated component matrix of 6 principal components using Varimax rotation and Kaiser normalization. Highest loadings are bold.

	Component					
	Income and land	Income from agriculture	Labor availability	Educational level	Non-farming income	Dependency ratio
$H_{income/cap}$	**0.924**	0.027	-0.062	0.036	-0.031	-0.101
$H_{land/cap}$	**0.913**	0.146	-0.155	0.062	0.060	0.038
H_{land}	**0.882**	0.191	0.020	0.061	0.063	0.056
H_{income}	**0.842**	0.029	0.373	0.013	-0.022	-0.058
$H_{in/agr}$	0.182	**0.825**	0.084	-0.008	0.199	0.044
H_{cin}	0.182	**0.772**	0.011	-0.062	-0.013	0.100
H_{road}	-0.034	**0.714**	-0.162	-0.210	-0.070	-0.055
H_{size}	-0.019	-0.033	**0.949**	0.000	-0.032	0.081
$H_{workers}$	0.060	-0.033	**0.820**	0.145	-0.035	-0.370
$H_{edu/head}$	0.019	-0.138	-0.026	**0.889**	-0.059	-0.044
$H_{edu/members}$	0.110	-0.110	0.142	**0.875**	-0.032	-0.080
$H_{in/other}$	-0.101	-0.401	-0.009	0.089	**-0.892**	-0.034
$H_{in/rem}$	-0.017	-0.135	-0.169	0.080	**0.682**	0.393
$H_{in/fish}$	-0.027	-0.197	0.114	-0.254	**0.578**	-0.506
H_{dep}	-0.044	0.045	-0.091	-0.177	0.160	**0.813**

Cluster Analysis

The hierarchical Cluster Analysis with single-linkage clustering eliminated 9 out of the 538 households due to exceptionally high income or high dependency ratio. Then a K-means Cluster Analysis was conducted with the remaining 529 cases. The process was repeated several times with different numbers of clusters, and the results were compared with information gathered during the field survey concerning different livelihood groups and their characteristics and strategies. This procedure led to the selection of a 5-cluster-solution with 190, 92, 175, 29, and 43 cases (Table 5.4).

Typologies of livelihood groups

Based on the results of the Cluster Analysis and knowledge of livelihoods in the study area, 5 livelihood groups were separated and characterized accordingly.

Group 1: Urban livelihoods with lower educational level

With 190 cases, this group contains 35.9 % of the surveyed households and is thus the largest group. It is one of two groups that receive nearly all their income from other activities (94.4 to 98 % in the 95 % confidence level; in contrast to income from agriculture, fishery, or remittances). It is differentiated from the other urban group through slightly lower income, but particularly through a lower educational level. The educational level of the household head is between grade 5.2 and 5.9, while the share of household members who had finished secondary school (grade 11) or higher is between 21.2 and 28.3 %. These values are the lowest for all five clusters. The overall means for these two variables are 7.9 and 49.8 %, respectively.

The first group mainly consists of households in the more urbanized areas in the western and southern part of the study area close to Galle Road, who earn their income as workers, employees, or with small-scale businesses such as small shops or food stalls.

Group 2: (Cinnamon) Farmers

This group consists of 92 households (17.4 % of the surveyed households) and is clearly characterized by its high share of income from agricultural activities (50.9 to 65.4 %). Thus, it is called farmers, although nearly none of these households generates its entire income from agriculture. However, this share is extremely high in comparison to the other groups. The size of the agricultural land of a household is frequently rather small, so that the members also have to look for other sources of income. However, land ownership is much higher in this group in comparison to the other groups, with a mean value of 784 to 1088 m^2 per person, while the overall mean for this variable is 481 m^2

per person. Farming households are mainly located in the more rural parts of the study region, which are north and particularly east of the estuary in the Karandeniya division.

Group 3: Urban livelihoods with higher educational level

Similar to group 1 (Urban livelihoods with lower educational level**),** this group also receives its income mostly from other activities (92.7 to 96.7 %) and is mainly located in the more urbanized areas around the estuary. It is the second largest group with 175 cases (33.1 % of the surveyed households). In comparison to the other groups, it is particularly characterized by its high educational level of grade 11.1 to 11.6 for the household head and 82.4 to 88.5 % of household members who had finished secondary school.

Group 4: Fishermen

Categorization of this group is easy due to its high share of income from fishery (72 to 90.1 %). Total income from fishery is often comparably high, so that the need for additional sources of income is not as great as in, for example, agriculture-dominated households. With only 29 cases, group 4 is the smallest group (5.5 % of the surveyed households).

Group 5: Poor households

The last group contains 43 households (8.1 % of the surveyed households). From the categorizing variables it can be derived that mainly poorer households are summarized under this group who receive most of their income from remittances from other people not living in the household (76.8 to 90.6 %). Furthermore, the number of potential workers and the monthly income per capita is lower in this group, while the dependency ratio is much higher than in the other groups.

Table 5.4: Descriptive statistics for the main categorizing variables for each livelihood group.

		N	Mean	Std. deviation	Std. error	95% confidence interval for mean	
						Lower bound	Upper bound
$H_{in/cap}$	1	190	3652	2045	148	3359	3944
	2	92	4478	2539	265	3952	5004
	3	175	3859	2518	190	3483	4235
	4	29	3663	1734	322	3003	4322
	5	43	3250	2397	365	2512	3987
$H_{land/cap}$	1	190	13	17	1	10	15
	2	92	37	31	3	31	43
	3	175	18	39	3	12	24
	4	29	10	15	3	4	16
	5	43	25	41	6	12	37
$H_{workers}$	1	190	2.9	1.2	0.1	2.7	3.0
	2	92	3.3	1.3	0.1	3.1	3.6
	3	175	3.3	1.4	0.1	3.1	3.5
	4	29	3.8	1.6	0.3	3.2	4.4
	5	43	2.3	1.5	0.2	1.8	2.7
H_{dep}	1	190	0.7	0.7	0.1	0.6	0.8
	2	92	0.6	0.7	0.1	0.4	0.7
	3	175	0.5	0.6	0.0	0.4	0.6
	4	29	0.4	0.5	0.1	0.2	0.6
	5	43	1.5	2.4	0.4	0.7	2.2
$H_{edu/head}$	1	190	5.5	2.4	0.2	5.2	5.9
	2	92	6.7	3.4	0.4	6.0	7.4
	3	175	11.3	1.6	0.1	11.1	11.6
	4	29	6.1	2.9	0.5	5.0	7.2
	5	43	7.6	3.2	0.5	6.6	8.5
$H_{edu/members}$	1	190	24.8	24.6	1.8	21.2	28.3
	2	92	41.9	28.6	3.0	35.9	47.8
	3	175	85.5	20.6	1.6	82.4	88.5
	4	29	35.0	29.0	5.4	24.0	46.1
	5	43	42.3	36.1	5.5	31.2	53.4
$H_{in/agr}$	1	190	2.2	7.6	0.6	1.1	3.3
	2	92	58.2	35.2	3.7	50.9	65.4
	3	175	2.4	8.3	0.6	1.2	3.7
	4	29	1.7	6.4	1.2	-0.7	4.2
	5	43	1.7	6.4	1.0	-0.2	3.7
$H_{in/fish}$	1	190	0.5	3.6	0.3	0.0	1.0
	2	92	0.0	0.0	0.0	0.0	0.0
	3	175	0.3	3.8	0.3	-0.3	0.8
	4	29	81.0	23.8	4.4	72.0	90.1
	5	43	1.2	5.3	0.8	-0.5	2.8
$H_{in/rem}$	1	190	0.5	5.1	0.4	-0.2	1.3
	2	92	1.9	10.6	1.1	-0.3	4.1
	3	175	2.4	9.9	0.7	0.9	3.9
	4	29	3.4	11.0	2.0	-0.7	7.6
	5	43	83.7	22.4	3.4	76.8	90.6
$H_{in/other}$	1	190	96.2	12.4	0.9	94.4	98.0
	2	92	39.9	34.0	3.5	32.9	47.0
	3	175	94.7	13.3	1.0	92.7	96.7
	4	29	13.8	21.7	4.0	5.5	22.1
	5	43	11.0	18.3	2.8	5.4	16.7

5.3.5 Binary logistic regression for determining household decision making

After having identified the 5 livelihood groups, binary logistic regression was applied in order to evaluate decision making with regard to land-use choices of households within the different livelihood groups.

Discrete regression analysis is a statistical tool used to explain the association of a dependent variable with one or more independent variables and to predict probabilities for the categorization of the cases within the dependent variable. In this type of logistic regression, the dependent variable is binary, thus the model is able to predict the probability if a case belongs to one of the two categories.

Logistic regression is part of the category of generalized linear models, which do not calculate the values for the dependent variable directly through a linear equation, but rather transform the regression line into a non-linear form through a link function. In a first transformation, the model calculates the odds ratio, which is the odds (relative probability p[y=1]) of belonging to one category in relation to the odds of belonging to the other category (p[y≠1 = 1-p[y=1]]. It is expressed as:

$$\frac{p(y=1)}{(1-p(y=1))} \tag{5.1}$$

In order to produce a variable that has a range from negative to positive infinity, a further transformation is conducted by logarithmic transformation of equation (1). The result is called the logit and may be used as the dependent variable. Thus, the transformation produces the following equation:

$$logit\ (y) = \alpha + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k \tag{5.2}$$

The logit can be converted back to the odds by exponentiation. Then the odds can be transferred back to the probability that y=1, which produces the logistic function:

$$p(y=1) = \frac{e^{(\alpha+\beta_1 x_1+\beta_2 x_2+...+\beta_k x_k)}}{1+e^{(\alpha+\beta_1 x_1+\beta_2 x_2+...+\beta_k x_k)}} \tag{5.3}$$

Logistic regression is a frequently used methodology in LUCC research. Sometimes it is also applied in combination with other types of regression (Braimoh 2004; Staal et al. 2002; Gobin et al. 2002; Serneels and Lambin 2001; Geoghegan et al. 2001).

For this study, a set of 15 different variables was used in the regression. These variables (Table 5.5) can be separated into three main categories: biophysical, socio-economic, and political variables. During the field surveys, it was observed that neither biophysical nor political parameters have a major influence on land-use decisions in this area. The terrain is rather flat and climate and soil conditions are quite uniform (see section 4.4). Therefore, it was decided not to include these factors into the regression model and to restrict the biophysical variables to distance-related parameters.

In spite of extensive discussions with governmental agencies and study of related secondary data, only very few national or local policies could be found that have an influence on land-use decision making around Maduganga. Thus, only one policy variable was included in the regression model.

Socio-economic factors on the other hand showed clear differences in the study region, therefore this category contains the largest share of all variables.

Table 5.5: Variables hypothesized to be relevant for households' decision making on land use around Maduganga estuary.

Variable	*Definition*	*Source*
Dependent	*Land-use choice by household (homestead, cinnamon, coconut, other)*	
Biophysical		
	Distance to town (in km)	GIS
	Distance from plot to nearest main road (in km)	GIS
Socio-economic		
	Number of plots	Questionnaire
	Number of potential workers (age 15-64 years)	Questionnaire
	Percentage of potential male workers	Questionnaire
	Dependency ratio (potential dependants/potential workers)	Questionnaire
	Monthly income per capita (in 1000 LKR)	Questionnaire
	Land per capita (in m^2)	Questionnaire
	Educational level of the household head	Questionnaire
	Number of memberships in local institutions/organizations	Questionnaire
	Leadership (at least one member with leading position in any local institution) (0/1)	Questionnaire
	Transportation index	Questionnaire
	Number of income sources	Questionnaire
	Damage from tsunami (in 1000 LKR)	Questionnaire
Policy		
	Access to agricultural extension services (0/1)	Questionnaire

Dependent variable – land-use choice

From the classification, land uses of importance for livelihoods in the study area were selected for the regression, i.e., homestead, cinnamon plantations, coconut, and other land uses. The latter category mainly refers to paddy fields, but also to other agricultural plots such as vegetables or bananas, and to all kinds of unused land. These land uses may be of great importance for the respective household, but their overall number is too small to be analyzed in the regression. Due to the available number of observations within the different groups, the occurrence of the different land uses, and the number of explaining variables it was decided to conduct a set of binary logistic regressions with one land use being tested against a combination of all the others uses.

Explanatory variables

Biophysical variables

There is a clear differentiation with regard to land use between the areas close to the coast and Galle Road and to the more inland parts of the study area, which are generally more rural. Furthermore, prices for land increase closer to the coast. Thus, the decision whether a piece of land is used for residential or agricultural purposes very much depends on its distance to the coast, which is captured by the variables "distance to town" and "distance to water". Unfortunately, these two variables showed strong collinearity. Multicollinearity is an issue in regression analysis that can severely bias results of the regression and is very difficult to overcome (Menard 2001). However, it was decided to exclude one of the two variables from the regression model. As "distance to town" is regarded as being of utmost importance, it was decided to omit "distance to water".

The variable "distance to town" measures the distance of the respective plot to Balapitiya, which was chosen because it is the by far most important settlement in and around the study area. There are other small settlements such as Karandeniya or Uragasmanhandiya, which serve as local markets, but are less important. The main bus station, where buses leave to Colombo and Galle as well as to smaller places further inland, is in Balapitiya. It also accommodates the local government and is thus the main administrative point for the whole divisional secretariat.

"Distance to nearest main road" is the second variable, which serves as a measure for access to markets and has proven to be of importance for livelihoods particularly in developing countries (Nelson 2000; Siegel 2005). To construct this variable, field knowledge was used to identify a network of major roads in good condition that are served by public transport and connect the main dwellings within and around the study area (Balapitiya, Ambalangoda, Ahungalle, Uragasmanhandiya, and Karandeniya) (Figure 5.4).

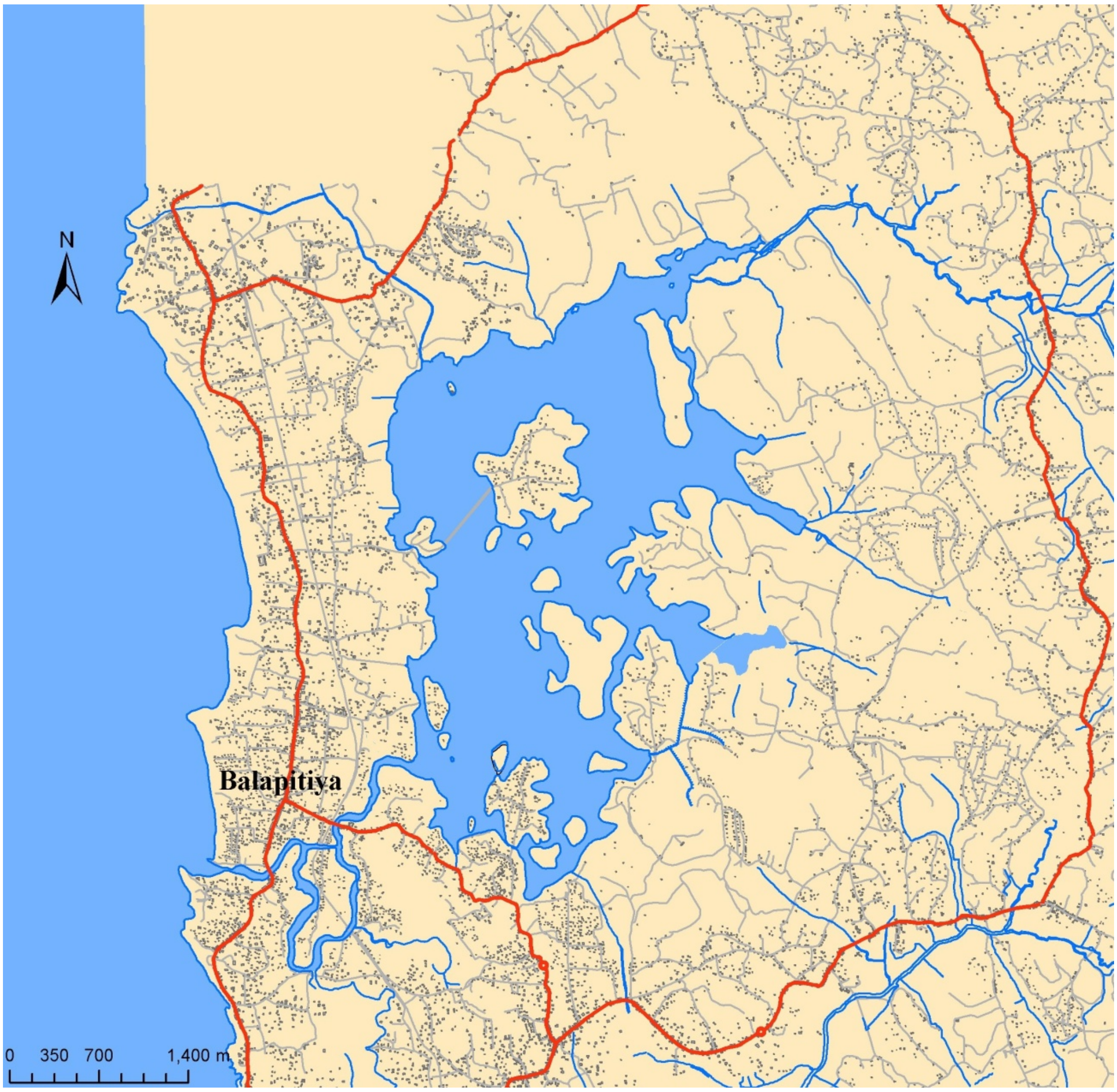

Figure 5.4: Map of main roads in the study region connecting the most important settlements (in red).

Socio-economic variables

Socio-economic variables were either taken directly from the questionnaires or were calculated from information received during the survey. The number of plots as the first variable serves as an indicator for whether a household is active in agriculture and thus might be willing to open more agricultural plots.

Labor is often seen as the main asset in the hands of poorer people (Ellis 2000). Therefore, it is covered by three different variables. The number of potential workers counts all people living in the household aged between 15 and 64 years, while the percentage of male workers only looks at the male workforce in relation to all family members. Although many women contribute to the income of the family by having different kinds of jobs, it is still the males who contribute most, while women have more responsibilities with regard to family issues. This is particularly valid when it comes to fishing and agriculture.

The dependency ratio measures the ratio between potential dependants (under 15 or over 64 years old or not able to work due to sickness, etc.) and potential workers. This ratio serves as a measure for economic security of a household and thus influences its strategic influence towards income and livelihood generation.

In spite of the numerous aspects influencing the livelihoods of people in developing countries, the availability of financial resources is one of the decisive factors. Therefore, monthly income per capita was included as another socio-economic variable. Financial resources are also an important factor for the proper management of cinnamon plantations, as access to subsidies for fertilizers is still limited, and labor cost for maintaining, harvesting and processing the cinnamon is high.

Another important factor is land per capita, as land ownership enhances possibilities for economic activities and for livelihood diversification. During the field surveys it was observed that there is a tendency to acquire more land when the household already manages land for agricultural purposes.

In most families in the study region, the oldest male has to be regarded as the head of the household who makes most decisions. As education strongly influences strategic thinking concerning livelihood options and income diversification (Schwarze 2004; Barrett et al. 2001; Buchenrieder 2003; Smith et al. 2001), the educational level of the household head has been included in the regression model.

The variable “number of memberships in local institutions/organizations” aims to capture the aspect of social capital, as it can be assumed that membership in any kind of institution is a measure of the social network the household is part of and influences the livelihood of the household and thus eventually also its land use. Another aspect is the sharing of knowledge concerning agricultural practices, governmental support, etc.

This latter aspect was also considered when including the variable “leadership”, which is in dummy scale and analyses whether any member of the family has a leading position such as chairman or president in any local institution. Having such a position often implies better access to various kinds of information.

The socio-economic variables also include a mobility-oriented variable, i.e., the transportation index. From the information collected in the questionnaire on household assets, an index was generated by assigning a certain number of points for different means of transport such as bicycle, motorbike, car, tractor, or lorry. By taking into account factors like price of the vehicle, its transport capacity, and usefulness with regard to road conditions this index gives a good idea of the mobility of the household and its possibilities to transport commodities to the market.

The importance of livelihood diversification has been recognized in recent years, particularly with the discussion on sustainable livelihoods (Ellis 2000; Reardon 1997; Smith et al. 2001; Barrett et al. 2001; Buchenrieder 2003; Block and Webb 2001). These studies conclude that diversification is an increasingly important tool for reducing risk and for enhancing household income, especially in rural areas of developing countries. Generally, it is the wealthier households who diversify, while the poorest mostly lack the assets (skills, access to information, etc.) to diversify their livelihoods. Due to this importance of diversification, the number of income sources has been included as a further variable influencing the households' decision-making process regarding land use.

Finally, a variable "damage from the tsunami" was added, as it was expected that the impacts of the waves might have significantly changed livelihoods and land uses of people living close to the coast.

Policy variable

In terms of external policy parameters, only one variable was found that is currently of importance for household decision making with respect to land use. Several farmers reported that they received advice from governmental agricultural agents on a more or less regular basis. Therefore, it was decided to include access to agricultural extension services as a dummy variable.

With regard to cinnamon, the Sri Lankan government started a trial in 2004 to establish subsidies for cinnamon fertilizers in certain parts of the study region (Lindara 2007 pers. comm.). During the surveys, it was observed that application of fertilizers and thus also yields differed considerably. Unfortunately, the program was still in a very early phase at the time of the survey, and the number of participants was too small to gain any significant results (see section 6.1.2).

5.3.6 Results

The majority of the plots of groups 4 and 5 are homesteads, while agricultural plots are only of minor importance (Table 5.6). Therefore, and due to the small size of these groups, their influence on LUCC in the study region can be expected to be fairly low. Finally, the number of plots other than homesteads is too small to obtain significant results from the chosen bi-logit model with its 15 independent variables. Therefore, groups 4 and 5 were omitted during the subsequent simulation process.

Table 5.6: Distribution of land-use types in different livelihood groups

Livelihood group	*Homestead*	*Cinnamon*	*Coconut*	*Other*	***Total***
1 – urban with lower education	148	51	5	9	**213**
2 – (cinnamon) farmers	16	126	1	18	**161**
3 – urban with higher education	135	36	23	7	**201**
4 – fishermen	24	3	2	1	**30**
5 – poor	38	8	1	3	**51**

For the remaining three groups, regression analyses were conducted for homestead and cinnamon against the other land uses. While groups 1 and 2 do not contain enough plots to conduct a regression for coconut, this was possible for group 3 with its 23 coconut plots.

Model fit was checked with the likelihood ratio test (chi-square-test), which measures the deviation between the model without modifying variables and the full model. Furthermore, the percentage of correct predictions is specified as well as the Nagelkerke Pseudo-R^2, which measures the percentage of the variance of the dependent variable that is explained by all independent variables. Nagelkerke was chosen, as it is a modification of the Cox and Snell's R^2, which generates values between 0 and 1. Thus, it is easier to interpret than other R^2 measures (Backhaus et al. 2006; Garson 2009).

Group 1 – Urban livelihoods with lower educational level

For group 1, two regression models were developed (Tables 5.7 and 5.8). No regression was conducted for coconut, since there are only 5 coconut plots within the first livelihood group (Table 5.6). The two models show very high accuracy with R^2-values of 0.652 and 0.665, respectively (Nagelkerke). Predictive capacity of the models is also high with 84.8 and 88.6 %.

The decision of the households of group 1 to establish a homestead is significantly influenced by the variables distance to town (-), land per capita (-), and number of income sources (-), while the parameters influencing the establishment of a cinnamon plantation are distance to town (+), number of workers (-), dependency ratio (-), transportation index (+), and number of income sources (+). The correlation of number of plots with cinnamon was not taken into account, as the significance is comparably weak (0.050), and the confidence interval does not give a clear picture of the direction of the correlation (0.100 to 1.002).

The strong influence of distance to town reflects the effort to stay as close as possible to the urban area as the business and administrative center, while the cinnamon plantations are established in remote areas, which are more difficult to reach. This corresponds to the positive correlation between cinnamon and the transportation index, i.e., households with better means of transport have a higher tendency to establish cinnamon plantations, as some of the areas around the estuary are fairly difficult to reach without private transport. Furthermore, private vehicles can be used to transport the harvest to the processing facility.

The second variable, which proved to be significant for both land uses, is the number of income sources. Apart from the fact that chances for ownership of a cinnamon plantation are higher when there are more income sources, this parameter may also indicate a higher flexibility and availability of financial resources of the household, which is a prerequisite for establishing a cinnamon plantation.

The negative correlation between homestead and land per capita is partly also due to the fact that chances of establishing more than just a homestead increase with increasing land ownership. The negative correlation between cinnamon and dependency ratio also shows that cinnamon is an activity that requires initial and continuous investments. Fairly often this is not possible for households where fewer workers have to care for more dependants.

There is a further negative correlation between cinnamon and the number of workers, which is due to the fact that cinnamon is not very labor intensive. Thus, it is a good source of income for households with a smaller workforce. These only have to pay for external labor for weeding, harvesting and processing the cinnamon. However, work on a cinnamon plantation can also be done by younger or older people, who are not regarded as potential workers here.

Table 5.7: Logistic regression model for household group 1 (urban with lower educational level; n = 213 plots) with homestead against all other land uses.

Homestead, group 1				*Confidence interval (95%)*	
Variable	*Significance*	*Odds ratio*	*Standard error*	*Lower bound*	*Upper bound*
Constant	0.000	250.725	1.496		
<u>*Biophysical variables*</u>					
distance to town (d_town)	*0.023*	*0.708*	*0.153*	*0.525*	*0.954*
distance to main road (d_roads)	0.155	0.501	0.486	0.193	1.299
<u>*Socio-economic variables*</u>					
number of plots (h_plots)	0.153	0.471	0.527	0.168	1.322
number of workers (h_workers)	0.383	1.245	0.251	0.761	2.037
male workers (h_maleworkers)	0.311	1.013	0.013	0.988	1.040
dependency ratio (h_dependents)	0.163	2.025	0.506	0.752	5.456
income per capita (h_income)	0.174	1.211	0.141	0.919	1.594
land per capita (h_land)	*0.006*	*0.945*	*0.020*	*0.908*	*0.984*
education of household head (h_education)	0.369	0.916	0.098	0.755	1.110
memberships in institutions (h_institutions)	0.355	0.793	0.251	0.485	1.297
leadership (h_leadership)	0.720	1.834	1.695	0.066	50.807
transportation index (h_transport)	0.403	0.966	0.042	0.890	1.048
number of income sources (h_income)	*0.000*	*0.183*	*0.449*	*0.076*	*0.442*
damage from tsunami (h_damage)	0.589	1.263	0.433	0.541	2.950
<u>*Policy variable*</u>					
access to extension services (h_extension)	0.445	0.351	1.372	0.024	5.157
<u>*Model fit and accuracy assessment*</u>					
Likelihood ratio test:					
chi-square = 131.085	p = 0.000				
Pseudo R^2 (Nagelkerke) = 0.652	Correct predictions: 84.8 %				

Table 5.8: Logistic regression model for household group 1 (urban with lower educational level; n = 213 plots) with cinnamon against all other land uses.

Cinnamon, group 1				*Confidence interval (95%)*	
Variable	*Significance*	*Odds ratio*	*Standard error*	*Lower bound*	*Upper bound*
Constant	0.018	0.024	1.581		
<u>*Biophysical variables*</u>					
distance to town (d_town)	*0.000*	*2.684*	*0.240*	*1.677*	*4.297*
distance to main road (d_roads)	0.978	1.014	0.499	0.381	2.699
<u>*Socio-economic variables*</u>					
number of plots (h_plots)	0.050	0.316	0.589	0.100	1.002
number of workers (h_workers)	*0.032*	*0.486*	*0.338*	*0.251*	*0.941*
male workers (h_maleworkers)	0.107	0.978	0.014	0.951	1.005
dependency ratio (h_dependents)	*0.002*	*0.106*	*0.717*	*0.026*	*0.434*
income per capita (h_income)	0.139	0.811	0.141	0.615	1.070
land per capita (h_land)	0.223	1.019	0.015	0.989	1.049
education of household head (h_education)	0.892	1.015	0.110	0.818	1.260
memberships in institutions (h_institutions)	0.822	0.822	0.275	0.480	1.410
leadership (h_leadership)	0.756	1.772	1.839	0.048	65.146
transportation index (h_transport)	*0.011*	*1.113*	*0.042*	*1.025*	*1.208*
number of income sources (h_income)	*0.000*	*13.562*	*0.607*	*4.126*	*44.575*
damage from tsunami (h_damage)	0.629	0.875	0.276	0.509	1.504
<u>*Policy variable*</u>					
access to extension services (h_extension)	0.218	4.130	1.152	0.432	39.533
<u>*Model fit and accuracy assessment*</u>					
Likelihood ratio test:					
chi-square = 124.144	p = 0.000				
Pseudo R^2 (Nagelkerke) = 0.665	Correct predictions: 88.6 %				

Group 2 – (Cinnamon) Farmers

The parameters influencing the decision making of group 2, which mainly consists of cinnamon farmers north and west of the estuary, are more difficult to interpret, as the regression model produced less significant variables than for group 1 (Tables 5.9 and 5.10). The accuracy of the two models is also weaker than for group 1 with Nagelkerke values of 0.284 and 0.211, respectively. The variable "damage from tsunami" was omitted from the model, as no plot in this group was affected by the tsunami, thus the variable was always set to "0".

The regression model for homestead resulted in only one significant variable, i.e., “distance to town” (-), while the model for cinnamon showed a negative correlation with “land per capita”. For the first correlation, as in group 1, people try to establish their homesteads as close to the business and administrative centers as possible. The negative correlation between cinnamon and land per capita is due to the fact that roughly 25 % of the households of this group only own one plot, which is then used for planting cinnamon. Other households with more plots prefer not to have their plantation around their house, but rather on additional plots.

Table 5.9: Logistic regression model for household group 2 (cinnamon farmers; n = 161 plots) with homestead against all other land uses; 4 plots were omitted from the calculation due to missing data.

Homestead, group 2				*Confidence interval (95%)*	
Variable	*Significance*	*Odds ratio*	*Standard error*	*Lower bound*	*Upper bound*
Constant	0.611	7.202	3.880		
Biophysical variables					
distance to town (d_town)	*0.012*	*0.397*	*0.366*	*0.194*	*0.814*
distance to main road (d_roads)	0.445	0.581	0.710	0.145	2.337
Socio-economic variables					
number of plots (h_plots)	0.251	1.617	0.419	0.712	3.676
number of workers (h_workers)	0.315	0.663	0.410	0.297	1.479
male workers (h_maleworkers)	0.859	0.996	0.024	0.950	1.044
dependency ratio (h_dependents)	0.939	1.029	0.374	0.494	2.142
income per capita (h_income)	0.547	1.102	0.161	0.804	1.510
land per capita (h_land)	0.842	0.996	0.018	0.962	1.032
education of household head (h_education)	0.121	1.211	0.124	0.951	1.543
memberships in institutions (h_institutions)	0.624	0.775	0.520	0.280	2.147
leadership (h_leadership)	0.153	7.507	1.410	0.473	119.092
transportation index (h_transport)	0.387	0.962	0.045	0.881	1.050
number of income sources (h_income)	0.497	0.713	0.499	0.268	1.894
Policy variable					
access to extension services (h_extension)	0.801	1.242	0.861	0.230	6.720
Model fit and accuracy assessment					
Likelihood ratio test:					
chi-square = 23.133	p = 0.058				
Pseudo R^2 (Nagelkerke) = 0.284	Correct predictions: 91.1 %				

Table 5.10: Logistic regression model for household group 2 (cinnamon farmers; n = 161 plots) with cinnamon against all other land uses; 4 plots were omitted from the calculation due to missing data.

Cinnamon, group 2				*Confidence interval (95%)*	
Variable	*Significance*	*Odds ratio*	*Standard error*	*Lower bound*	*Upper bound*
Constant	0.032	40.606	1.726		
Biophysical variables					
distance to town (d_town)	0.627	1.092	0.181	0.766	1.557
distance to main road (d_roads)	0.597	0.832	0.347	0.422	1.643
Socio-economic variables					
number of plots (h_plots)	0.386	0.799	0.258	0.482	1.326
number of workers (h_workers)	0.666	0.910	0.218	0.594	1.395
male workers (h_maleworkers)	0.301	0.985	0.014	0.958	1.013
dependency ratio (h_dependents)	0.862	0.951	0.292	0.536	1.686
income per capita (h_income)	0.263	1.133	0.111	0.911	1.410
land per capita (h_land)	*0.029*	*0.979*	*0.010*	*0.960*	*0.998*
education of household head (h_education)	0.441	0.940	0.080	0.803	1.100
memberships in institutions (h_institutions)	0.952	0.981	0.315	0.529	1.818
leadership (h_leadership)	0.136	0.277	0.863	0.051	1.500
transportation index (h_transport)	0.775	1.008	0.030	0.952	1.069
number of income sources (h_income)	0.771	1.100	0.328	0.579	2.090
Policy variable					
access to extension services (h_extension)	0.441	0.661	0.538	0.230	1.896
Model fit and accuracy assessment					
Likelihood ratio test:					
chi-square = 23.080	p = 0.059				
Pseudo R^2 (Nagelkerke) = 0.211	Correct predictions: 79.0 %				

Group 3 – Urban livelihoods with higher educational level

Group 3 produced more significant results than group 2, together with a better model accuracy for the models for cinnamon and homestead with Nagelkerke values of 0.616 and 0.570 for homesteads and cinnamon, and good predictive capacity of more than 80 % for all 3 models (Tables 5.11 to 5.13).

Five variables showed a significant influence on the decision to establish a homestead: distance to town (-), number of workers (+), dependency ratio (+), membership in institutions (-), and number of income sources (-). The model for cinnamon resulted in 6 significant variables, namely distance to town (+), number of workers (-), dependency ratio (-), income per capita (-), number of income sources (+), and access to extension services (+). For this group, it was also possible to conduct a regression analysis for coconut against the other land uses, as there are 23 coconut plots in this group. The significant variables of this model are distance to town (-), distance to roads (+), dependency ratio (-), education of household head (-), membership in institutions (+), and number of income sources (+).

Group 3 shows the same distribution concerning the variable “distance to town" as groups 1 and 2, with homesteads being closer to the town, while cinnamon plantations are situated in more remote areas. According to the regression model, coconut plantations are located closer to towns, because unlike cinnamon, coconuts are not a cash crop but are for self consumption or sale on the local market, thus they are planted and harvested in areas closer to markets. Although the coconuts are transported to the market by road, it was observed that main roads are not necessary, as transport is mostly organized with smaller vehicles (bicycles, motorbikes). Thus, locations close to the main roads are occupied by homesteads, while coconut plantations are further away. This explains the positive correlation of coconut to "distance to roads".

The tendency to establish a homestead rather than a cinnamon plantation with increasing number of workers is due to the fact that households rely on other sources of income when a large enough workforce is available, since cinnamon does not require a regular labor input. Thus, the work on a cinnamon plantation can also be done by younger or older household members or women, who do not have any other regular jobs. The number of income sources is another variable that was significant in the models of all groups. Explanation of this variable was already given for group 1.

The negative correlation of dependency ratio with cinnamon was also observed for group 1, although in group 3 it is accompanied by a cumulative negative correlation with coconut and a positive correlation with homestead. Again, this demonstrates the lower financial flexibility of households with an adverse relation of dependants and workers.

The decision to establish a coconut plantation is negatively correlated with the educational status of the household head. Households with a lower educational level generally rely more on agricultural activities for income generation, while households with higher education concentrate more on different activities. This is supported by a large number of options for non-agricultural jobs, as Balapitiya and Ambalangoda are administrative and business centers in the region. Some people also work in Colombo and come home only at the weekend. This does not exclude these educated households from managing a cinnamon or a coconut plot as an additional source of income.

Membership in institutions is negatively correlated to homestead and positively to coconut. This indicates that people carrying out farming activities are often organized either in small local unions or in governmental institutions in order to have better access to information and financial support, which in turn might encourage them to open more agricultural plots.

Access to extension services encourages households to establish cinnamon plantations. As mentioned before, the Sri Lankan government initiated a program in 2004 to test the impact of fertilizer subsidies on cinnamon harvests. This variable might already indicate future effects of the program if it should be expanded.

Finally, the negative correlation between cinnamon and income per capita is contradictory at a first glance, as generally cinnamon plantations require significant financial input in the beginning. However, poorer households, who do not generate much income from non-farming activities, often manage to establish a small plantation around their house that generates additional income. They do not have to spend additional money for harvesting and processing of the cinnamon, as they have sufficient workforce in the household.

Table 5.11: Logistic regression model for household group 3 (urban with higher educational level; n = 201 plots) with homestead against all other land uses; 4 plots were omitted due to missing data.

Homestead, group 3				*Confidence interval (95%)*	
Variable	*Significance*	*Odds ratio*	*Standard error*	*Lower bound*	*Upper bound*
Constant	0.760	2.089	2.407		
<u>*Biophysical variables*</u>					
distance to town (d_town)	*0.003*	*0.583*	*0.184*	*0.406*	*0.837*
distance to main road (d_roads)	0.325	0.566	0.578	0.182	1.757
<u>*Socio-economic variables*</u>					
number of plots (h_plots)	0.185	0.491	0.538	0.171	1.407
number of workers (h_workers)	*0.010*	*2.027*	*0.274*	*1.186*	*3.464*
male workers (h_maleworkers)	0.582	0.993	0.013	0.967	1.019
dependency ratio (h_dependents)	*0.047*	*3.194*	*0.585*	*1.015*	*10.050*
income per capita (h_income)	0.143	1.230	0.141	0.932	1.623
land per capita (h_land)	0.119	0.984	0.010	0.965	1.004
education of household head (h_education)	0.052	1.374	0.164	0.997	1.894
memberships in institutions (h_institutions)	*0.018*	*0.539*	*0.261*	*0.324*	*0.899*
leadership (h_leadership)	0.890	0.898	0.780	0.195	4.139
transportation index (h_transport)	0.823	0.993	0.033	0.930	1.059
number of income sources (h_income)	*0.000*	*0.183*	*0.446*	*0.076*	*0.438*
damage from tsunami (h_damage)	0.383	0.999	0.002	0.996	1.002
<u>*Policy variable*</u>					
access to extension services (h_extension)	0.067	0.282	0.692	0.073	1.095
<u>*Model fit and accuracy assessment*</u>					
Likelihood ratio test:					
chi-square = 114.290	p = 0.000				
Pseudo R^2 (Nagelkerke) = 0.616	Correct predictions: 86.8 %				

Table 5.12: Logistic regression model for household group 3 (urban with higher educational level; n = 201 plots) with cinnamon against all other land uses; 4 plots were omitted due to missing data.

Cinnamon, group 3				*Confidence interval (95%)*	
Variable	*Significance*	*Odds ratio*	*Standard error*	*Lower bound*	*Upper bound*
Constant	0.258	0.034	2.984		
Biophysical variables					
distance to town (d_town)	*0.000*	*2.398*	*0.220*	*1.558*	*3.691*
distance to main road (d_roads)	0.478	0.656	0.594	0.204	2.102
Socio-economic Variables					
number of plots (h_plots)	0.595	1.356	0.574	0.441	4.175
number of workers (h_workers)	*0.000*	*0.289*	*0.349*	*0.146*	*0.572*
male workers (h_maleworkers)	0.661	1.007	0.015	0.977	1.038
dependency ratio (h_dependents)	*0.042*	*0.216*	*0.754*	*0.049*	*0.945*
income per capita (h_income)	*0.038*	*0.745*	*0.141*	*0.565*	*0.983*
land per capita (h_land)	0.921	0.999	0.006	0.989	1.010
education of household head (h_education)	0.498	1.142	0.196	0.778	1.677
memberships in institutions (h_institutions)	0.515	1.253	0.347	0.635	2.473
leadership (h_leadership)	0.173	0.220	1.110	0.025	1.939
transportation index (h_transport)	0.067	0.917	0.047	0.837	1.006
number of income sources (h_income)	*0.000*	*6.273*	*0.497*	*2.366*	*16.630*
damage from tsunami (h_damage)	0.564	0.944	0.100	0.776	1.148
Policy variable					
access to extension services (h_extension)	*0.030*	*4.886*	*0.733*	*1.161*	*20.558*
Model fit and accuracy assessment					
Likelihood ratio test:					
chi-square = 82.783	p = 0.000				
Pseudo R^2 (Nagelkerke) = 0.570	Correct predictions: 88.8 %				

Table 5.13: Logistic regression model for household group 3 (urban with higher educational level; n = 201 plots) with coconut against all other land uses; 4 plots were omitted due to missing data.

Coconut, group 3				*Confidence interval (95%)*	
Variable	*Significance*	*Odds ratio*	*Standard error*	*Lower bound*	*Upper bound*
Constant	0.286	20.863	2.848		
Biophysical variables					
distance to town (d_town)	*0.013*	*0.505*	*0.276*	*0.294*	*0.868*
distance to main road (d_roads)	*0.009*	*7.348*	*0.766*	*1.637*	*32.982*
Socio-economic variables					
number of plots (h_plots)	0.152	2.291	0.578	0.737	7.118
number of workers (h_workers)	0.194	0.680	0.297	0.380	1.216
male workers (h_maleworkers)	0.476	1.013	0.018	0.978	1.048
dependency ratio (h_dependents)	*0.046*	*0.151*	*0.946*	*0.024*	*0.965*
income per capita (h_income)	0.381	0.883	0.142	0.668	1.166
land per capita (h_land)	0.388	1.007	0.008	0.991	1.024
education of household head (h_education)	*0.001*	*0.502*	*0.207*	*0.334*	*0.753*
memberships in institutions (h_institutions)	*0.029*	*2.028*	*0.323*	*1.076*	*3.821*
leadership (h_leadership)	0.527	1.672	0.812	0.341	8.203
transportation index (h_transport)	0.349	1.034	0.035	0.965	1.107
number of income sources (h_income)	*0.037*	*2.414*	*0.423*	*1.053*	*5.535*
damage from tsunami (h_damage)	0.244	1.002	0.002	0.999	1.005
Policy variable					
access to extension services (h_extension)	0.493	1.851	0.897	0.319	10.744
Model fit and accuracy assessment					
Likelihood ratio test:					
chi-square = 43.924	p = 0.000				
Pseudo R^2 (Nagelkerke) = 0.397	Correct predictions: 88.8 %				

5.4 Biophysical input to SRL-LUDAS

In addition to the importance of human decision making on land management, differing parameters of heterogeneous biophysical environments also have a strong impact on land use, either directly through differences in adaptive reactions of these biophysical systems to any changes or indirectly through their influence on human decision making. The interplay between the spatio-temporal dynamics of landscapes and differences in human behavior together with additional socio-economic factors and external influences lead to the non-linearity of such complex coupled systems.

The landscape in LUDAS is organized as grid cells with a size of 15 m x 15 m. To ensure the spatially explicit characterization of the single patches, they have to be characterized by using empirical data, which were collected during the surveys. In terms of topography as one of the most important parameters influencing agricultural land use, the study area around Maduganga was very homogenous: except for a few minor elevations in the northern part it is completely flat. The surveys also did not show any differences in agricultural practices or productivity with regard to soil conditions. A comprehensive survey of soils in the study area was beyond the scope of this study, and in addition no soil classifications on a detailed level were available. Therefore, it was decided to omit this factor from the simulation process.

5.4.1 Land-cover classification

Current land cover plays a major role for the initial categorization of the landscape as a whole and its individual patches (grid cells), and thus is a prerequisite for developing scenarios of future changes. Remote sensing is an efficient, time-saving and widely accepted methodology for generating land-use/cover (LUC) maps of an area under investigation, especially since high-resolution sensors such as Quickbird and Ikonos have become readily available. Therefore, most land-use studies in general and modeling studies in particular make regular use of satellite images (Weng 2002; Geoghegan et al. 2001; Laney 2004; Klepeis and Turner 2001; McConnell et al. 2004; Walsh et al. 2003). However, findings gained from the remote sensing process should be complemented by other sources in order to increase the accuracy of the classification. Useful tools in this regard include spatial data with a higher resolution, such as maps or aerial photographs, but also expert knowledge from investigations in the area under consideration.

Initially, a Landsat ETM+ image from January 2003 [1] was intended for classification of LUC around Maduganga. Several attempts with unsupervised and supervised classification did not manage to produce appropriate results for further utilization. While the densely populated areas in and around Balapitiya can be distinguished from the remaining parts through automated classification procedures, classification of all other areas failed due to several reasons. To a large extent, the

[1] Freely available at the *Tsunami Satellite Data Catalog* of the *International Water Management Institute* (http://tsdc.iwmi.org)

landscape consists of small-scale mosaics, which are mainly formed by a mixture of cinnamon plantations, mixed cinnamon and coconut plantations, and homesteads, often surrounded by different types of home gardens. Due to this fragmentation and strong similarities in appearance, it was not possible to separate the different land covers through the abovementioned techniques. Therefore, images with a higher spatial resolution were acquired. Two Ikonos images from July 2005 and January 2006 were used, which were kindly provided by the Joint Research Centre (JRC) of the European Commission. Ikonos is a commercial earth observation satellite, which was launched in 1999. It carries four multispectral sensors (blue, green, red, and near-infrared band) with a resolution of 4 m and one panchromatic sensor with a resolution of 1 m.

The classification process was supported by additional material: topographic maps (1:10,000) from the Sri Lankan Survey Department, aerial photographs from 1994 and 1999, a land-use classification conducted by the Land-Use Policy and Planning Department (LUPPD), a land-use classification carried out for the SAM plan (CCD 2005), and a classification of near-shore vegetation conducted by IUCN (Bambaradeniya et al. 2002).

Both Ikonos images were acquired in georeferenced form. They were used with two different band combinations, near-infrared, red, and green (4-3-2), which is a common combination for detecting vegetation, and as a "real-color" image with the red, green, and blue bands (3-2-1) to support the classification process. The two band combinations of the two images were first sharpened (HSV) with the high-resolution panchromatic band and orthorectified. After conducting a spatial subset of the study region, texture filters were applied to the 4-3-2 files. It was then decided to use the combination of the red, the near-infrared, and the variance of red from the texture analysis for further classification. The 3-2-1 files were used in their original band combinations.

Several unsupervised classifications, both K-means and Isodata with different numbers of classes, were conducted, which were at least able to separate between the major classes with different reflecting patterns, such as residential areas, areas dominated by vegetation, and water. They also managed to distinguish the wetland areas in the northern part of the study area from their surroundings to a certain degree. As a next step, training sites were created and supervised classification with maximum likelihood and minimum distance was conducted. Unfortunately, no classification procedure was able to satisfactorily separate the different types of vegetation such as mangroves, home gardens, or cinnamon plantations. Conventional pixel-based classification approaches are limited when dealing with satellite images with a very high resolution such as Ikonos. Therefore, object-based classification either alone or in combination with pixel-based approaches is increasingly being used for classification of such images (Wang et al. 2004). As this complex approach is beyond the scope of this study, it was decided to analyze land use by conducting visual classification due to detailed knowledge of the study area and the availability of additional high-resolution material, as mentioned above.

Before starting the classification process, the four images were pasted into the GIS. All files were georeferenced again using the 3rd-order polynomial with a root mean square error of 3.55 for the 2005 (west) file and 4.17 for the 2006 (east) file.

Results

The classification separated 11 land-cover classes (Figure 5.5).

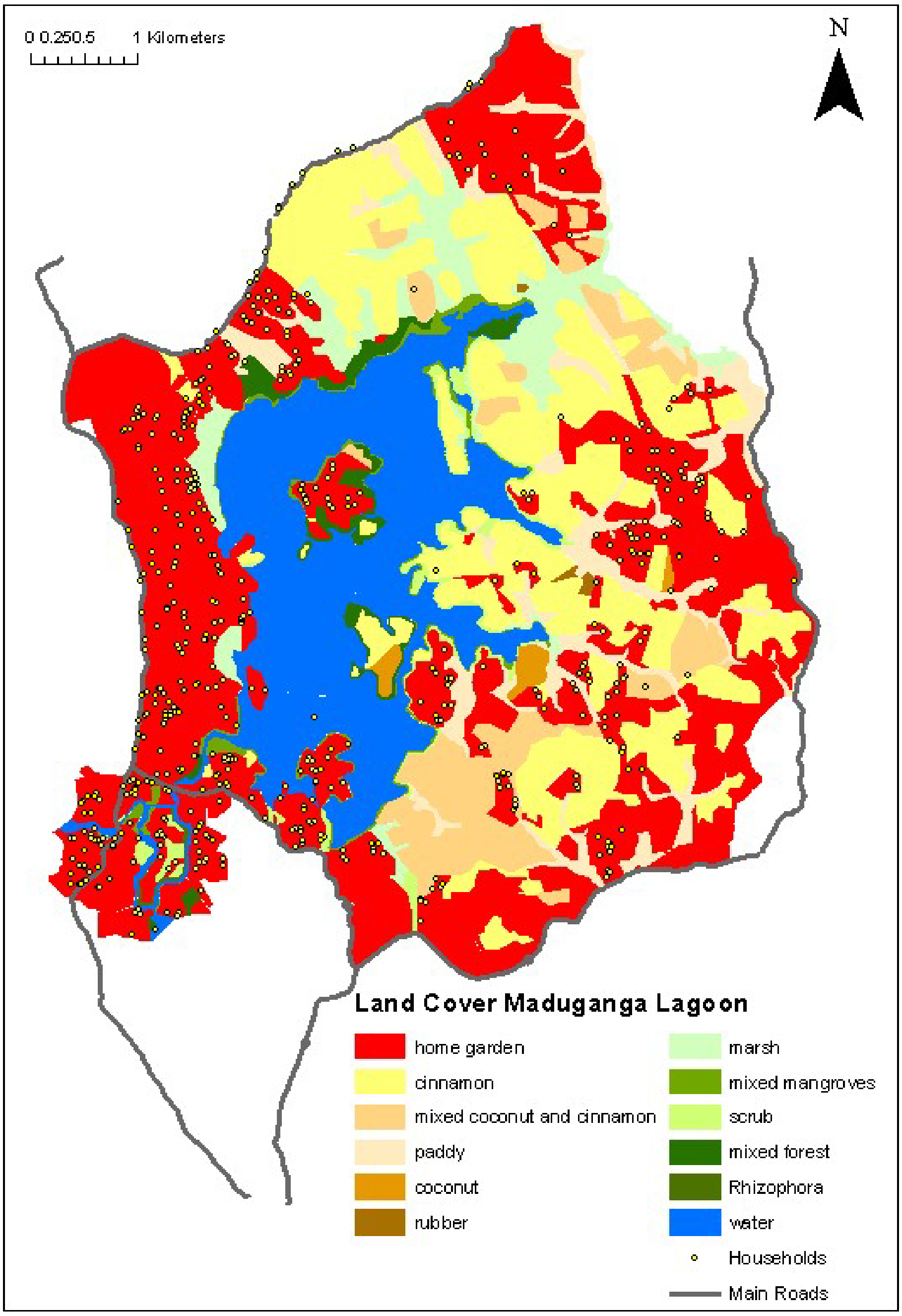

Figure 5.5: Land-cover map of Maduganga; grey lines show the main roads, yellow circles depict the interviewed households.

The classification clearly shows that the study area is dominated by human-influenced land covers. While the western and southern parts are mostly composed of homesteads, the northern and eastern areas are mainly a mixture of homesteads and agricultural uses (Table 5.14).

Table 5.14: Land-cover types and their share in the study area.

Land cover	*Area (ha)*	*Share of study area (%)*
Homestead	1,579	39.1
Cinnamon	808	20.0
Mixed coconut and cinnamon	270	6.7
Paddy	261	6.5
Coconut	23	0.6
Rubber	4	0.1
Marsh	201	5.0
Mixed mangroves	50	1.2
Scrub	62	1.5
Mixed forest	66	1.6
Rhizophora	4	0.1
Water	714	17.7

Most of the land around Maduganga (nearly 40 %) is occupied by homesteads, which are particularly abundant in the western and the southern parts of the study area. This category includes a variety of land uses, which are dominated by human settlements with cinnamon or coconut plantations or other agricultural land uses, as long as homesteads are the main use on the respective plot. While homesteads close to Galle Road and also in the northern part along the road to Uragasmanhandiya mainly consist of houses with small gardens, settlements in the Karandeniya division on the eastern side of the estuary are often more loosely arranged, with the spaces being filled either with cinnamon or mixed coconut and cinnamon plantations.

Pure cinnamon plantations are the second most abundant land use around Maduganga. *Cinnamomum zeylanicum* is an evergreen tree belonging to the family of Lauraceae, which can grow up to more than 20 m when undisturbed. On plantations, it usually has a height of approximately 3 to 5 m. Most farmers grow cinnamon on small plantations (less than 0.4 ha), sometimes around their house, although there are also some large-scale plantations in the eastern part of the study area. The extent of cinnamon plantations has increased in recent years due to the high demand on the world market and thus rising prices (CCD 2004b). In the western part around Ahungalle, the Spanish Red Cross started a program after the tsunami to establish cinnamon farming as an alternative livelihood opportunity by training people on how to plant and process cinnamon and also by providing them with young cinnamon trees.

In order to promote cinnamon cultivation in the area, the Sri Lankan government started a pilot project in 2004 with an expected duration of 6 years (Lindara 2007 pers. comm.). In addition to training on different cinnamon-related issues, this project also provides subsidies for new plants and fertilizer in five cluster villages in Karandeniya.

Problems from cinnamon cultivation around Maduganga arise from the lack of skilled workers for harvesting and processing the cinnamon and from the uncontrolled use of fertilizers and pesticides, which are eventually deposited in the estuary and contribute to eutrophication of the water body (CCD 2004b). In most cases, cinnamon is planted as a monocrop, as it prefers direct sunlight. However, sometimes it is also mixed with other tree crops such as *Cocos nucifera* (coconut palm), but also *Artocarpus altilis* (breadfruit), *Artocarpus heterophyllus* (jackfruit), or *Alstonia scholaris*. When cinnamon plantations contain a significant number of coconut trees (i.e., the harvest is not only used for self-supply anymore), these plantations fall under the third category "mixed coconut and cinnamon", which is, however, not very common in this area.

Particularly in the western parts of the study area, many households have small coconut plantations around their houses for self-supply. As these plots are usually rather small and not the main land use in these areas, they are included in the category homestead. In the Balapitiya DS, 94 % of the coconut plantations are smallholdings (CCD 2004b). Only in the rural east of the estuary some locations with large-scale coconut plantations can be found, which only make up a minor part of the whole study area.

Rain-fed paddy is still an important crop around Maduganga with most of the harvest being consumed by the farming household. However, in recent years, the area used for paddy cultivation has decreased significantly by 44 % from 1994 to 2003 (CCD 2004b). Information gathered from farmers revealed that one reason for this decrease is the malfunction of the gates at the shore of the main water body, which are supposed to keep the brackish water away from the fields. Therefore, many of the former paddy fields are regularly flooded with brackish water and thus have had to be abandoned. Furthermore, the existing irrigation channels are not properly maintained, which results in waterlogging in the fields. In this classification, the abandoned paddy fields have been included in the category marsh. As a benefit, they can serve as filters for surface fertilizer runoff between the estuary and agricultural plots (CRMP 2006). Finally, rubber is of marginal importance. There are only very few small plots in the eastern part of the study area, although generally rubber is a rather common crop in the southwestern part of Sri Lanka.

Apart from water, there are five different non-agricultural land covers around Maduganga. While marshes are still fairly easy to separate from other ecosystems, as they have a different appearance on the satellite images, the discrimination of the other ecosystems from each other is difficult. Therefore, the study mainly used field knowledge as well as ground control points taken with GPS as support for the visual classification. Additionally, previous work conducted by IUCN (Bambaradeniya et al. 2002) was used as support for classification of the non-agricultural land covers.

The marshes in this study comprise regularly flooded ecosystems mainly consisting of *Ischaemum*-*Panicum*-*Cyperus* communities. They also occur as sedge brackish marshes dominated by *Cyperus*, *Eleocharis*, and *Xyris* (Bambaradeniya et al. 2002).

Pure mangrove stands are rare in this area. There are a few spots on Pathamulla Island in the inlet connecting the estuary with the sea, which consist exclusively of *Rhizophora apiculata*. Otherwise mangrove spots are mixed with mangrove associates or non-mangrove vegetation like *Hibiscus tiliaceus*, *Mimusops elengi*, *Cerbera odollam/manghas*, *Annona glabra*, and *Pandanus spp.* (see also IUCN 2000). The forefront of the mostly small mangrove strips is dominated by *Rhizophora apiculata*, which is the most common mangrove species around Maduganga, followed by different combinations of *Sonneratia caseolaris*, *Bruguiera gymnorhiza*, *Acrostichum aureum*, and *Lumnitzera racemosa*. There are also few places with *Nypa fruticans*, the only mangrove palm, which in its young form is a popular vegetable in this area. With increasing distance from the sea in the northern part of the estuary, the extent of *Rhizophora* decreases in favor of the other mentioned mangrove species due to decreasing salinity.

Scrubs describe degraded forests (mangrove or other), which are also mainly located in small strips close to the shore of the estuary or the inlet. The main species in these plots are *Hibiscus tiliaceus* and *Pandanus Spp.*, together with, e.g., *Clerodendrum* and *Cerbera*.

Finally, mixed forest may also contain mangrove species, but non-mangroves make up the majority of this ecosystem type. Most common species are *Alstonia scholaris*, *Aegle marmelos*, *Annona glabra*, *Pandanus Spp.*, *Terminalia catappa*, *Artocarpus*, *Cerbera*, and *Mimusops elengi*. The main spread of these forests is in the northern part of Maduganga, where salinity is lower than closer to the sea. These forests are mostly found close to the banks of the estuary, where they occupy habitats that previously probably were mangroves and have been degraded due to human disturbance.

5.4.2 Spatial accessibility

Accessibility can generally be defined as the ease with which a location may be reached from other locations (Nelson 2000). It is an important factor of development, because it "is a precondition for the satisfaction of almost any need" (Nelson 2000). Therefore, it is seen as an important factor influencing the livelihood particularly of poor people in rural areas (Siegel 2005).

Poor infrastructure and thus restricted accessibility limits opportunities for improving economic status (Nelson 2000) and can generally influence land use and cropping patterns (Edmonds 2002), while on the other hand improved accessibility may also trigger deforestation (Angelsen and Kaimowitz 1999). Therefore, the distance to roads and to markets is often taken as an important parameter in attempts to model LUCC (Agarwal et al. 2002).

Based on information from interviewed households and knowledge of the study area, a network of a few major roads was extracted that, as the main transport hubs, connect the larger settlements within the area with Balapitiya as the largest dwelling and Galle Road as the by far most important road (Figure 5.6). Euclidean distances from the homesteads to the next main road [P_{road}] were calculated with the software package ArcGIS. In this analysis, aspects like condition of the roads leading to these main roads or the actual distance that has to be covered in order to get to the main road were not taken into account. Thus, this measure can only give a basic idea about the limitations of accessibility in the study area. Nevertheless, when considering the fairly extensive network of roads in quite good condition in most parts of the region and the fair availability of public (buses and three-wheelers) as well as private (mostly motorcycles) transport, it is still a helpful measure to discover limitations in access to roads and markets.

Basically, spatial accessibility is comparably good in the study area, as there is an extensive network of tar and dirt roads. However, in the rural areas in the eastern part of Maduganga the dirt roads tend to be in comparably poor condition, which hampers transport during the rainy season. These regions are also not covered by public transport.

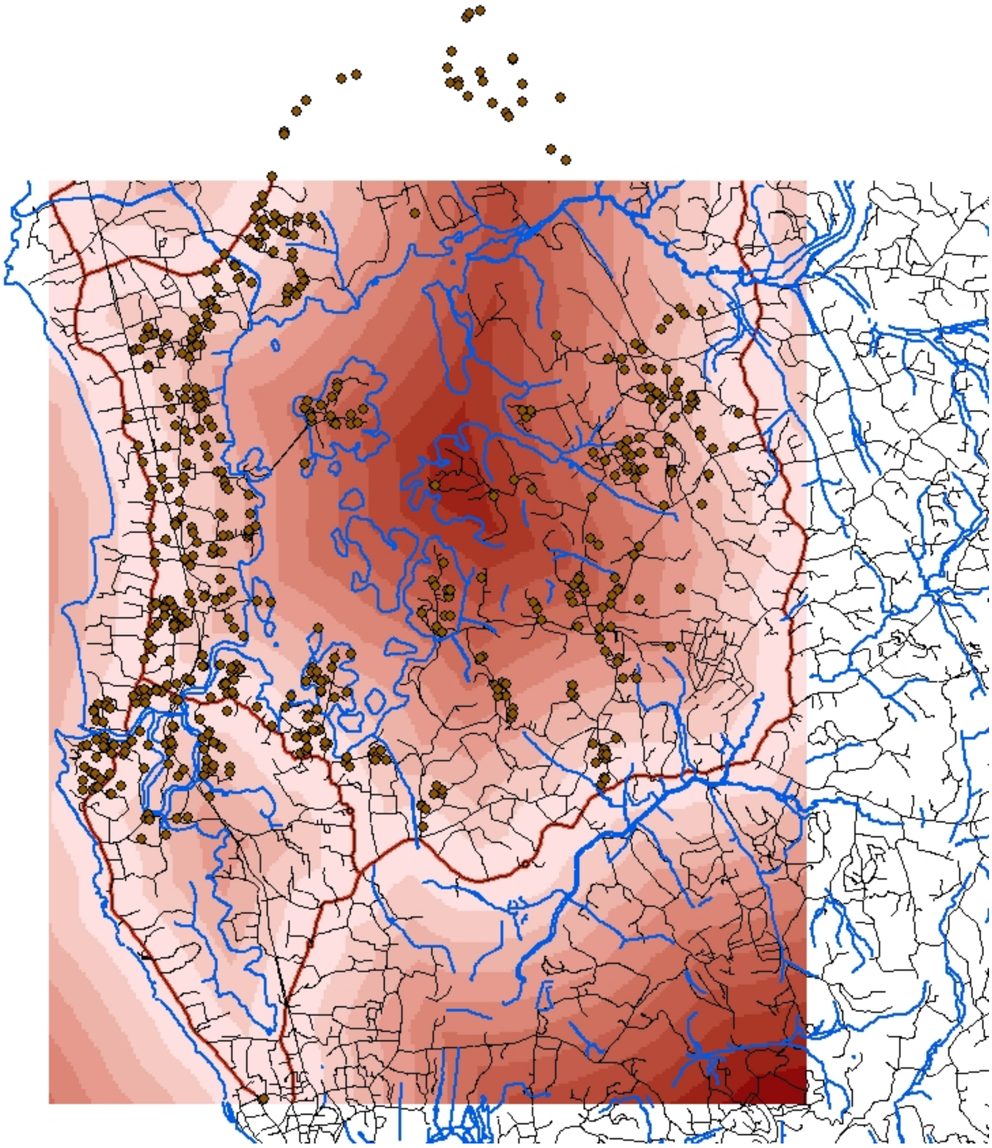

Figure 5.6: Distance of homesteads to next main road (red); scale of distance grid 300 m; main roads in red, homesteads are brown dots.

The same procedure was applied for the Euclidean distance to Balapitiya. As Balapitiya serves as the administrative, transport, and trading center for this region, distance to this town can significantly influence economic behavior and livelihood strategies.

5.5 Summary and conclusions

This chapter introduced the conceptual framework of the agent-based model LUDAS with its four main modules landscape, human, policy, and decision making. It described how LUDAS uses the bounded rationality approach to deal with human decision as one of the most challenging tasks when simulating LUCC. Bounded rationality is a mixture of reflex decision-making mechanisms and rational behavior with the goal of optimizing utility and the prerequisite of complete knowledge. This approach is regarded as being most adequate for a realistic reproduction of human behavior (Huigen 2003; Manson 2004). Similarities and main differences were shown between VN-LUDAS as the original version of the model and the modified SRL-LUDAS, which was designed for the different socio-economic and biophysical conditions in the study region.

In a next step, the Sustainable Livelihoods Framework was introduced, as its assets categories served as the guiding principle for collecting the empirical data necessary for the identification of livelihoods in the study area and the relevant factors influencing decision making on land use of the different livelihood groups. The utilization of the framework ensured that a comprehensive picture of livelihoods was generated, moving beyond the easily identifiable income category.

PCA and Cluster Analysis were used to divide the sampled households into five different livelihood groups. Two of these groups were small with 29 (group 4 – fishermen) and 43 (group 5 – poor households) households, thus it was not possible to include them into the logistic regression for determining their decision making on land use. It is suggested that due to their small size and their livelihoods, which do not depend on land for generating income, their influence on LUCC is low and thus can be omitted from simulations.

The binary logistic regression tested the probability of either homestead or cinnamon to be established against all other land uses. Households of group 3 (urban livelihoods with higher educational level) also had a sufficient number of coconut plots, thus three regression models could be calculated for this group.

The analysis of current land cover is of utmost importance for the biophysical calibration of the landscape grid cells and for generating scenarios of future land cover and land use. The land-cover classification resulted in a fragmentation of the study area into two parts. While the western and southern part of the estuary has an urban profile with only few agricultural plots, the northern and particularly the eastern area has a more rural character with a mixture of homesteads, cinnamon plantations and some paddy fields.

In addition to the land-cover classification, distance measures to the main roads and to Balapitiya served as the main biophysical inputs for SRL-LUDAS. Due to the homogeneity of the study area, further biophysical elements such as topography and soil conditions were not considered for the simulation.

6 INTEGRATED SIMULATION OF SPATIO-TEMPORAL DYNAMICS FOR DEVELOPING SCENARIOS OF LAND-USE AND LAND-COVER CHANGES AROUND MADUGANGA ESTUARY

The previous chapters have shown the complexity of the interplay between socio-economic and biophysical factors including human decision making, when attempting to model LUCC in an integrated way. This complexity implies further aspects such as uncertainty and contingency, and thus makes it impossible to develop accurate predictions about the future development of human-influenced landscapes (Peterson et al. 2003; Le et al. 2010; Nguyen and de Kok 2007). The sustainable management of natural resources requires long-term perspectives, which further increase the degree of uncertainty with regard to the behavior of the system.

Based on the characterization of current conditions, uncertainties and drivers of change, scenarios provide various alternatives for hypothetical future development under contrasting conditions (Nassauer and Corry 2004; Swart et al. 2004; Peterson et al. 2003; Blyth 2005). They show the consequences of certain actions and thus support decision making and understanding of connections between relevant elements of the system. The performance of a scenario depends on how well the model is able to represent reality and particularly human-environment interactions. The heterogeneous influences on land systems require an integrated and long-term scenario-building approach that considers all relevant sectors, disciplines and their methodologies as well as time and spatial scales (Swart et al. 2004). To fulfill this task, a comprehensive understanding of multiple factors driving land-use changes is needed. This requirement can be met by agent-based approaches. When designed adequately, agent-based models (ABMs) are able to simulate the interplay between the human and the biophysical subsystem on various scales in an integrated manner. Many approaches still have a tendency to focus on LUCC on the macro scale while neglecting human decision making on the micro level (Matthews et al. 2005; Manson and Evans 2007; Veldkamp et al. 2001). On the other hand, approaches rooted in the social or the economic sciences prefer to operate on the micro level. Thus, they tend to neglect emergent properties of coupled systems and to treat the biophysical environment as a more or less static component that only reacts to human interventions (Verburg et al. 2004; Veldkamp et al. 2001).

6.1 Policy factors

External influences on the system under consideration are represented by the policy module, which captures and parameterizes land-use related policies, which are assumed to have an impact on the land use and economic patterns in the study region (see section 5.1). With the LUDAS framework, the implementation of these policies will affect the performance of the human-landscape system by:

- modifying the interaction rules between the human agents and their environment;
- affecting decision making with regard to land use through the policy-related variables of the decision model;
- changing the institutional variables of the study landscape that govern human access to land resources.

The selection and parameterization of relevant land-use policies is based on both expert knowledge and the field surveys. Through modifying the policy parameters, users are enabled to simulate the outcome of various policy interventions.

6.1.1 Coastal zone policies in Sri Lanka

The coastal zone in Sri Lanka is mainly under the jurisdiction of the Coast Conservation Department (CCD), which is part of the Ministry of Fisheries and Aquatic Resources Development (MOFARD). The CCD was established in 1963 as the Coastal Protection Unit, and since 1978 it is part of the MOFARD. The Coast Conservation Act, approved in 1981, serves as the legal basis for the work and responsibilities of the CCD. In 1981, the focus of coastal zone management was mainly on erosion control, which is still an important issue. In 1990, the CCD published the first Coastal Zone Management Plan (CZMP), which has been revised approximately every four years. The current version is from 2004 and was approved by the cabinet in 2006 (CCD 2004a).

In the early 1990s, the CCD and the University of Rhode Island revised the policies for coastal zone management in Sri Lanka. In the Coastal 2000 document, they came to the conclusion that more research and a more comprehensive approach is needed for a successful management of the coastal resources (Olsen et al. 1992; Lowry et al. 1999). Thus, in the following years the focus shifted more and more to an integrated coastal zone management and to participatory approaches, with the aim to protect the natural resource base of the coastal zone and at the same time support the livelihoods of the people living in the coastal areas (Aeron-Thomas 2003; Clemett et al. 2004; Samaranayake 2000).

Whereas the CCD is the leading agency for the management of coastal areas in Sri Lanka, further governmental institutions are in charge of different elements of the coastal zone: Forests are under the responsibility of the Forest Department, protection of fauna and flora fall within the remit of the Department of Wildlife Conservation (DWC), and agricultural issues are managed by the Agricultural Department, just to mention a few. These multiple responsibilities, accompanied by a lack of human resources and inefficient governmental processes in general often complicate the implementation of legislative and management measures (UNEP 2003; FAO 2001). This impression was enforced by interviews with the respective agencies, which revealed the rather weak cooperation between the different governmental institutions.

The CZMP serves as the basic tool for all planning activities within the coastal zone, which is defined as the area lying within a limit of 300 m landward of the mean high water line and 2 km seaward of the mean low water line. When there are water bodies connected to the sea either permanently or periodically, the landward boundary extends to a limit of 2 km measured perpendicular to the straight base line drawn between the natural entrance points thereof (CCD 2004a). However, as coastal waters are also influenced by activities implemented further upstream, this definition is regarded as being much too narrow (Aeron-Thomas 2003) and is currently under revision (CCD 2004a).

In 1991, the first two pilot projects of the newly designed “Special Area Management” (SAM) process started in Rekawa and Hikkaduwa. This approach was developed in order to satisfy the need for a more comprehensive and participatory management of the coastal resources. The SAM describes a geographically specific planning process in which the government only serves as a facilitator and mediator. The planning and management is to be mainly conducted by the people concerned, who are represented through “Community Coordinating Committees” (CCC). The SAM process attempts to mediate between the different demands for the utilization of natural resources, while at the same time ensuring a sustainable management of the ecosystems and natural resources (CCD 2004b; Clemett et al. 2004). The sites to be managed under the SAM plan are selected based on the severity of resource management issues, biodiversity, viability of the project, and economic significance (CCD 2004a).

Maduganga is one of the 23 areas that are currently managed as SAM sites. Selection of the sites is based on the severity of issues, biodiversity, viability of the project, and economic significance. The projects are implemented by the “Coastal Resources Management Project” (CRMP), which is financed by the Asian Development Bank and the Dutch as well as the Sri Lankan government.

In addition to these plans and processes, further activities have become important after the 2004 Tsunami. These include measures for coastal protection against natural hazards such as the establishment of a buffer zone in which no construction work is allowed (see Chapter 7). Furthermore, the Ministry of Disaster Management developed a plan for an integrated disaster management (Ministry of Disaster Management 2005) that, for example, calls for integration of disaster risk reduction into development planning. Finally, the Urban Development Authority in cooperation with other governmental agencies developed a practical guide for the establishment of coastal vegetation for protection purposes (UDA 2006).

6.1.2 Coastal zone management in Maduganga

The first management plans for Maduganga were developed in 1997 by the Wetland Conservation Project, which is part of the Central Environmental Authority (Wetland Conservation Project 1997) and in 2000 by IUCN for the Forest Department (IUCN 2000). Although the recommendations in these plans were never implemented, their results served as a basis for the SAM process in Maduganga, which started in 2002 and ended in December 2006 with the development of the SAM plan, which identifies relevant management issues (see section 4.4.1) and gives recommendations for further activities. After the expiration of the project, the process was expected to be continued by the Maduganga Development Foundation. It was established out of the CCC with additional support from the government. So far, no results of this community management process are available.

In addition to the SAM plan, the process also produced an environmental profile of the study area (CCD 2004b) and a zoning study (CRMP 2006). The latter divides the SAM area into different conservation zones, which cover the water body and the flood-prone area up to 2 m above sea level, an uplands area, and the upper catchment. The conservation zone is further subdivided into a protection, partial protection, flood-prone, eco-tourism, motor boat restriction, fisheries, and historic zone. The other two zones are subdivided into agricultural, residential, and tourism development zones. At the time of writing, the zoning study was still awaiting approval by the Sri Lankan government.

The weak enforcement of existing regulations due to limited human resources has to be seen as another aspect with negative impacts on the management of the area. Maduganga was declared as a sanctuary by the Forest Department in 2006, which implies, that sustainable human activities and private ownership of land are allowed and at the same time protection of fauna and flora is ensured. However, so far no monitoring and enforcement activities are intended (Ratnayake 2006 pers. comm.), thus the impact of this protected status on land use in Maduganga is likely to be rather low. The SAM plan also does not give any information on enforcement of implemented regulations.

In addition to the governmental agencies, there are several NGOs that became active around Maduganga after the tsunami and started to implement measures for the improvement of livelihoods. The Red Cross is one of these organizations, which supports people mainly in the northern part of the estuary by establishing cinnamon plantations as a new means for livelihoods. Other organizations promote the reforestation and protection of mangroves, particularly along the inlet connecting the main water body with the sea.

In spite of the several responsible agencies and the existing guidelines and frameworks, there are hardly any regulations that result in concrete impacts on human decision making on land use in the study area. Current zoning and protection rules are only relevant for the area close to the water bodies and thus do not have any large-scale influence on land use around Maduganga. However, after studying relevant government documents, discussing planning issues with various government representatives on the national, regional, and local level, and evaluating information given by local people and local experts, it was decided to evaluate the impact of two policy factors that potentially influence decision making on land use around Maduganga. Apart from homesteads, cinnamon plantations are the most important land use in the area not only in terms of coverage but also in terms of economic importance. Thus, policy factors concerning the cultivation of cinnamon were selected in this study.

6.1.3 Selected policy factors

Fertilizer subsidies

During the surveys, only a few people reported that they had received subsidies for cinnamon cultivation, mainly in the form of lower prices for fertilizer, i.e., lowering the price to half of the original price. As fertilizer is one of the few required inputs for cinnamon cultivation, apart from manpower, for increasing the yield, the effect of this measure can be expected to be very strong. Chemical fertilizers increase the productivity of the agricultural activities and thus contribute to a higher profit of the farming household. In addition to the intensification of crop production on existing cinnamon plots, the distribution of fertilizers may also encourage the opening of new plots. Furthermore, subsidized fertilizers may be redistributed to other crops such as paddy, and through this pathway may foster rice production. The eligibility for receiving subsidies depends on membership in an agricultural society, which, according to information received during the questionnaires, is open to everybody. However, most respondents were not aware of such societies and the possibilities of receiving subsidies. Subsidies for paddy were mentioned much less frequently, and for coconuts no subsidies were reported.

Interviews with local government representatives revealed that in 2004 a pilot project was initiated to provide the farmers in the area not only with subsidies for fertilizer, but also with young cinnamon plants. This support, which was established for an initial period of six years, is complemented by training activities for the proper management of the cinnamon plantations. The program has been implemented in five villages in the Karandeniya division. If the project proves to be a success, it is expected to be extended to further villages around the estuary.

Due to the potential importance of agricultural subsidies for the spread of cinnamon plantations and due to the actual implementation of a subsidy project by the Sri Lankan government, it was decided to set the access to subsidies as one external policy factor for simulation in SRL-LUDAS. It is represented by the percentage of households who receive subsidies for agricultural activities.

Access to agricultural extension services

During the surveys, 51 out of the 538 interviewed households mentioned access to some kind of extension services on various topics related to agricultural activities during the last two cropping seasons; 35 of these households reported advice on issues related to cinnamon. The frequency mostly varied between one and four contacts with an extension agent within this period. Discussions with local agricultural offices in Ahungalle and Karandeniya revealed that there are several extension programs for various crops with a focus on cinnamon and to a lesser extent on coconut. There is one agricultural field officer for every GN division as the smallest administrative level in Sri Lanka. The pilot program on cinnamon subsidies also includes the provision of training to cinnamon farmers. Looking at this information and taking into account the importance of particularly cinnamon as a cash crop, but also of coconuts and paddy rice for local households, the low amount of extension services as mentioned during the survey is rather surprising.

When designed properly, access to extension services has significant impacts on the economic performance of agricultural activities (Birkhaeuser et al. 1991; Anderson and Feder 2007). It can increase the economic return of farmers and thus influence their decision making on acquiring new land. It may also influence the behavior of people currently not involved in agricultural activities, as it affects attractiveness of farming. This important aspect and the fact that extension activities already exist and have a potential for expansion led to the decision to include this parameter as the second policy factor, which is expected to influence human decision making on land use in the study area. It is parameterized through the percentage of households who have access to extension services.

6.2 Policy intervention scenarios

Based on the two selected policy factors and the respective parameters, several scenarios were defined and tested for a simulation period of 20 years. All scenarios were run 6 times in order to take into account the stochastic elements of the description of human behavior and to reduce the effect of stochasticity on the results. The application of stochasticity provides an adequate means to deal with the complex, uncertain, and stochastic nature of human decision making (Bonabeau 2002; Briassoulis 2000). The scenarios can be grouped into four different categories:

6.2.1 Baseline scenario

The baseline scenario (S-0) reflects the policy setting at the time of the field work (2006). The field survey reveals that the number of households reached by extension services and by subsidies with regard to cinnamon was very low at that stage. Particularly the subsidy program for cinnamon fertilizer and plants had not spread very far, so that only 1.7 % of all surveyed households reported receiving support from the government. Therefore it was decided to set both access to extension services and to subsidies to 0 % for the baseline scenario.

Scenarios for the impacts of changes in access to extension services

Three different scenarios were tested to analyze the impact of changes in the access to extension services. In these scenarios, access to subsidies was always set at 0 % while the value for access to extension was set on different levels: In the low-extension scenario ($S\text{-}ext_{low}$) access to extension services was set to 25 %, in the medium-extension scenario ($S\text{-}ext_{med}$) to 50 %, and in the high-extension scenario ($S\text{-}ext_{high}$) to 75 %.

Scenarios for the impacts of changes in access to agricultural subsidies

The scenarios for analyzing the impacts of changes in access to agricultural subsidies were developed in the same manner as the extension scenarios: In the low-subsidies scenario ($S\text{-}sub_{low}$) access to extension services was set to 25 %, in the medium-extension scenario ($S\text{-}sub_{med}$) to 50 %, and in the high-extension scenario ($S\text{-}sub_{high}$) to 75 %. The access to extension services in these scenarios was always set at 0 %.

Combined scenario

The single scenarios only checked the impact of changes in one policy factor, while the other factor was set on a constant level. The combined scenario modified both factors in order to see if the combination of increased access to agricultural subsidies and agricultural extension services produces any differences in the development of land use or livelihoods. Due to the comparably small effect of the selected policy factors in the single scenarios, the combined scenario was designed with high access to both factors (75 %) to see if this strong intervention results in any meaningful changes. The above-mentioned subsidies program by the Sri Lankan government is accompanied by more intensive extension services, so the combined scenario can be seen as a simulation of this program. Finally, the results of the combined scenario were compared to the single scenarios.

6.3 Visualization and testing of impacts of land-use related policies with SRL-LUDAS

6.3.1 Input

For the initialization of the socio-ecological system, LUDAS uses two types of data. GIS data are imported as text files, while the household data are available as worksheets (Excel). Before importing the data into the model, both types of data had to be processed in order to provide a realistic description of the coupled system (see Chapter 5).

The cluster analysis resulted in the separation of the surveyed households in five different livelihood groups (see section 5.3.4). However, the simulations with SRL-LUDAS were only conducted with groups 1 (urban livelihoods with lower educational level), 2 (cinnamon farmers), and 3 (urban livelihoods with lower educational level), while groups 4 (fishermen) and 5 (poor households) were omitted. The number of plots of these two groups in the various land-use categories was not sufficient to develop binary logistic regression models (Table 5.6). The households in these groups mainly rely on non-farming activities for their livelihoods. For this reason and the fact that the two groups are by far the smallest of the 5 livelihood groups, it is assumed that their influence on land use and land cover in the study area is negligible, and their omission does not cause meaningful changes in the simulation results.

Parameters for SRL-LUDAS can also be separated into two different categories. The modeler input parameters are embedded in the model and cannot be changed by the user. They contain the extracted coefficients from the data processing of the spatial and the land-use information. The user input parameters on the other hand are mainly the policy parameters, which can be modified by the user in order to test the effect of different policies on land use and livelihoods. One of the main characteristics of SRL-LUDAS is its simplicity, which makes it particularly easy to use also for inexperienced users (Figure 6.1). They can modify the global parameters (e.g., number of households) and the policy factors through simple sliders to test the impact of various policy scenarios on land use and land cover. Through the sliders, the user determines the percentage of households in the study area having access to agricultural subsidies and to agricultural extension services.

6.3.2 Output

The results of these scenarios are shown in blocks 3 and 4 of the user interface: Block 3 contains the maps of the temporal development of land use/cover over space, while block 4 shows the time-series graphs, displaying the development of various indicators of the coupled socio-ecological system under consideration. These indicators are divided into two categories: Biophysical indicators include the extent of main land use/cover types in the study area and the extent of the various landholdings of the households, split into the three main livelihood groups. Socio-economic indicators comprise share of income of households from various income-generating activities, overall monthly income per person, number of households, Lorenz curve, and Gini index. The first three indicators are again split into the three livelihood groups. The share of income from different activities is split into income from farming, farm employment, fishery, and non-farming activities.

These analyzed parameters clearly show one of the main differences between SRL-LUDAS and VN-LUDAS: Not only does the VN version have a stronger focus on biophysical indicators, it also does not differentiate between the various livelihood groups. The groups around Maduganga show strong differences in their livelihood profiles, which naturally also affects their utilization of land for income generation and their decision making on land use. Thus, the different tested policy scenarios caused behavioral differences with regard to land use and livelihood strategies between the three analyzed livelihood groups.

The Lorenz curve is a graphic description of an economic function and represents the probability distribution of statistical values. It is often used for displaying the distribution of income. The straight black line depicts an equal distribution, i.e., it is the line of perfect equality, while the red Lorenz curve describes the observed distribution. The Gini index or Gini coefficient as a measure of inequality in income is also calculated on the basis of the Lorenz curve. It describes the ratio of the area between the line of equality and the Lorenz curve to the total area under the line of equality. The Gini index can range from 0 to 1. The closer the Lorenz curve approximates the line of perfect equality, the lower the value of the Gini index. Thus, a Gini index closer to 1 describes a higher inequality in income distribution.

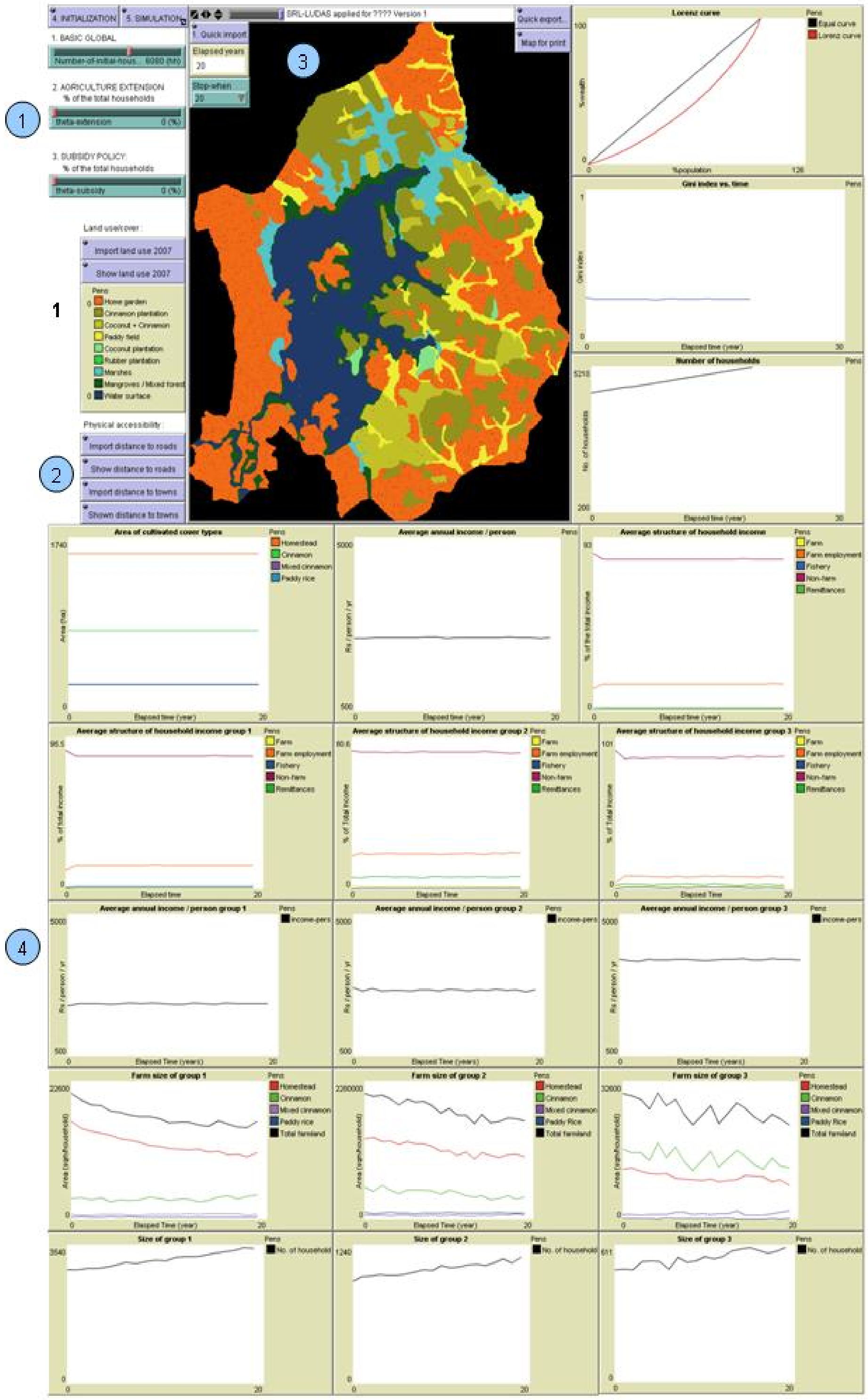

Figure 6.1: Graphic user interface of SRL-LUDAS. Main components are: 1. Global parameters, modifiable by the user; these are the number of initial households and the two policy factors. 2. Spatial attributes of study area (distance to main roads, distance to town). 3. Multi-temporal maps of land use/cover and landholdings; 4. Time-series graphs of various landscape dynamics and socio-economic indicators. Details of graphs are given in the text.

6.4 Results

6.4.1 Impacts of changes in access to fertilizer subsidies

The increase in agricultural subsidies had only marginal effects on the gross income of the households around Maduganga in any group. The simulations reveal that better access to subsidies for fertilizer lead to a higher gross income of the households. The income over all groups is slightly higher for S-sub$_{med}$ and S-sub$_{high}$, which is due to group 2, where these trends also became visible (Figure 6.2 for S-sub$_{high}$). When comparing S-sub$_{med}$ to the S-0 scenario, the difference is even smaller. However, due to the large uncertainties the significance of these differences cannot be confirmed.

Increases in agricultural subsidies do not cause any changes in the share of income from fishery and farm employment activities. Irrespective of access to subsidies, the share of income from farming decreases in all scenarios for all groups. For the base scenario, this results in a reduction of this variable by 13 % on average after 20 years. The subsidies scenarios all stay on a significantly higher level than the base scenario (Figure 6.3 to 6.5). Furthermore, the share of income from agricultural activities increases with increasing subsidies.

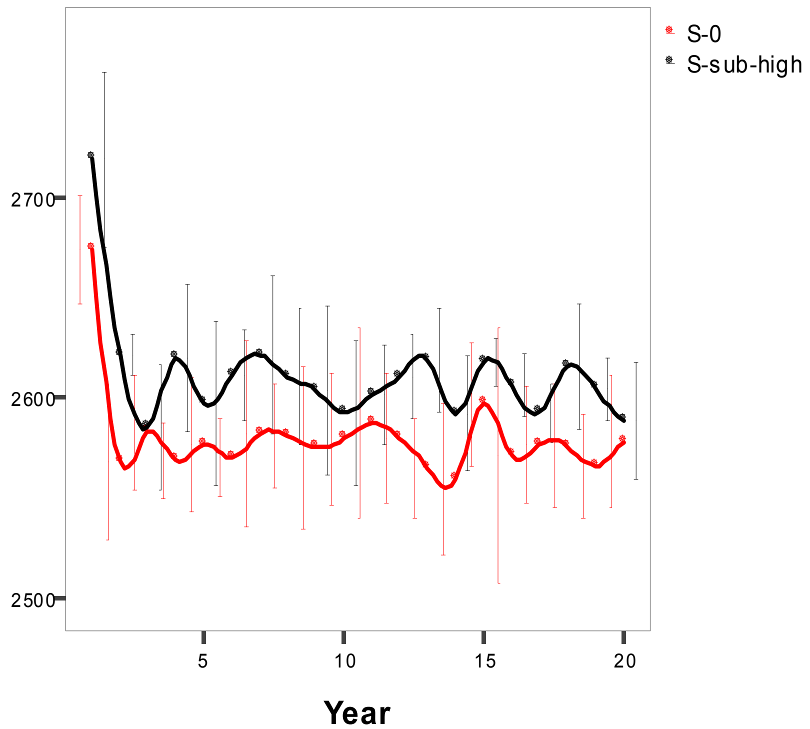

Figure 6.2: Gross income per person (LKR) for households of group 2 in scenario S-sub$_{high}$ versus baseline (S-0).

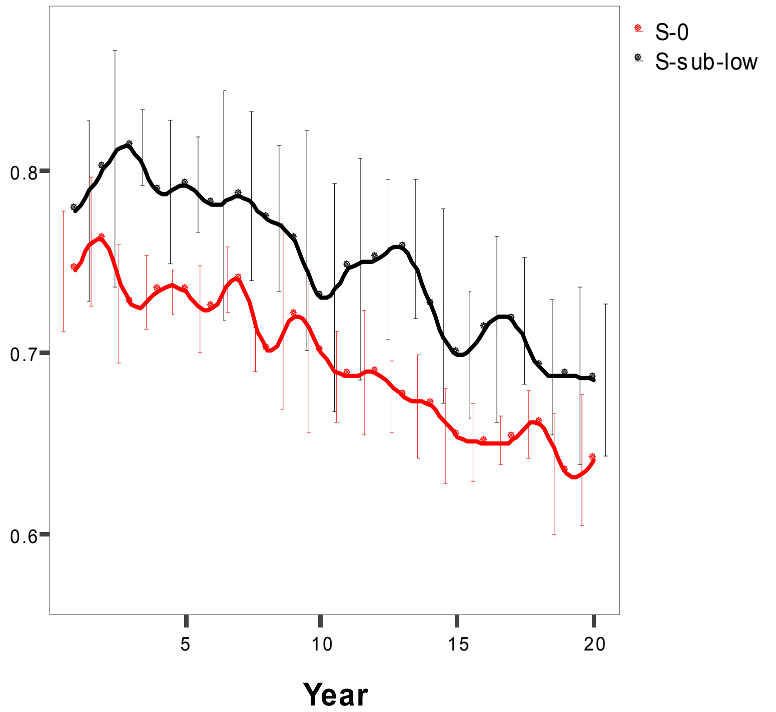

Figure 6.3: Income from farming (percentage of total income of household), all groups, in S-sub$_{low}$ versus baseline (S-0)

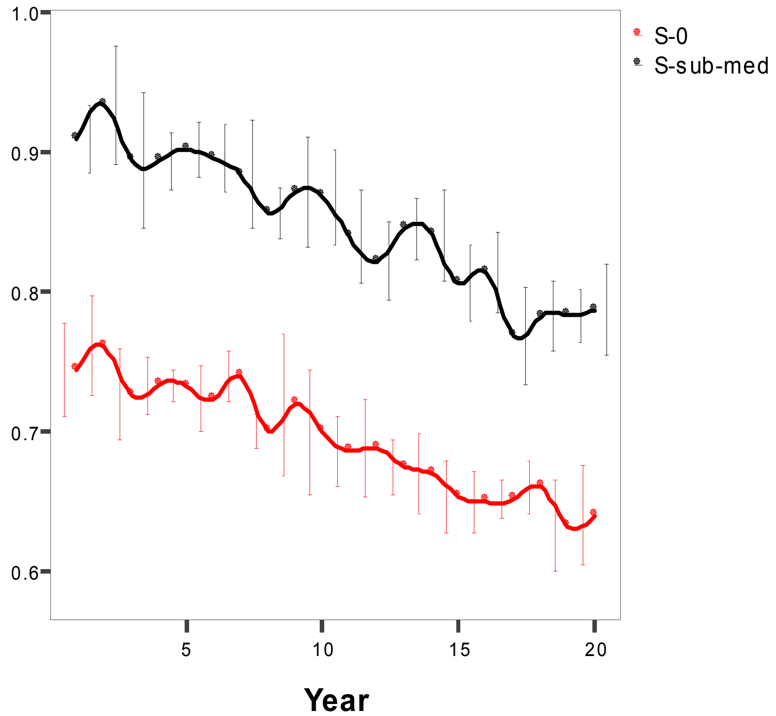

Figure 6.4: Income from farming (percentage of total income of household), all groups, in S-sub$_{med}$ versus baseline (S-0)

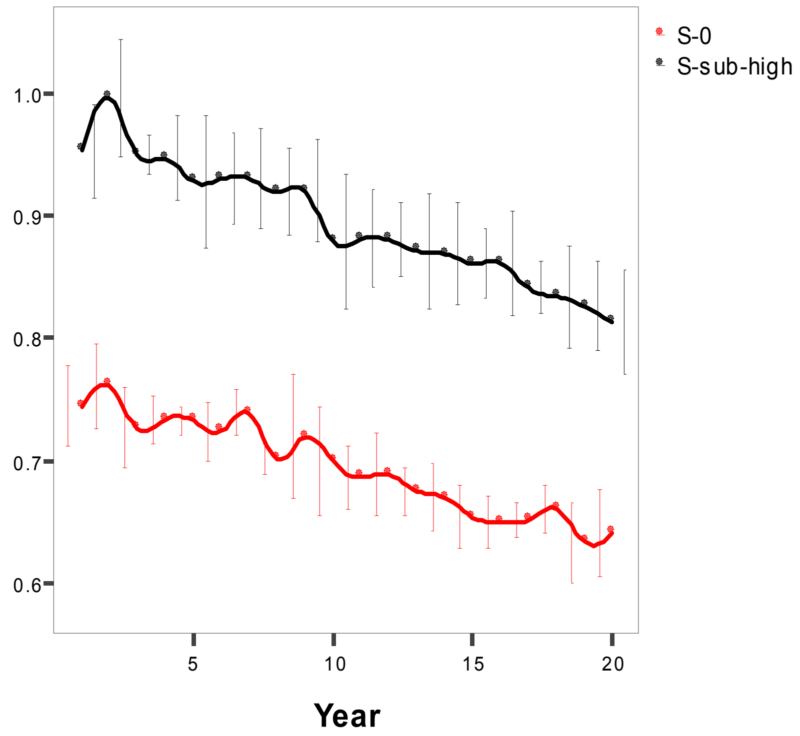

Figure 6.5: Income from farming (percentage of total income of household), all groups, in S-sub$_{high}$ versus baseline (S-0)

The response of income from farming to changes in access to fertilizer subsidies is different across the three livelihood groups. For group 2, this response is strongest and similar to the response of the whole population. It shows that the share of income from farming activities increases significantly with higher access to subsidies (Figure 6.6 to 6.8). The share of income from farming is higher in groups 2 and 3 compared to group 1. While for group 2 as the (cinnamon) farmers, this could be expected, it is rather surprising for the urban group 3. However, it is suggested that due to their higher income, households of group 3 have the ability to keep cinnamon plots in addition to their main non-farming activities. Work on the cinnamon plots is then not carried out by the household members themselves. They would rather hire external workforce, which is comparably expensive for cinnamon production.

The share of income from non-farming activities in group 2 decreases slightly with increasing subsidies (Figure 6.9 to 6.11). This development suggests that increasing the access of the (cinnamon) farmers to fertilizer subsidy programs would lead to a higher resource allocation (e.g., labor) to agricultural activities, subsequently reducing the resources available for non-farm activities.

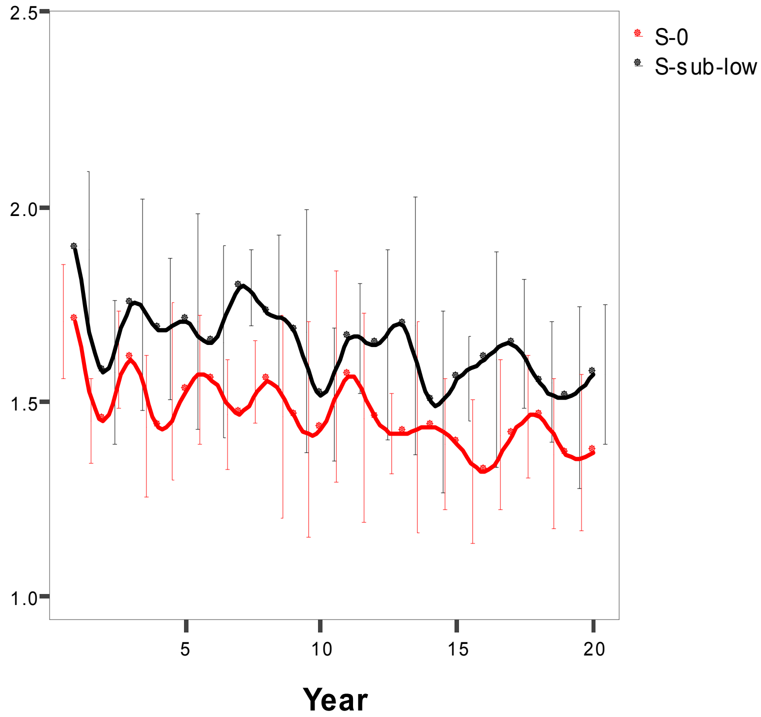

Figure 6.6: Income from farming (percentage of total income of household), group 2, in S-sub$_{low}$ versus baseline (S-0)

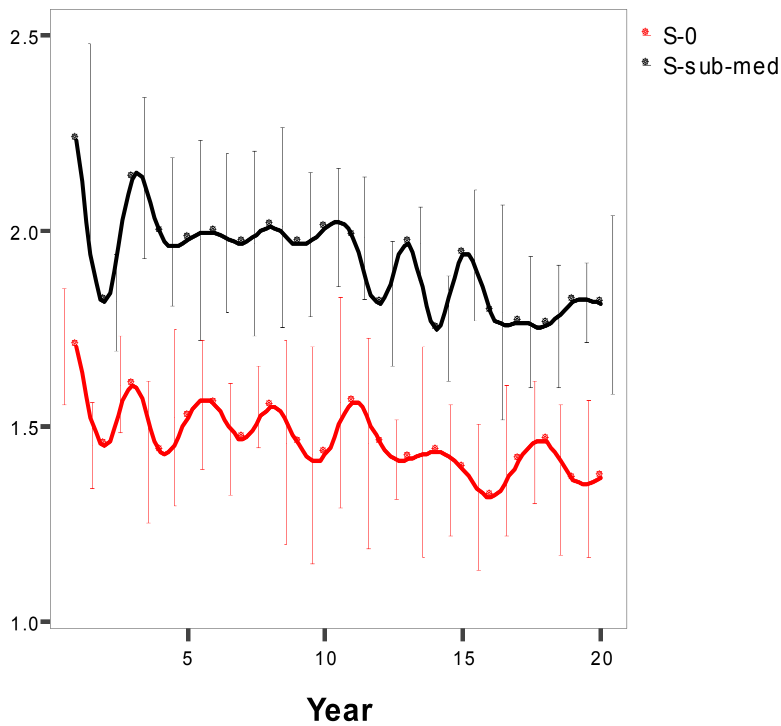

Figure 6.7: Income from farming (percentage of total income of household), group 2, in S-sub$_{med}$ versus baseline (S-0)

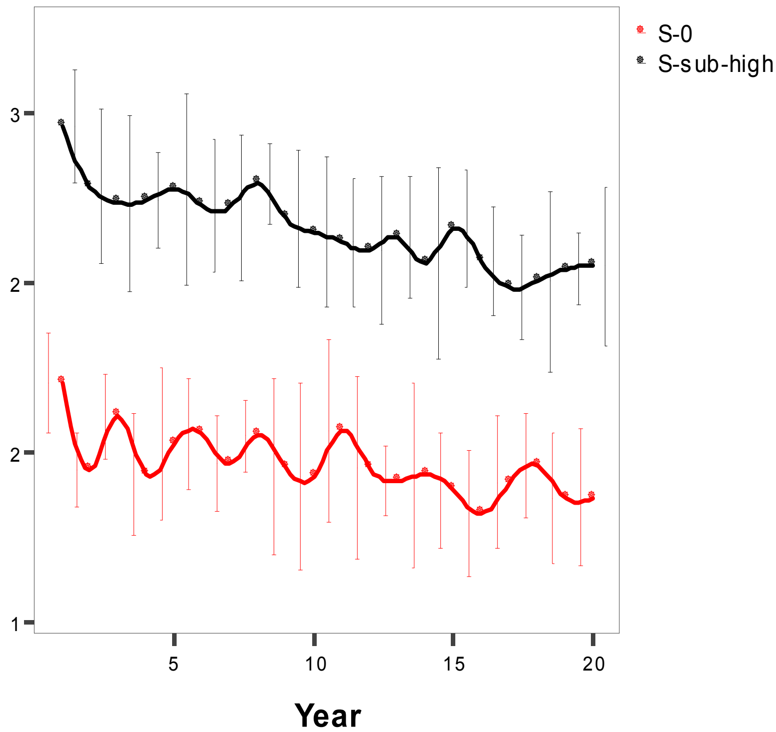

Figure 6.8: Income from farming (percentage of total income of household), group 2, in S-sub$_{high}$ versus baseline (S-0)

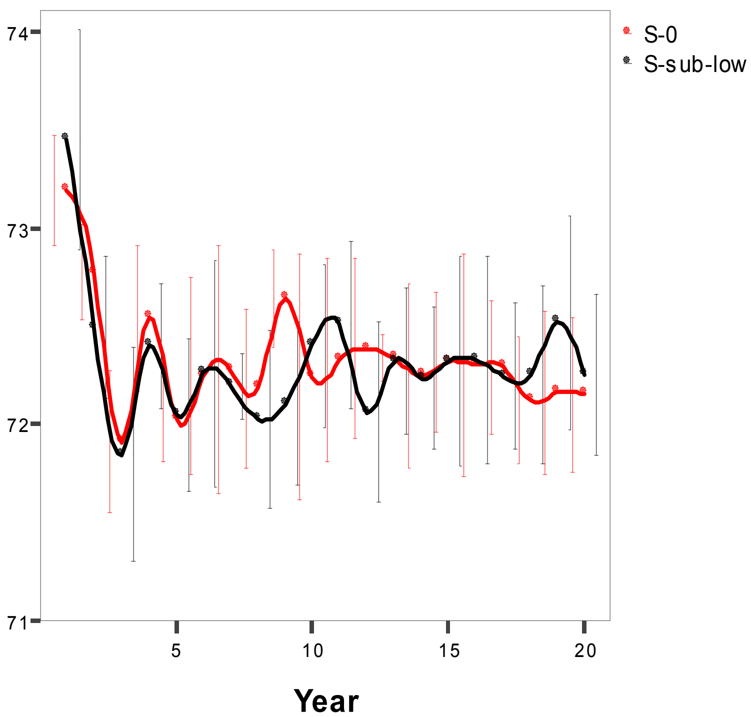

Figure 6.9: Income from non-farming activities (percentage of total income of household), group 2, in S-sub$_{low}$ versus baseline (S-0)

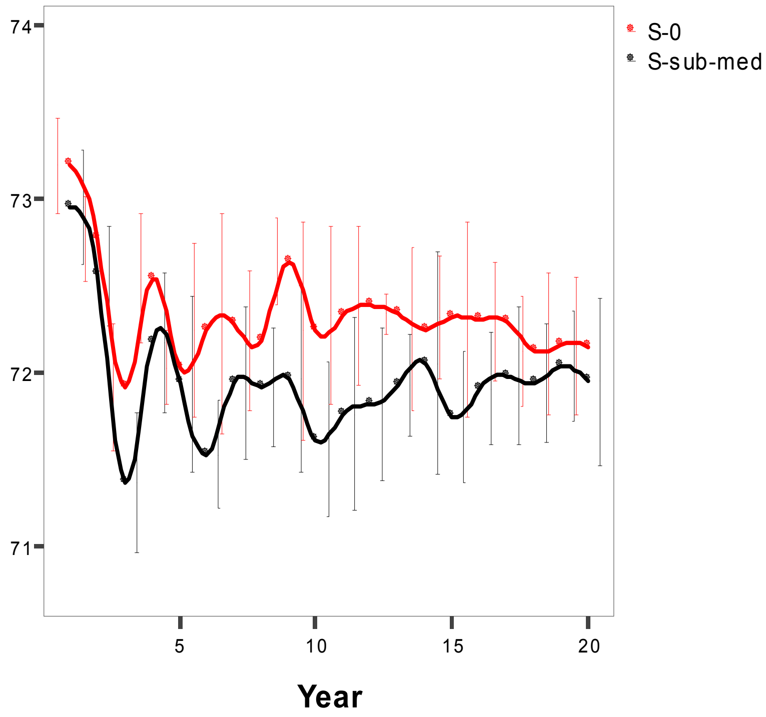

Figure 6.10: Income from non-farming activities (percentage of total income of household), group 2, in S-sub$_{med}$ versus baseline (S-0)

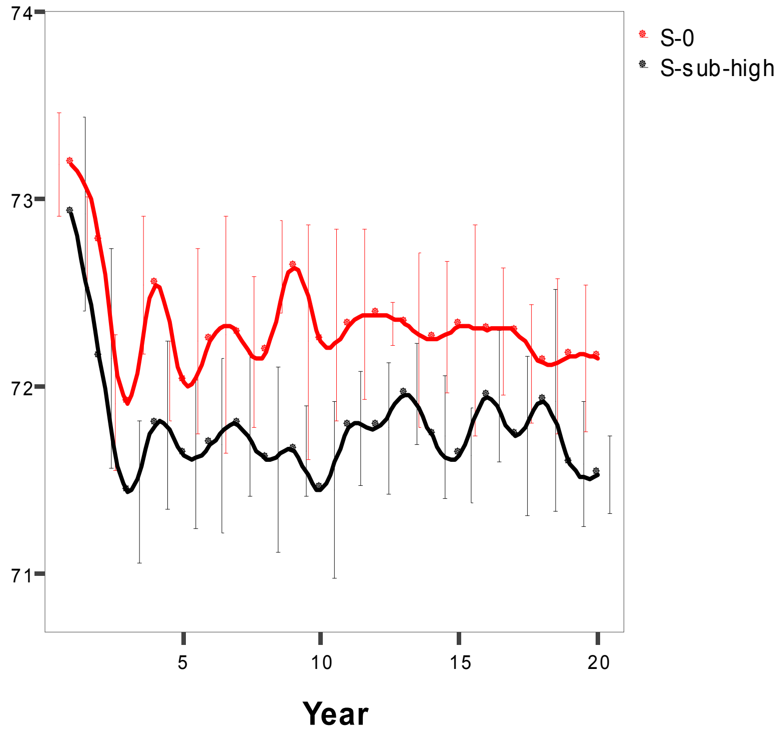

Figure 6.11: Income from non-farming activities (percentage of total income of household), group 2, in S-sub$_{high}$ versus baseline (S-0)

With regard to the effect of the subsidies scenarios on the various land uses around Maduganga, the overall decrease in the households' landholdings in all scenarios indicates that land pressure will become a serious problem in the study area in the next decades. In S-0, the total amount of landholdings after 20 years for households of group 1 is only 77 % on average of the starting value, while this number is 79 and 73 % for groups 2 and 3, respectively. The impact of the three subsidies scenarios on this development is only minor. Increases in agricultural subsidies do not modify the decrease in landholdings of the households in groups 2 and 3. In group 1, the decrease stops after approximately 14 years in the S-sub$_{low}$ and S-sub$_{high}$ scenarios, and then there is a slight upward trend, which however is not significant (Figure 6.12 to 6.14).

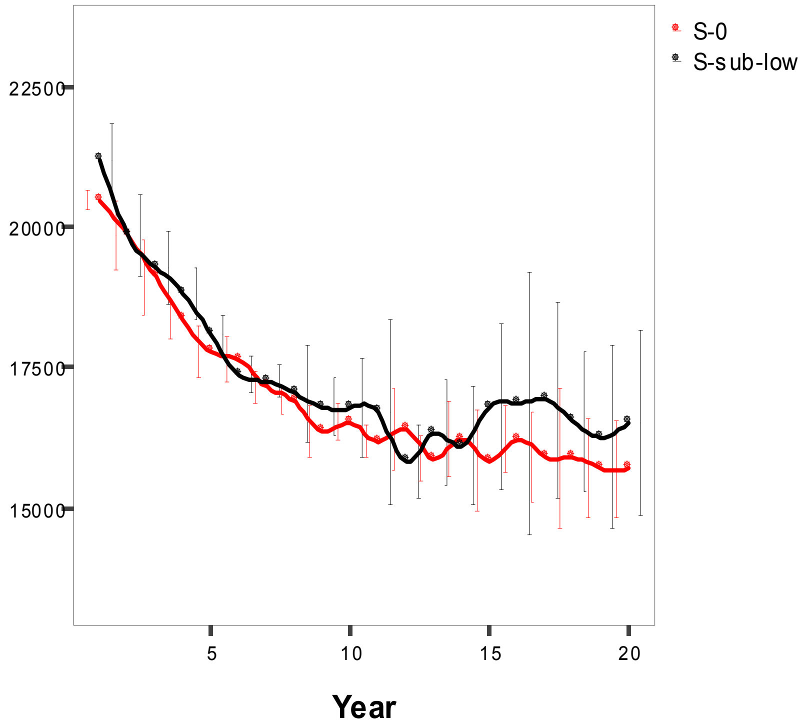

Figure 6.12: Total landholdings (in m^2), group 1, in S-sub$_{low}$ versus baseline (S-0)

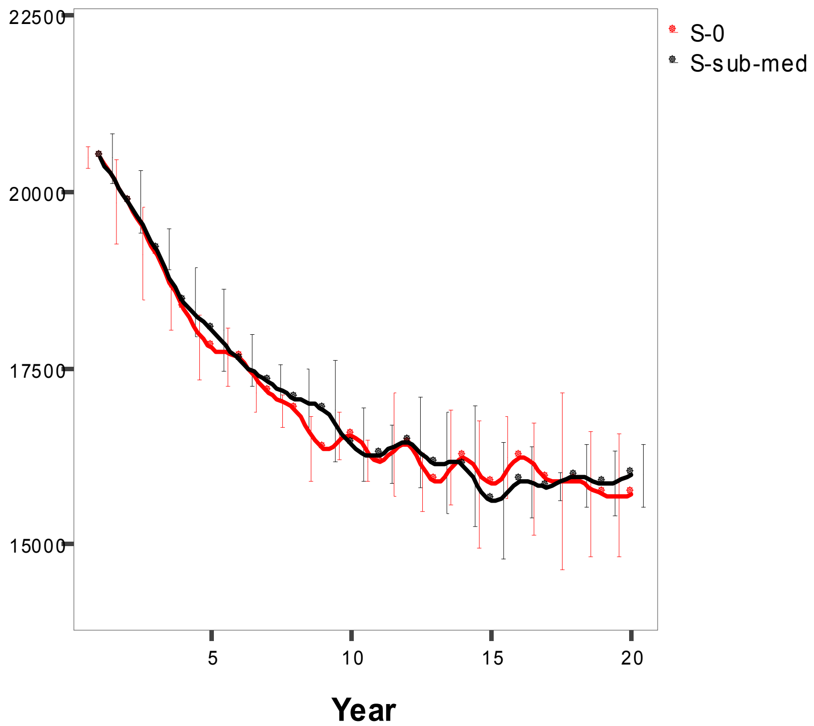

Figure 6.13: Total landholdings (in m^2), group 1, in S-sub$_{med}$ versus baseline (S-0)

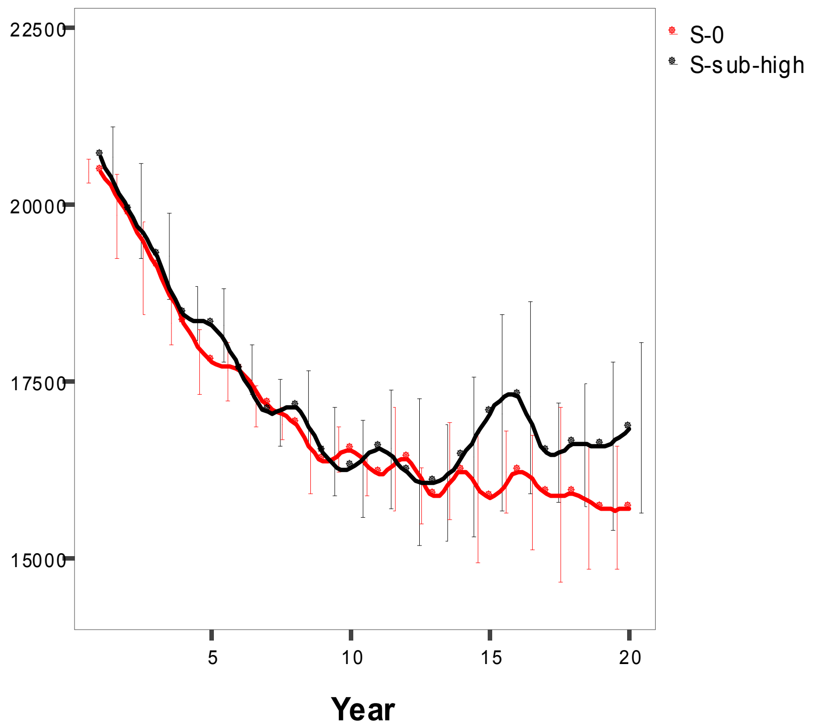

Figure 6.14: Total landholdings (in m^2), group 1, in S-sub$_{high}$ versus baseline (S-0)

Looking at the different land uses in detail reveals that the area of cinnamon plantations also shows a slightly decreasing trend in all groups and all scenarios. For S-0 in group 1, the cinnamon area is still 89 % on average of the starting value after 20 years, while it is only 79 and 74 % for groups 2 and 3, respectively. However, the simulations did not show a significant impact of changes in access to subsidies due to large uncertainties ranges of the scenarios over the whole period (Figure 6.15 to 6.17 for group 2).

Mixed cinnamon plantations were more influenced by changes in access to agricultural subsidies. In groups 1 and 2 subsidies caused decreases in mixed cinnamon area, while in group 3 mixed cinnamon plantations increased through the introduction of subsidies (Figure 6.18 to 6.26). But again, uncertainty ranges for the various scenarios are large, so that the observed trends cannot be confirmed.

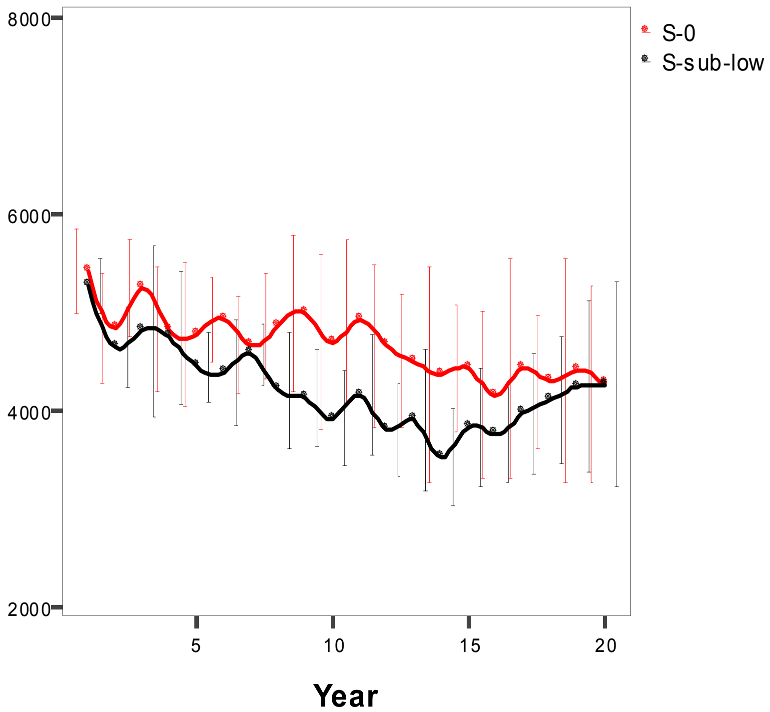

Figure 6.15: Cinnamon area (in m^2), group 2, in S-sub$_{low}$ versus baseline (S-0)

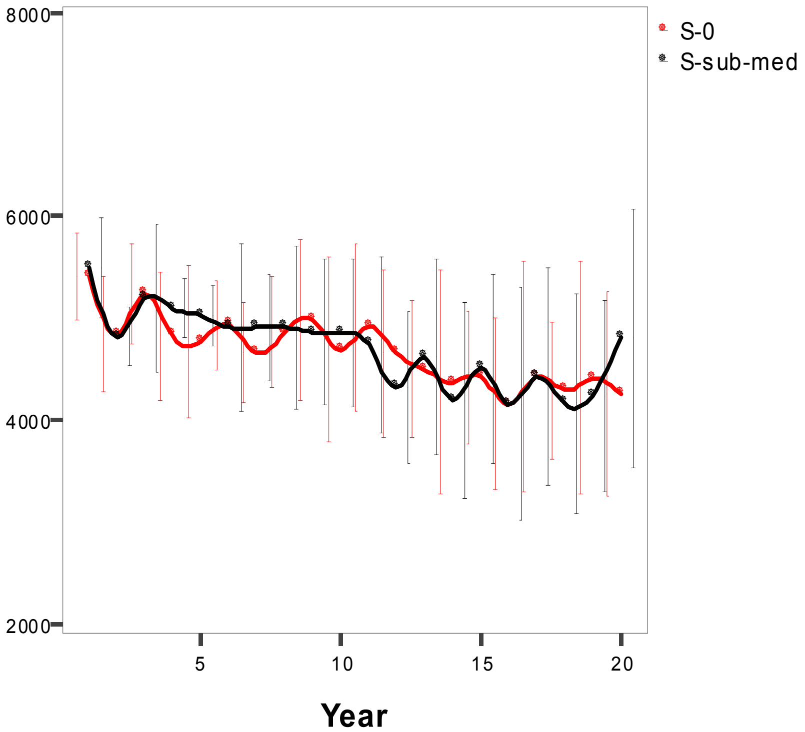

Figure 6.16: Cinnamon area (in m^2), group 2, in S-sub$_{med}$ versus baseline (S-0)

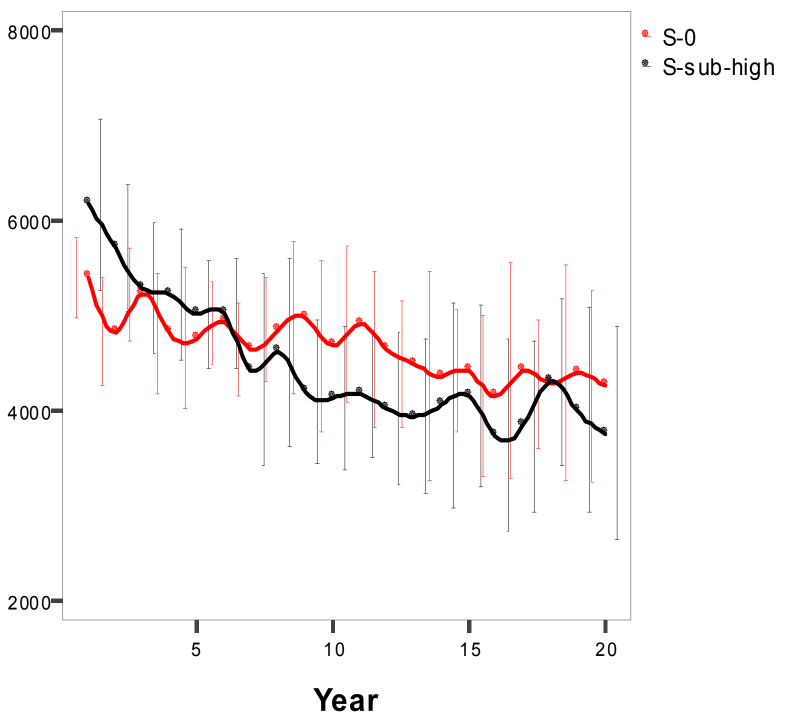

Figure 6.17: Cinnamon area (in m^2), group 2, in S-sub$_{high}$ versus baseline (S-0)

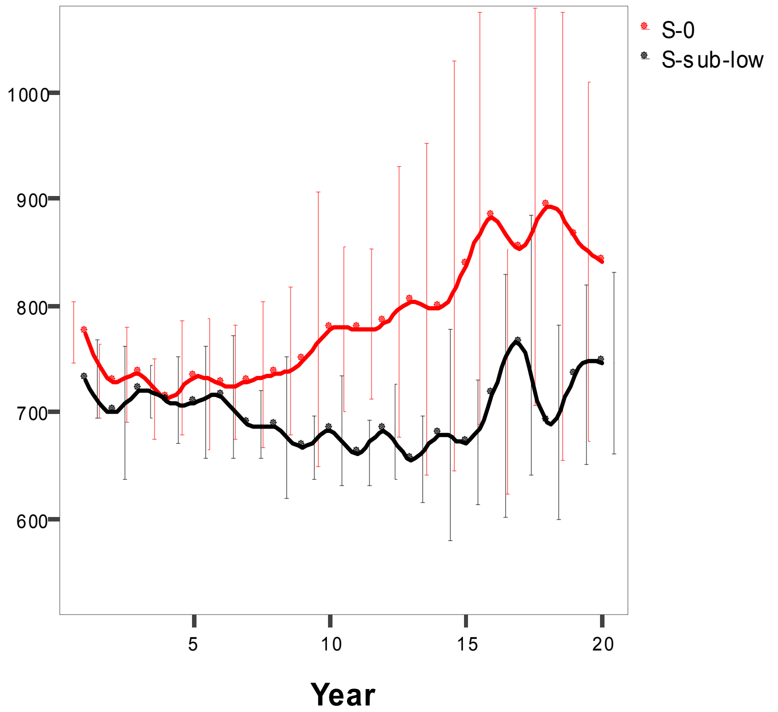

Figure 6.18: Mixed cinnamon area (m^2), group 1, in S-sub$_{low}$ versus baseline (S-0)

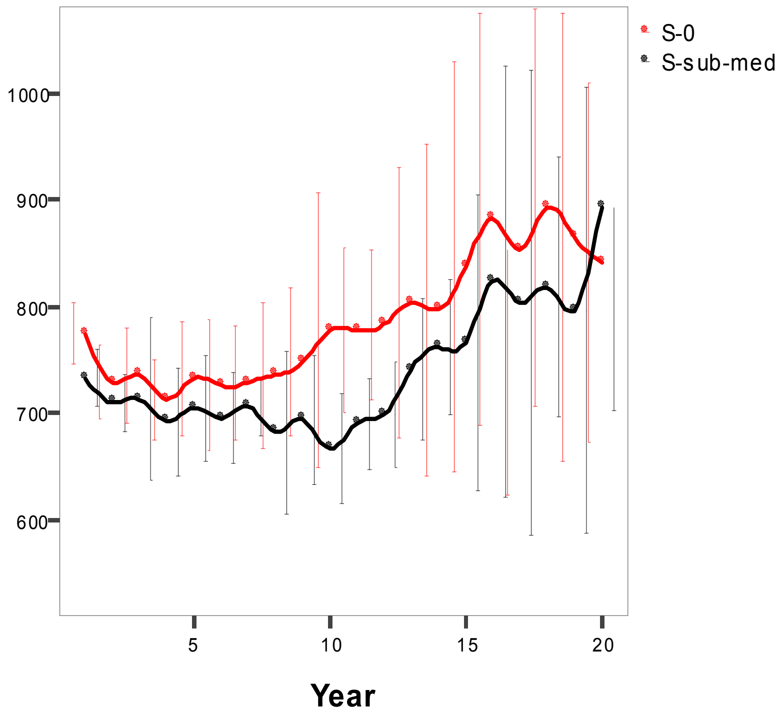

Figure 6.19: Mixed cinnamon area (m^2), group 1, in S-sub$_{med}$ versus baseline (S-0)

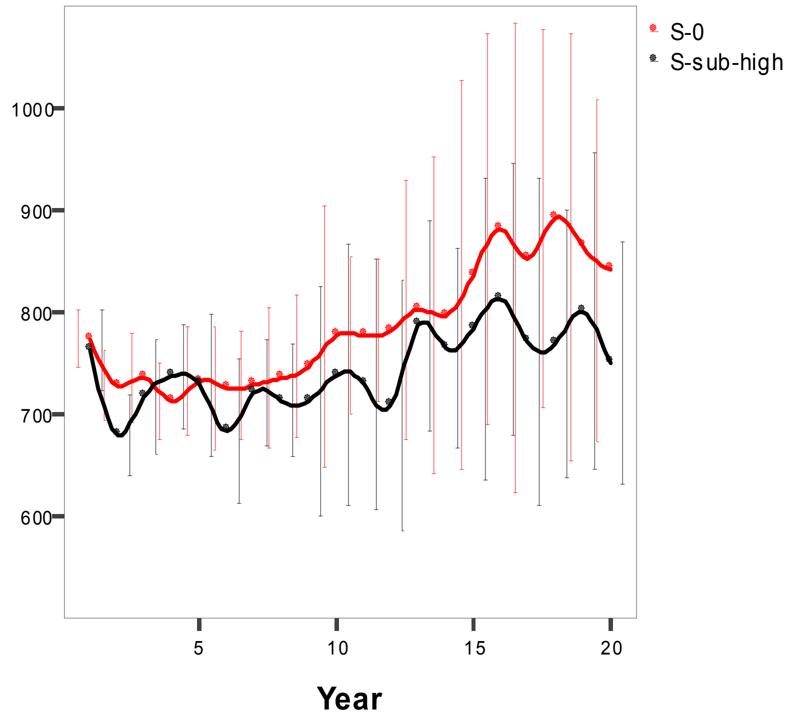

Figure 6.20: Mixed cinnamon area (m²), group 1, in S-sub$_{high}$ versus baseline (S-0)

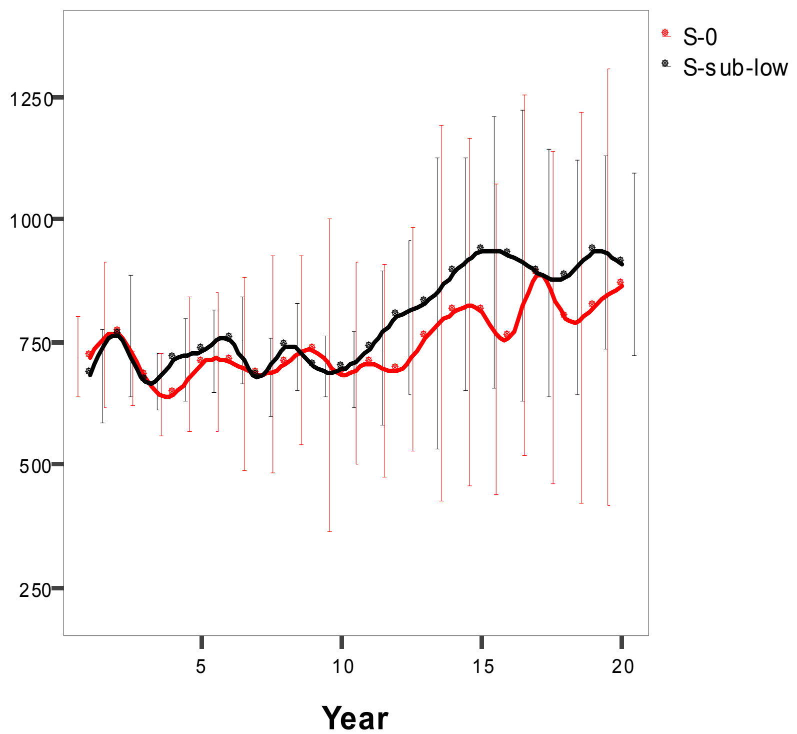

Figure 6.21: Mixed cinnamon area (m²), group 2, in S-sub$_{low}$ versus baseline (S-0)

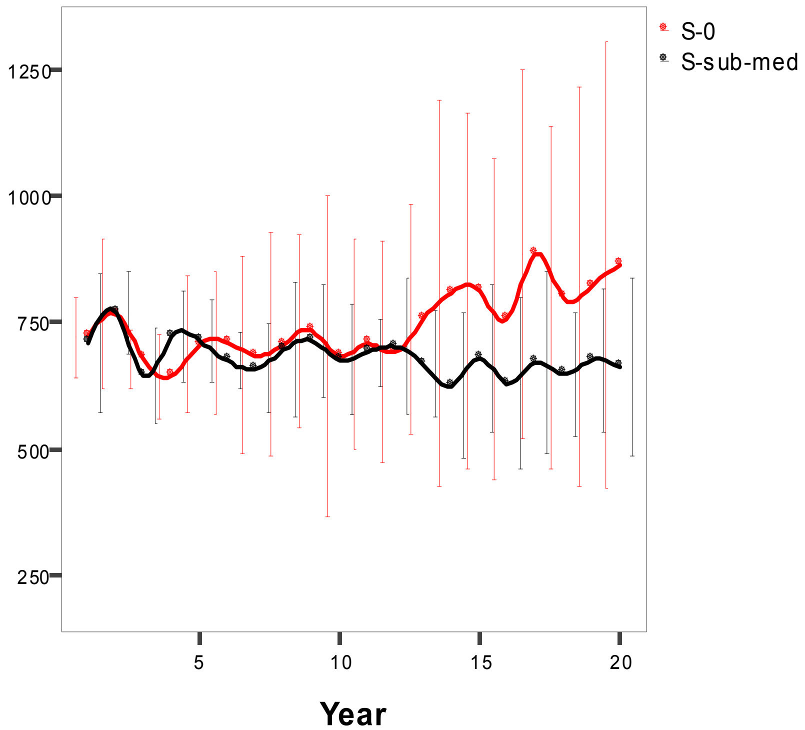

Figure 6.22: Mixed cinnamon area (m^2), group 2, in S-sub$_{med}$ versus baseline (S-0)

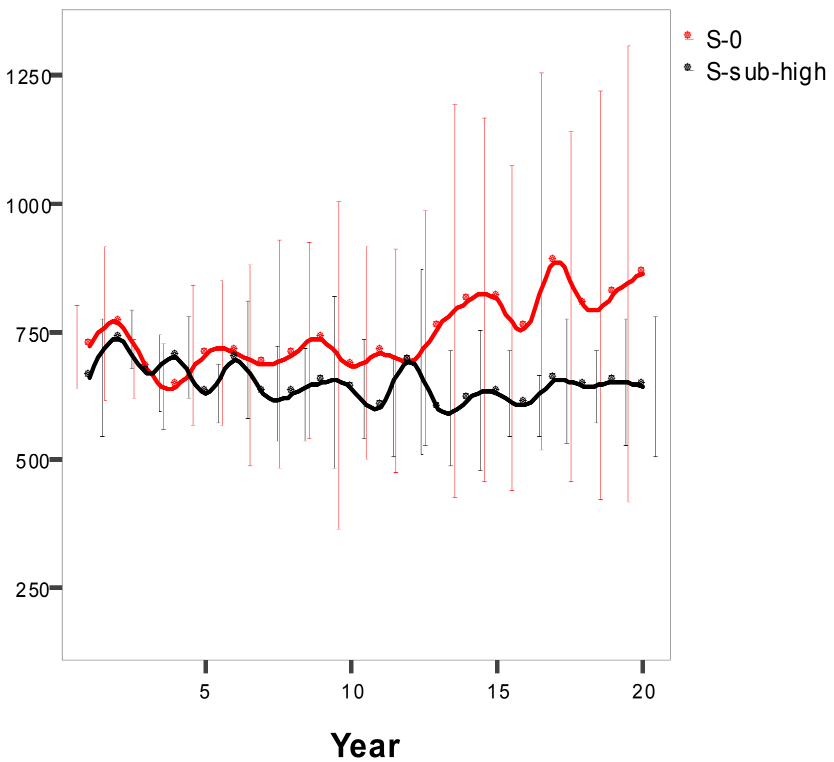

Figure 6.23: Mixed cinnamon area (m^2), group 2, in S-sub$_{high}$ versus baseline (S-0)

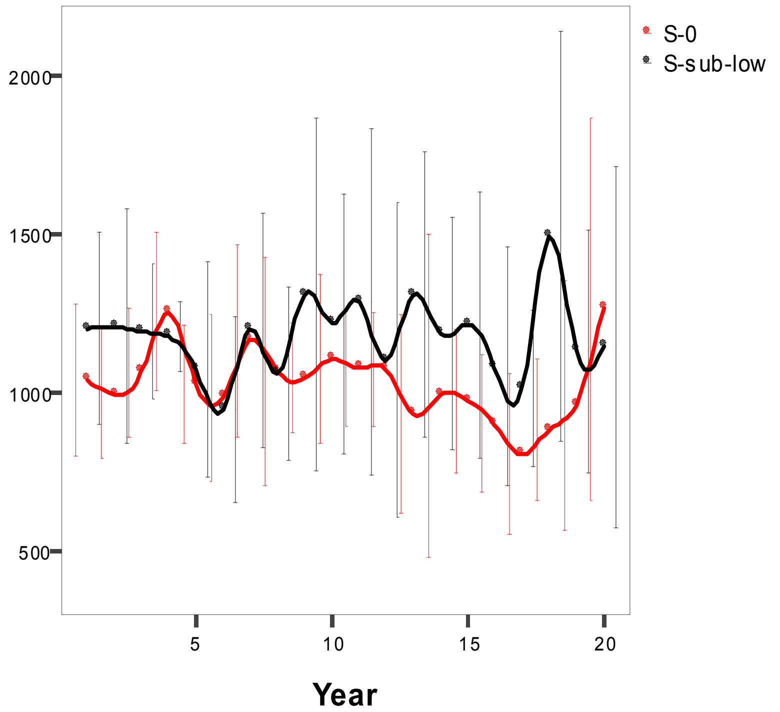

Figure 6.24: Mixed cinnamon area (m^2), group 3, in S-sub$_{low}$ versus baseline (S-0)

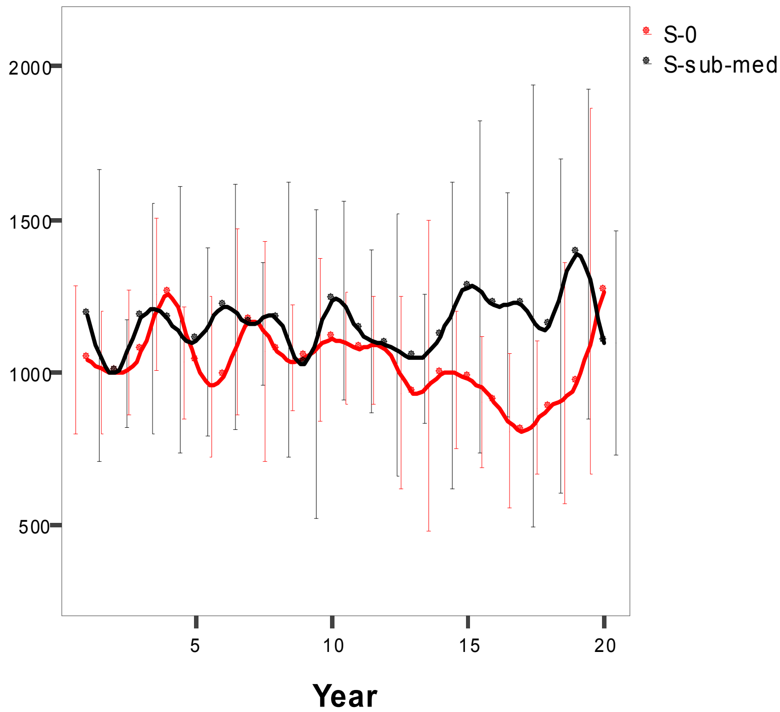

Figure 6.25: Mixed cinnamon area (m^2), group 3, in S-sub$_{med}$ versus baseline (S-0)

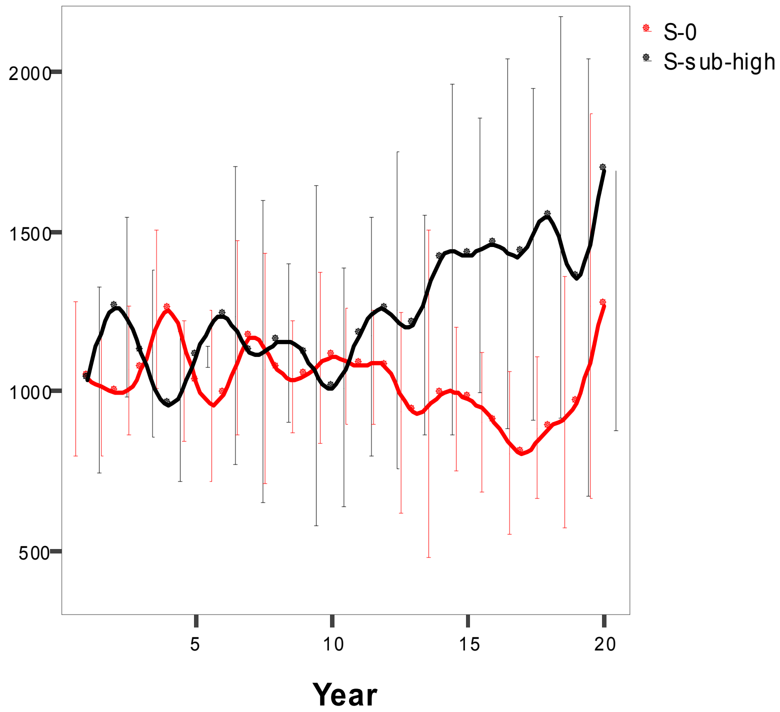

Figure 6.26: Mixed cinnamon area (m^2), group 3, in S-sub$_{high}$ versus baseline (S-0)

The effect of changes in agricultural subsidies on the paddy area varies between the three groups. While no clear pattern is visible for group 3, there are clear differences between S-0 and the subsidies scenarios for groups 1 and 2. The paddy area of group 1 stays more or less on the same level over the 20-year simulation period in S-0, while it seems to increase after approximately 10 years in the other scenarios (Figure 6.27 to 6.29). This development indicates a delayed redistribution of subsidized cinnamon fertilizers to rice production by the households to ensure their food security. It is a common feature of coupled socio-ecological systems that certain policy interventions may not reveal their impacts on the system immediately, but at a later stage of the development of the system (Liu et al. 2007; Le et al. 2010). The paddy area of group 2 increases in all scenarios, being slightly higher in the subsidies scenarios.

The decrease in landholdings is strongest for all groups within the homestead category. The value after 20 years is 72, 80, and 67 % on average of the original value for the three livelihood groups in the S-0 scenario. The amount of agricultural subsidies does not have a meaningful effect on the homestead area of the different groups.

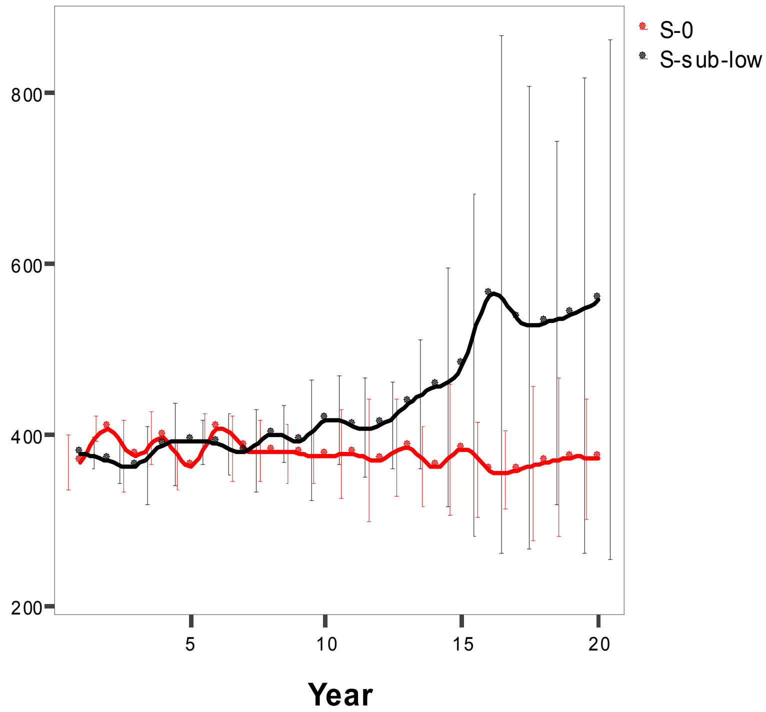

Figure 6.27: Paddy area (m^2), group 1, in S-sub$_{low}$ versus baseline (S-0)

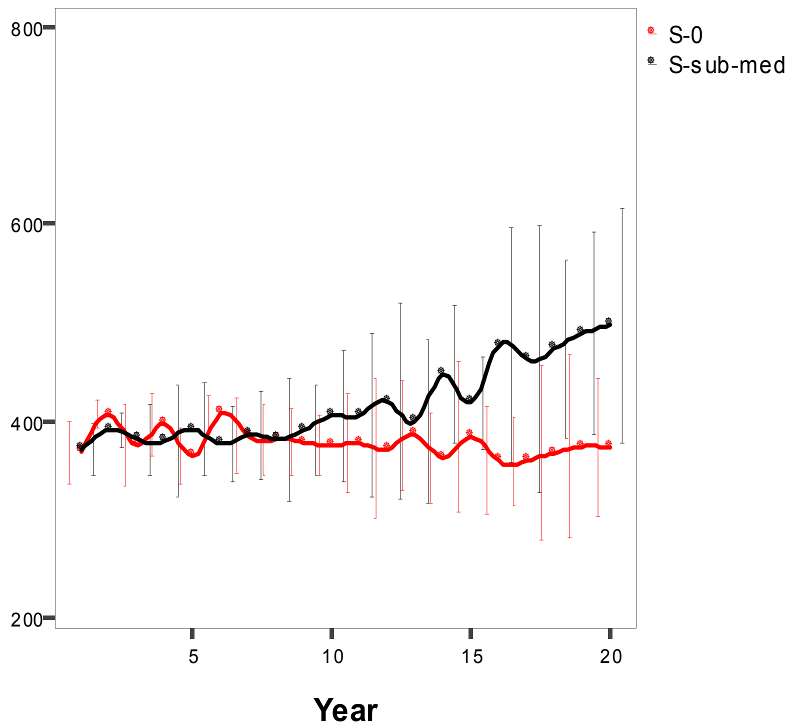

Figure 6.28: Paddy area (m^2), group 1, in S-sub$_{med}$ versus baseline (S-0)

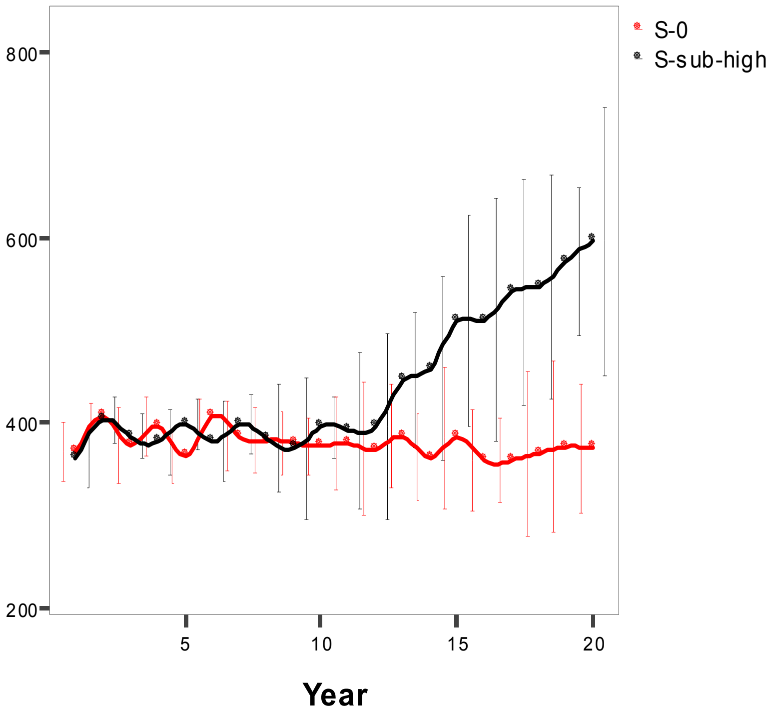

Figure 6.29: Paddy area (m^2), group 1, in S-sub$_{high}$ versus baseline (S-0)

The Gini index and the number of households in the different groups do not show any differences between the various scenarios. While the Gini index remains more or less on the same level over the whole simulation period, the annual population growth rate of 0.97 %, which is the average population growth rate in the Galle district, is embedded in the model code.

6.4.2 Impacts of changes in access to extension services

The impacts of changes in access to agricultural extension services on simulation results are much less pronounced than for access to agricultural subsidies. While the simulations reveal certain trends of future developments, due to high uncertainty ranges none of these results proved to be significant.

The scenarios do not show any differences with regard to the various income sources and the overall income of the households in the three livelihood groups. The development of the various land covers shows some changes over the simulation period. When looking at the total landholdings, it is again mainly in group 1 that there are some differences between the scenarios. In S-ext$_{med}$, the access to extension services reduces the total available land, while in S-ext$_{low}$ and S-ext$_{high}$ it remains on the same level as in

S-0. In S-ext_{high}, it increases again after 15 years in contrast to the general trend of decreasing farmland (Figure 6.30 to 6.32). However there are great uncertainties in all scenarios.

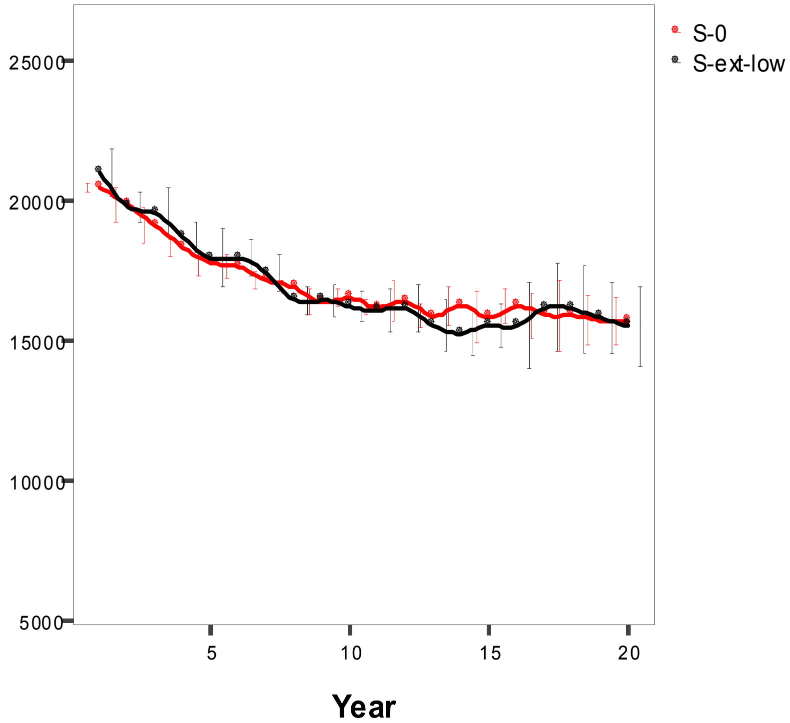

Figure 6.30: Total farmland area (m^2), group 1, in S-ext_{low} versus baseline (S-0)

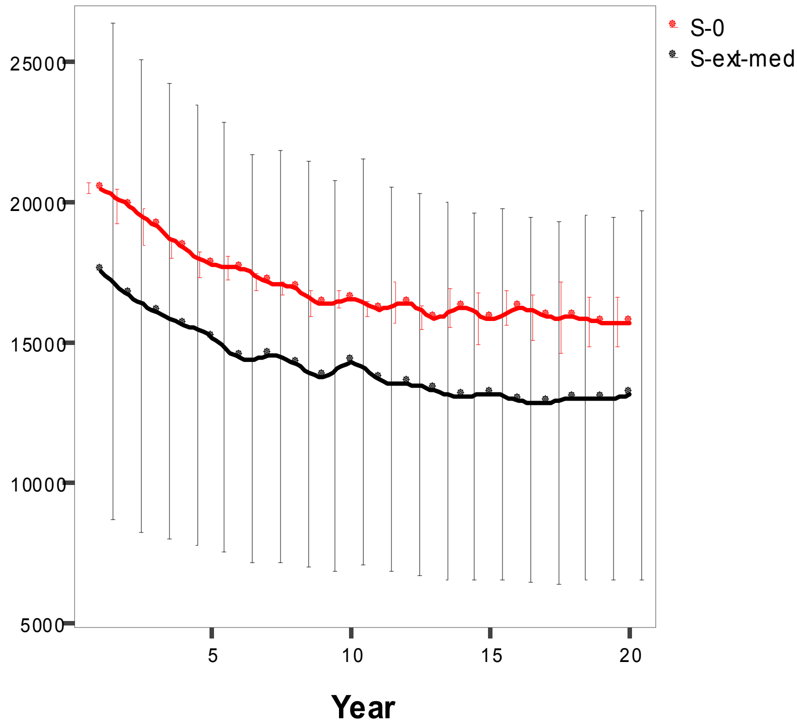

Figure 6.31: Total farmland area (m^2), group 1, in S-ext_{med} versus baseline (S-0)

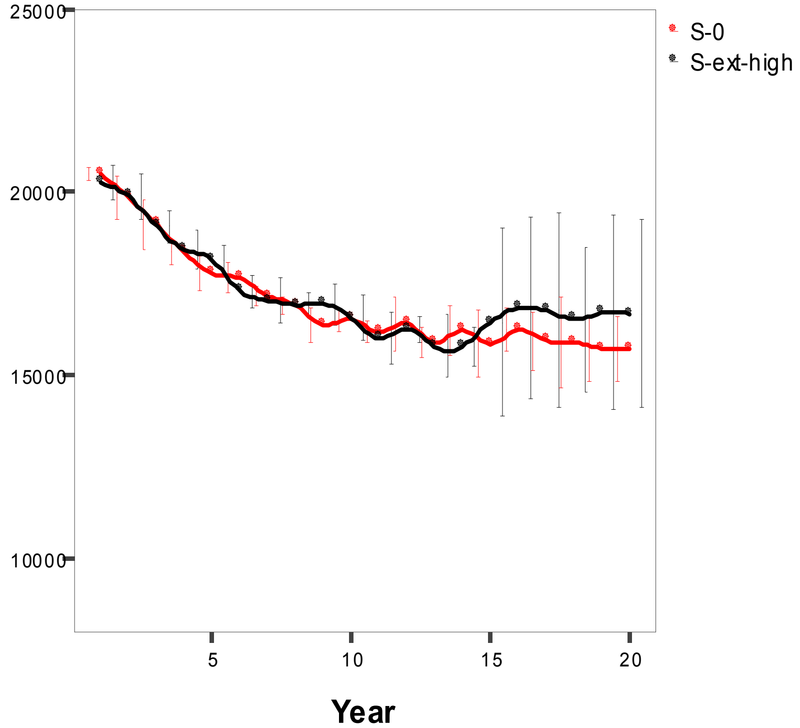

Figure 6.32: Total farmland area (m^2), group 1, in S-ext$_{high}$ versus baseline (S-0)

The cinnamon plantations of groups 1 and 3 are not affected by changes in extension services, while the cinnamon area of group 2 shows a decreasing trend in all extension scenarios compared to the baseline scenario (Figure 6.33 to 6.35).

The impacts of changes in access to extension services on the mixed cinnamon area vary considerably between the different groups. For group 1, this area is lower in all extension scenarios, while at the same time it increases with higher access to extension services (Figure 6.36 to 6.38). In group 2, the cinnamon area of all extension scenarios is lower than the S-0 scenario with the largest difference in S-sub$_{high}$ (Figure 6.39 to 6.41). Again, all scenarios have great uncertainties. Finally, simulations for group 3 do not show any changes.

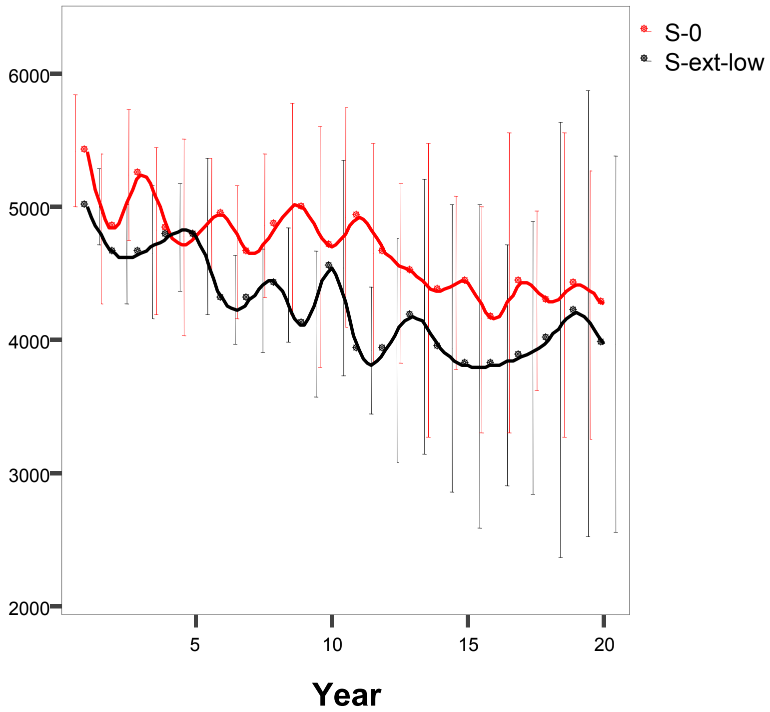

Figure 6.33: Cinnamon area (m^2), group 2, in S-ext_{low} versus baseline (S-0)

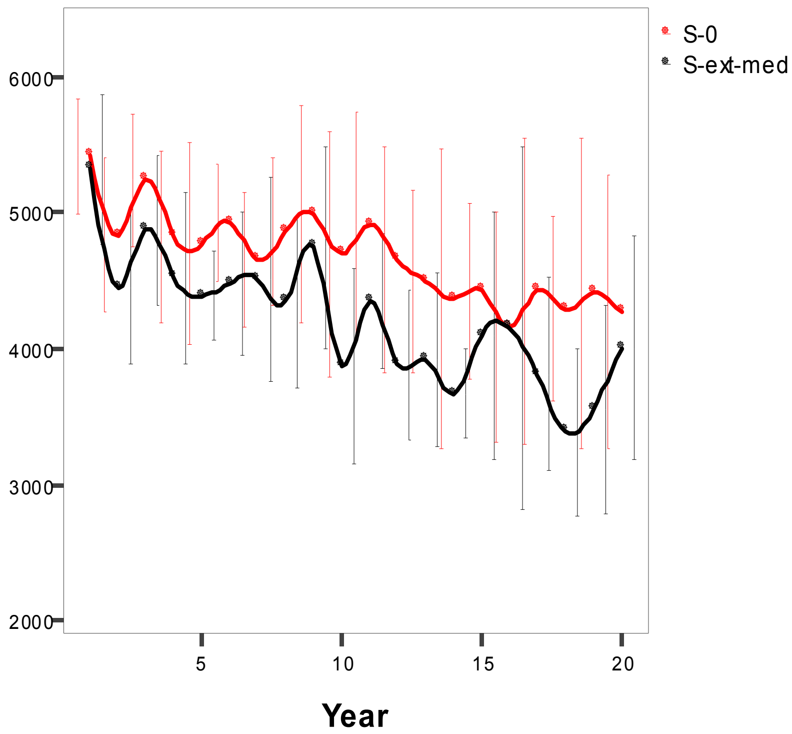

Figure 6.34: Cinnamon area (m^2), group 2, in S-ext_{med} versus baseline (S-0)

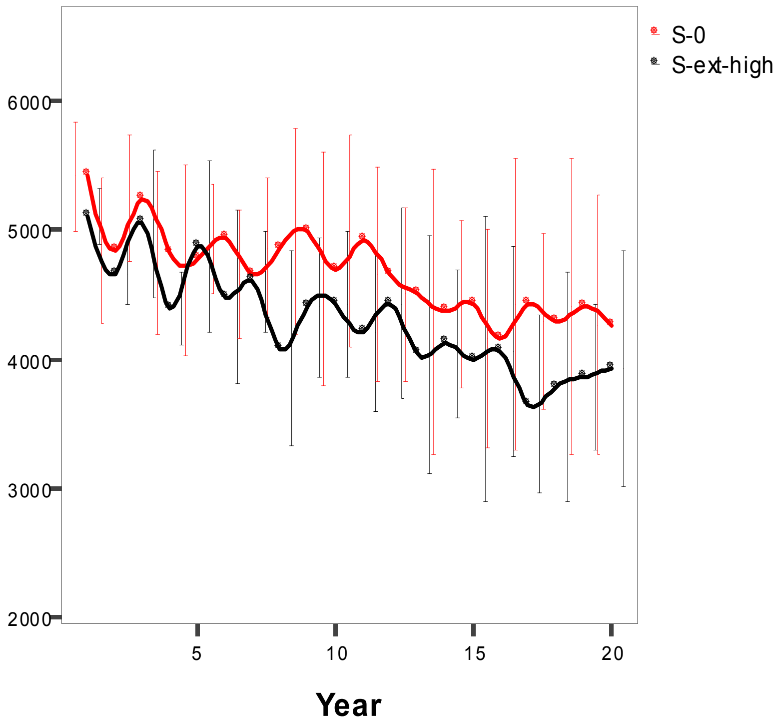

Figure 6.35: Cinnamon area (m^2), group 2, in S-ext$_{high}$ versus baseline (S-0)

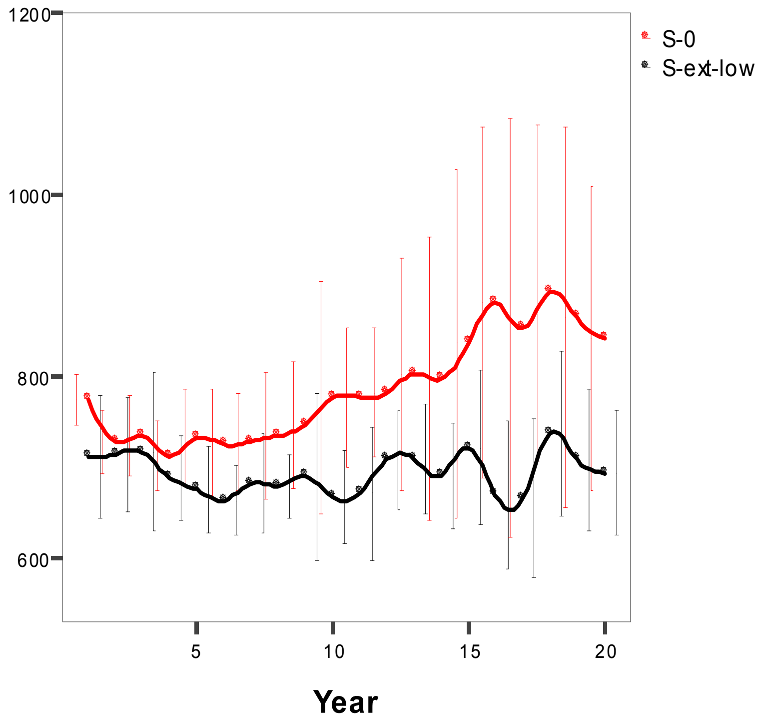

Figure 6.36: Mixed cinnamon area (m^2), group 1, in S-ext$_{low}$ versus baseline (S-0)

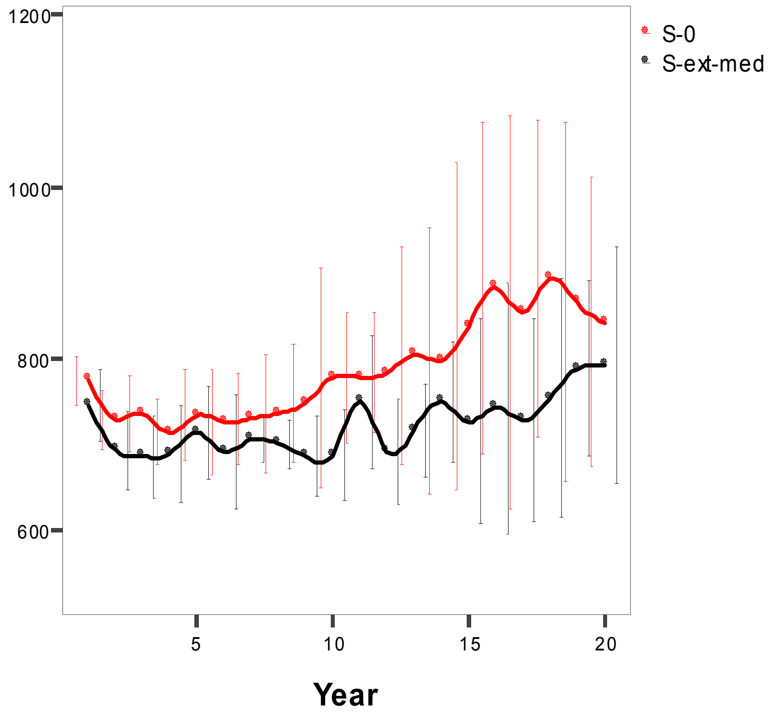

Figure 6.37: Mixed cinnamon area (m^2), group 1, in S-ext$_{med}$ versus baseline (S-0)

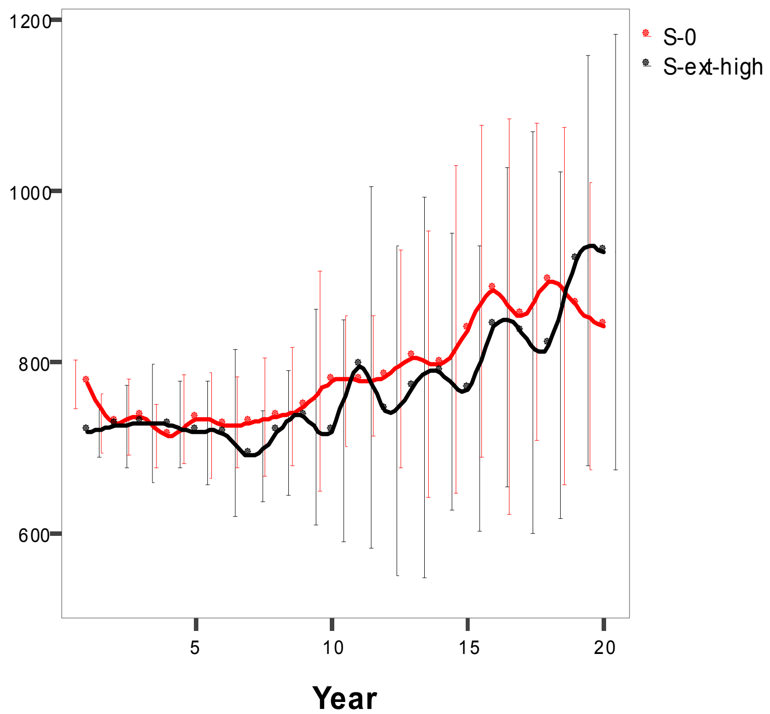

Figure 6.38: Mixed cinnamon area (m^2), group 1, in S-ext$_{high}$ versus baseline (S-0)

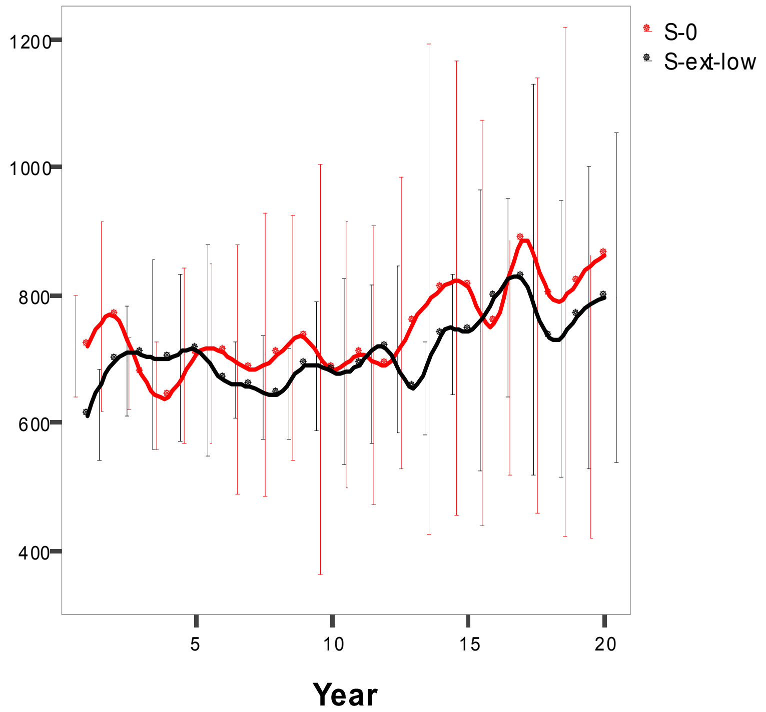

Figure 6.39: Mixed cinnamon area (m^2), group 2, in S-ext$_{low}$ versus baseline (S-0)

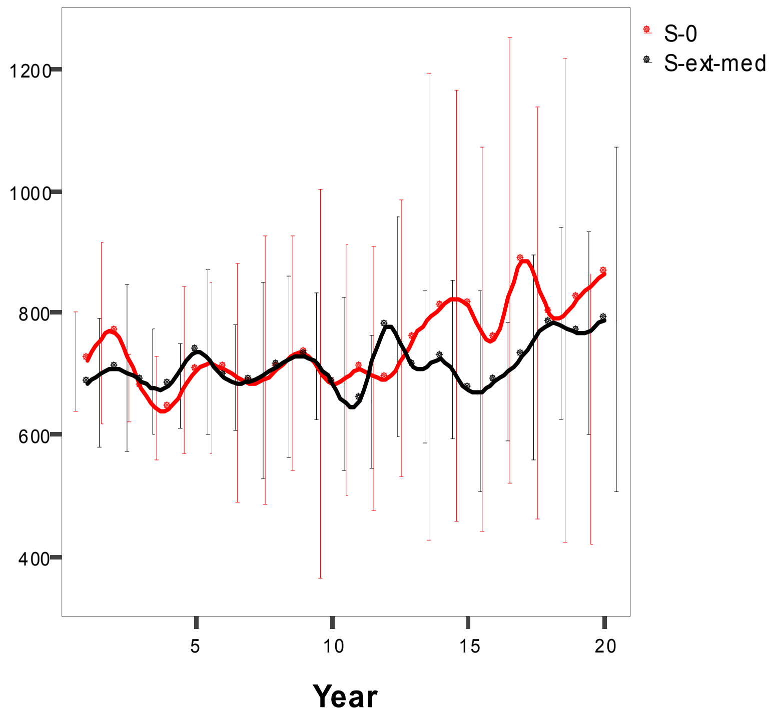

Figure 6.40: Mixed cinnamon area (m^2), group 2, in S-ext$_{med}$ versus baseline (S-0)

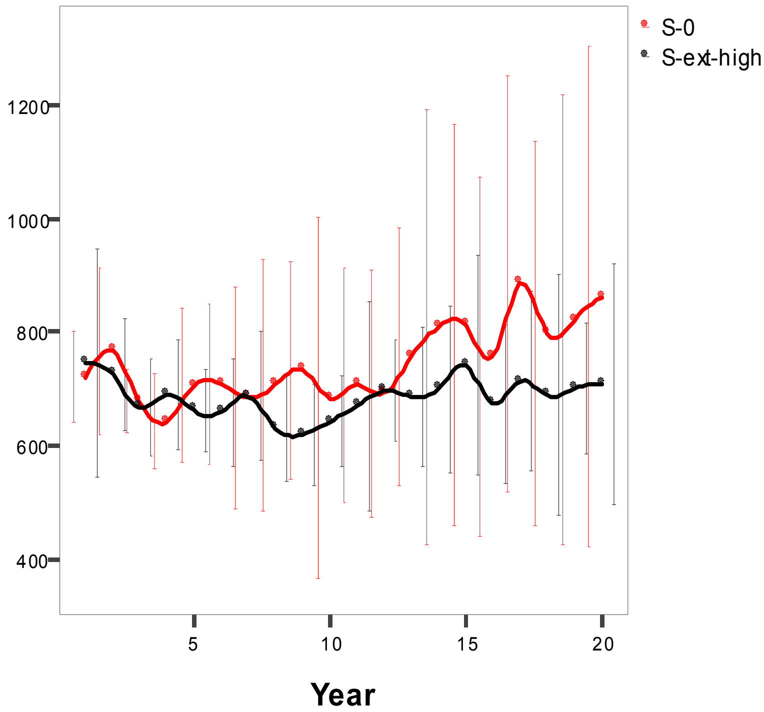

Figure 6.41: Mixed cinnamon area (m^2), group 2, in S-ext_{high} versus baseline (S-0)

For the paddy fields, only group 1 shows any differences between the three scenarios. While in S-ext_{low} and S-ext_{high} the access to extension services reveals an increasing trend with regard to paddy area after some 13 years, this trend is much less pronounced for S-ext_{med} (Figure 6.42 to 6.44). The delayed response of paddy area on changes in extension services again depicts the legacy effect as a typical element of coupled socio-ecological systems (Liu et al. 2007).

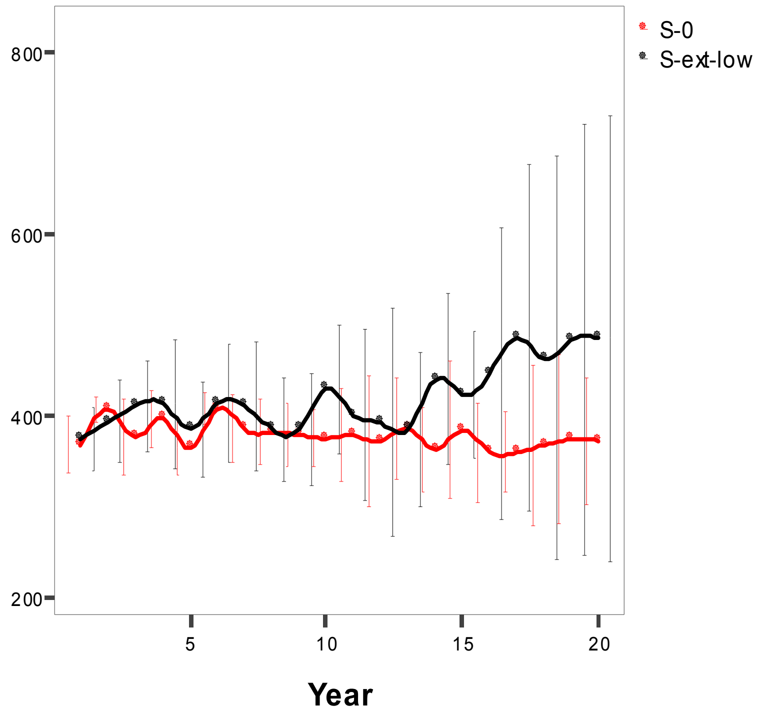

Figure 6.42: Paddy area (m^2), group 1, in S-ext$_{low}$ versus baseline (S-0)

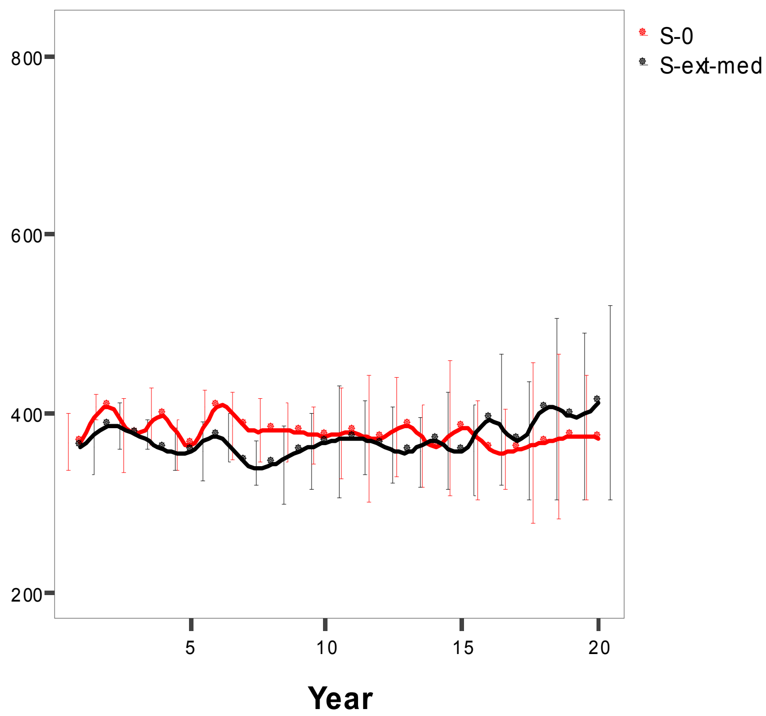

Figure 6.43: Paddy area (m^2), group 1, in S-ext$_{med}$ versus baseline (S-0)

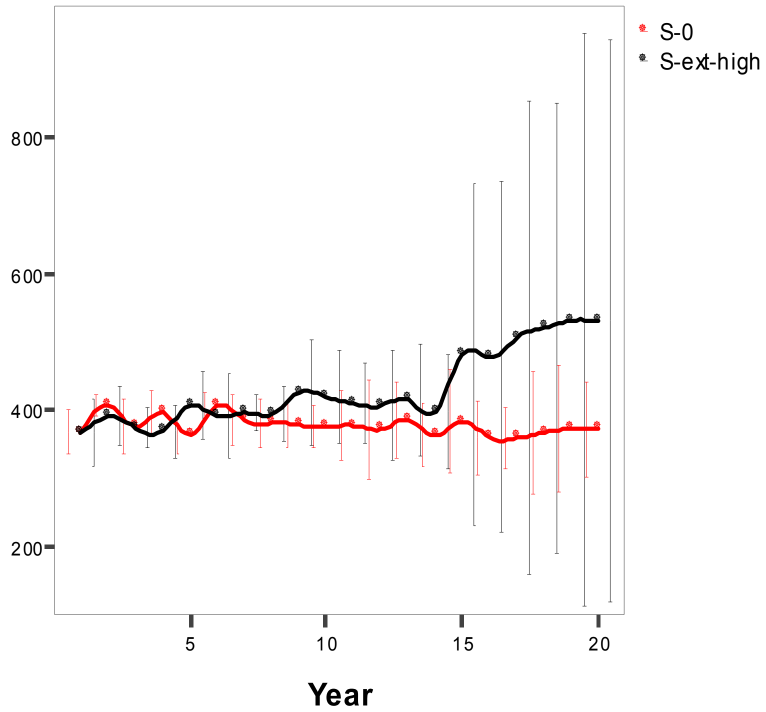

Figure 6.44: Paddy area (m^2), group 1, in S-ext_{high} versus baseline (S-0)

As for the subsidies scenarios, the Gini index and number of households do not show any meaningful variations within the different scenarios.

6.4.3 Combined scenario

The single scenarios reveal that most changes in land use and livelihoods are due to an increased access to agricultural subsidies. Therefore, the combined scenario links high access to subsidies with a high access to extension services to evaluate if this combination results in additional changes.

The combined scenario shows no major differences compared to the S-sub_{high} scenario. There are slight differences with regard to paddy area within the three groups. The paddy area of households in group 1 is higher in the combined scenario than in the baseline scenario. However, the increase after 12 years is less pronounced than in the S-sub_{high} scenario, so that the differences compared to the S-0 scenario are not significant (Figure 6.45). For group 2, the combined scenario generates increases in paddy area compared to the S-0 scenario, although these differences are uncertain due to large confidence intervals (Figure 6.46). The increases in paddy area are also more pronounced than for the S-sub_{high} scenario.

Finally, there is no difference between the total landholdings of households in group 1. While they show a slightly increasing, however non-significant, trend after 14 years in the S-sub$_{high}$ scenario (Figure 6.14), there is no increase in the combined scenario, so that the landholdings remain nearly on the same level as for the baseline scenario over the whole simulation period (Figure 6.47). It is suggested that higher access to extension services results in a better management of the agricultural plots and thus in a higher output. Therefore, the pressure to open new plots to increase agricultural production is reduced. This hypothesis is backed by the observation that at the time of the survey many cinnamon farmers did not manage their plots properly and that thus harvests were significantly lower than they could be under optimal management conditions. However, a more detailed analysis of content and quality of the offered extension services would be needed to verify this hypothesis.

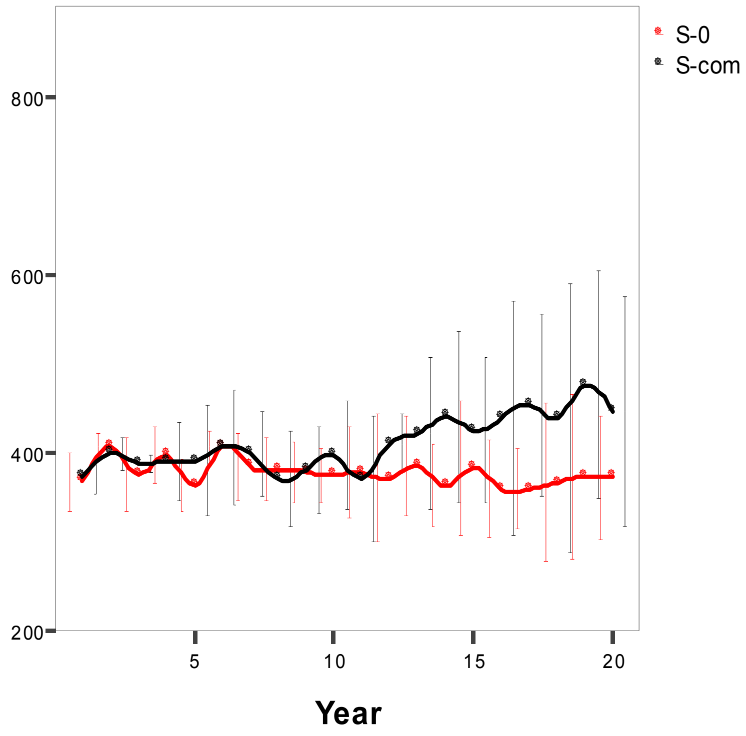

Figure 6.45: Paddy area (in m^2), group 1, in combined scenario versus baseline (S-0)

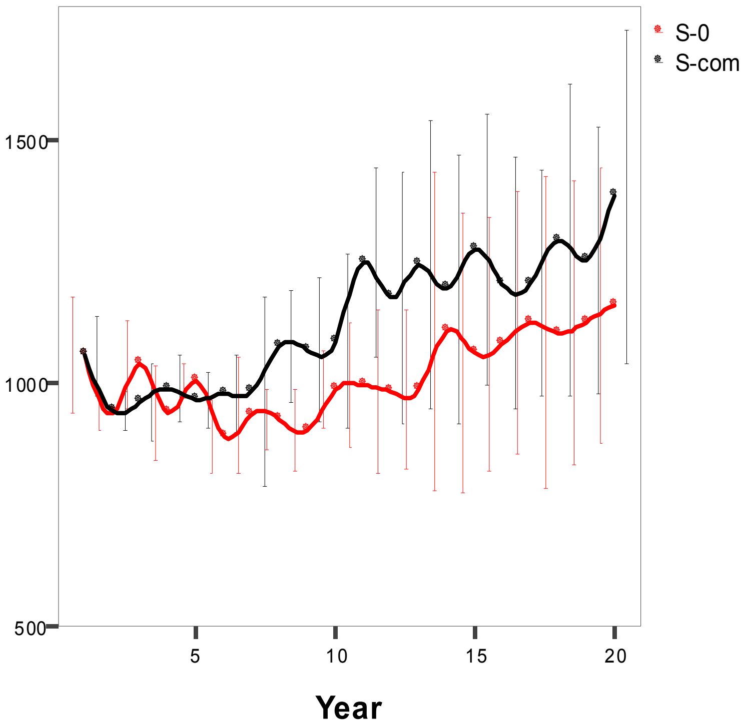

Figure 6.46: Paddy area (in m^2), group 2, in combined scenario versus baseline (S-0)

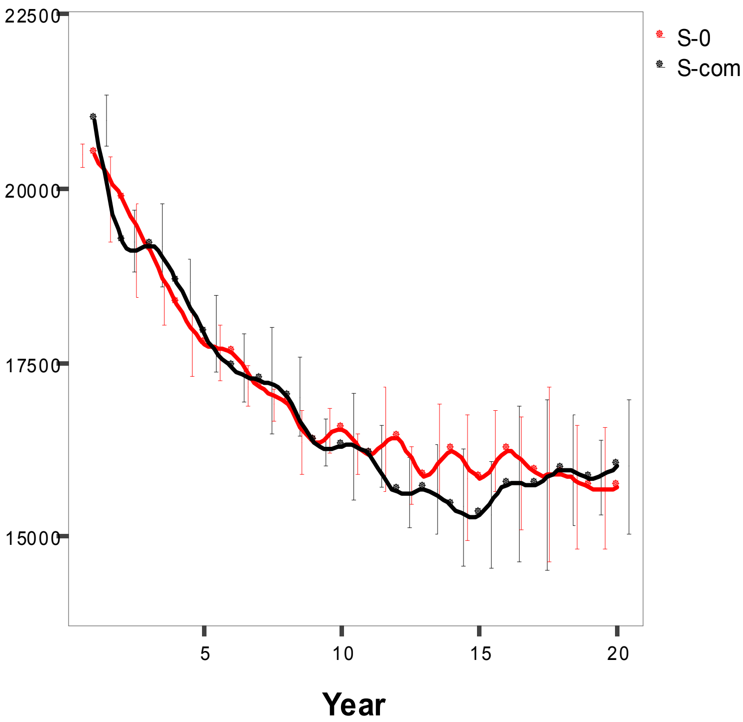

Figure 6.47: Total landholdings (in m^2), group 1, in combined scenario versus baseline (S-0)

6.4.4 Summary and conclusions

SRL-LUDAS can be used as a Decision Support System (DSS) to facilitate landscape planning processes by simulating and comparing various scenarios of land-use and community changes driven by different policy interventions. DSS are suited to evaluate the outcomes of different land-management strategies favored by various stakeholders in order to find compromise solutions, and thus to support spatial planning processes (Etienne et al. 2003; Ligtenberg et al. 2004; Castella et al. 2005; Le et al. 2010). The aim of the DSS is to bring together all necessary information from the natural and social system as well as their interactions and to communicate the results to all stakeholders in the process. Therefore, modern DSS need to consist of 1) a spatial dynamic modeling component that analyses possible future outcomes of any current actions, 2) a visualization tool to illustrate existing and potential future conditions, 3) and a communication tool to spread relevant information to the stakeholders (Orland et al. 2001).

Notwithstanding the impact of policy factors, all scenarios reveal slight decreases in the share of income from farming activities, while the overall income of households of all groups remains more or less constant over the whole simulation period. The most striking result is the decrease in the landholdings of all households, which is mainly due to decreases in homestead area, while all other land uses remained on the same level or showed slight increases. Pressure on land and internal population growth are seen as the main drivers for this development. This result confirms the observed trend of diminishing farm size in many Asian countries (Eastwood 2010; Nagayets 2005).

The simulations with changes in the two selected policy factors generated two main results. First, they reveal that access to agricultural subsidies has a stronger effect on land use and livelihoods than access to agricultural extension services. It increases the share of income from farming activities compared to the baseline, and it modifies the development of mixed cinnamon and paddy area. For groups 1 and 2, mixed cinnamon area decreases with increasing subsidies, while it increases for group 3. Paddy area shows increases over all groups with higher access to fertilizer subsidies. However, this is only seen after some 14 years. Changes in access to extension services on the other hand only result in minor changes of cinnamon, mixed cinnamon, and paddy area with large uncertainties for all changes. It must be considered that not only is the quantity of the extension services important, but that also the topics and quality of such services have a decisive impact on land use and livelihoods. This would require an in-depth study of the quality of current extension services and how this affects decision-making processes. Therefore, this aspect was omitted in SRL-LUDAS.

Finally, the combined scenario with high access to both subsidies and extension services confirms the minor importance of access to extension services, as the results of the combined scenario are similar to the high subsidy scenario with only few minor differences.

Most of the scenarios show large confidence intervals, so that many differences between the scenarios can only be interpreted as trends, because of the great uncertainties. These uncertainties mostly increase at the end of the simulation periods (e.g., Figure 6.32), a phenomenon that is typical for the behavior of complex systems, where uncertainties tend to become larger due to growing interconnectedness and emergent properties. Human behavior is the main uncertainty, as it is particularly non-linear and open to various influences. Therefore, path dependency, i.e., the prediction of future developments on the basis of historical data, does not work in such systems (Le et al. 2010; Nguyen and de Kok 2007). Thus, the results of SRL-LUDAS should not be used for concrete predictions, but should rather be seen as heuristic tools that give guidance for further studies and provide generic ideas about the direction of impacts for various policy measures.

7 VULNERABILITY ASSESSMENT IN BALAPITIYA AND MADUGANGA

The tsunami that hit the coasts of several Asian and African countries on 26 December 2004 caused some 226,000 fatalities (EM-DAT 2010) and severe damage to livelihoods and infrastructure. It revealed the inherent vulnerability of coastal communities in the affected countries. Even four years after the event, the observations and surveys of this study showed that some people had not managed to recover completely. Based on the theoretical considerations presented in Chapter 3, 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. The comprehensive and combined view of the impacts of the event as well as of sensitivity and resilience of the affected people, as it is promoted by the Turner framework (see section 3.2), is expected to be a reasonable tool to detect these underlying aspects. In this study, the Turner framework was selected, as it puts a particular emphasis on the linkages between the socio-economic and the environmental components and thus generates a comprehensive picture of the vulnerability of the coupled socio-ecological system under consideration.

In the Galle district 4,214 people were killed by the tsunami. Only 177 of these fatalities were reported for the DS Division of Balapitiya (HIC 2005). When taking only the GN divisions into account that were part of the survey, 209 people were injured (DCS 2005a) out of an affected population of 10,631 (DCS 2005b). However, the waves caused severe damage to houses, assets, and infrastructure. Out of the 2,329 housing units, 447 were destroyed, 101 were partially damaged and could not be used anymore, and 774 were damaged but could still be used (DCS 2005b).

For the southwestern coast of Sri Lanka, wave heights of around 4 m were recorded (Liu et al. 2005; Wijetunge 2006), and information from interviewed households revealed maximum heights of about 4.5 to 5.4 m. The highest recorded inundation distance of the waves was around 1.2 km from the shore.

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 (see section 4.2). Although several different methods have been applied, no study has proven such a buffering mechanism, which would be of great significance for livelihoods in coastal areas worldwide.

The objectives of this part of the research were twofold. By conducting an ex-post assessment based on the Turner framework, the study attempted to detect the particular vulnerability of different livelihood groups in the study area, which were revealed by the impacts of the tsunami. In a next step, the protective effect of coastal vegetation and differences between vegetation classes in the study area was analyzed.

7.1 Methodology for vulnerability assessment

The data for the vulnerability assessment were collected through a detailed questionnaire for 157 households in September 2007. The location of the households was determined with a GPS device (Figure 7.1). The households were selected by stratified random sampling according to their closeness 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, damage to the house, and on the household's recovery from the tsunami. In a first step, all water levels that appeared inaccurate when comparing them with the other statements in this survey and with information from other studies (Liu et al. 2005; Wijetunge 2006) were deleted. Altogether, 3 out of the 157 data points were deleted, one of which was relevant for the vegetation survey. The 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 (see section 5.4.1).

Figure 7.1: Surveyed households for the vulnerability assessment; red dots show households of the "sea group", green dots households of the "inlet group" (for explanation see section 7.3).

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, external effects were largely omitted apart from the enforcement of the buffer zone. Immediately after the tsunami, 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. Later, the extent of this buffer zone was modified. The buffer zone resulted in serious implications for 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, e.g., fishermen.

In addition to the Turner framework, 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 taken into account (see section 5.3.1). Although the rather general and broad approach of the SL framework makes it unsuitable as an exclusive tool for analyzing vulnerability to natural hazards, it can nevertheless serve as a valuable complement and checklist for other frameworks in order to capture the sensitivity and coping capacity of vulnerable people (Birkmann 2006; Twigg 2001).

Natural capital was captured by the vegetation survey and the land-cover classification, while the other assets were covered through the questionnaire. Human capital is expressed by the number of household members, their educational status and occupations. The financial capital was determined by investigating the income of the household members before and after the tsunami as well as any savings of the households. Social capital includes the support received from friends, family or neighbors, and from various organizations such as the Red Cross, CHF International, or local Sri Lankan organizations. Finally, for analyzing the physical capital, the construction material of the house, access to drinking water and sanitary facilities were surveyed.

Table 7.1: Indicators used for analyzing vulnerability following the framework by Turner et al. (2003a).

Vulnerability		
Exposure	**Sensitivity**	**Resilience (impact, coping/response, adaptation)**
Distance to the sea	Income of household	Changes in income after the tsunami
Coastal topography	Structure of household	Time without work after the tsunami
	Occupations of household members	Savings before and after the tsunami
	Construction material of house	Loans taken after the tsunami
	Extent and condition of coastal vegetation	Impact of tsunami on household members
	Infrastructure (roads, water supply, electricity)	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

The combined application of the two frameworks resulted in a selection of indicators that were analyzed for detecting vulnerability at the local level divided into the three different categories exposure, sensitivity, and resilience according to the Turner framework (Table 7.1).

Exposure was determined by looking at the distance of the homestead to the sea. The results of the mapping exercise and the subsequent statistical analyses (see section 7.3) show the importance of the distance of the homestead from the sea, especially as the coastal area is completely flat. Another study conducted in southern Sri Lanka has also proven the relevance of this indicator by showing that houses within the first 100 m from the sea faced higher damages than houses situated behind this zone (Birkmann and Fernando 2008).

Sensitivity is analyzed through six indicators, although classification of indicators into the respective categories is sometimes subjective, as some of them can also be assigned to exposure or resilience. Although there is an increasing emphasis on non-monetary issues when dealing with livelihoods, vulnerability, and poverty, it is uncontested that income and other types of financial capital are still of utmost importance (UNDP 2007b; DFID 2001). 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 as a result of the impacts of the tsunami were included in the resilience category.

This study refers to the income of the household head or the highest income in the household, which corresponds in most cases. It puts a strong focus on income-generating activities, as they are the most important factor for generating financial assets. So income is, for example, mentioned as one of three indicators for abating extreme poverty in the Millennium Development Goals (Goal 1). 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 differences 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 might be different for different occupational groups due to the above-mentioned reasons. This indicator has a severe impact on the recovery of the household, as the most important source for generating financial capital is not available during that period. This indicator was assigned to the resilience category.

The final indicator linked to financial capital is the access to loans in order to support recovery after the event. Access to loans has proven to be an important aspect of generating financial capital (DFID 2001; Tilakaratna et al. 2005), which is particularly needed in the aftermath of such a harmful event like the tsunami (Becchetti and Castriota 2007; Tilakaratna et al. 2005).

The structure of the household comprises the number of people living together in one homestead as well as age distribution and education. Like its respective indicator under resilience – impact of tsunami on household members – structure describes the human capital of a household, which is of central importance as it serves as a prerequisite for the generation of other types of assets (DFID 2001). Since there were hardly any severe injuries or fatalities among the surveyed households, this aspect was not analyzed.

Due to the importance of biophysical systems for the vulnerability of coupled socio-ecological systems (see Chapter 3), extent and condition of the coastal vegetation was included as an indicator for sensitivity.

Adequate housing and access to proper water supply are two basic aspects of physical capital (DFID 2001) and seen as basic human rights that contribute to security and health (UNHCHR 2006). The building material of a house has a strong influence on its capacity to withstand the forces of a tsunami wave (Dominey-Howes and Papathoma 2007). However, nearly all of the houses within the study area had brick or stone walls and a tile or asbestos roof; this indicator was therefore not analyzed.

Damage to the house was assessed in terms of monetary losses. In addition to the damage to the other assets of the household, the overall financial damage was determined, which served as an indicator of the impact of the tsunami on the respective household. The loss of assets is the hardest impact of a natural hazard apart from the loss of human lives, and assets are particularly difficult to recover for poorer people in developing countries, who often do not have savings or any insurance against such losses. This fact was confirmed by the respondents during the survey.

Access to infrastructure such as roads, water, sanitation facilities, and electricity as another indicator related to sensitivity did not show any differences within the affected population before the tsunami, as nearly all surveyed people have access to the above-mentioned facilities. However, the tsunami had a differentiating effect on access to drinking water. Proper access to safe drinking water is a prerequisite for a healthy life and for development (UNEP 2007; MA 2005) and is also one of the indicators for fulfilling the Millennium Development Goal on environmental sustainability. The lack of a clean drinking water source not only has negative impacts on health, it may also tie up the workforce of some household members, which is then not available for other activities (UNEP 2007; MA 2005). This indicator has therefore been included as an indicator for recovery and coping.

One important element of resilience and coping after the tsunami is the support received after the event. Help from the government came mainly in the form of money for rebuilding the houses or for replacing other assets. The amount of financial support required was derived from the damages to the house. Help from national or international NGOs varied – it came either as non-financial help like food, medicine, kitchen equipment, or fishing gear, or the organization built a new house for the affected household. Help from friends came mostly as food, money, and accommodation.

While financial help increases the financial capital of the household in the aftermath of the event, the support from friends, family, and neighbors is a particular form of social capital, which, like financial help, supports recovery and enhances the coping capacity of the household. The general value of social capital as well as its particular value in the case of shocks has been acknowledged by the Sustainable Livelihoods Framework (DFID 2001).

Preparedness is an important element in the analysis of vulnerability (Villagrán De León 2008). As this study was carried on the local level, analysis of preparedness for the next event referred to households and did not consider communities or political institutions. Some people in the study area chose to move to other places further inland, or they were resettled by the government because they were living in the buffer zone before. Other people who remained in their homes mentioned other preventive measures to protect themselves. Because of its importance, preventive measures were included as an indicator for resilience in the vulnerability assessment.

Finally, all types of land policies were analyzed that might have an influence on the vulnerability of coastal people. This indicator was added because policies have the ability to significantly influence the vulnerability of people (DFID 2001). The main policy in Sri Lanka with regard to coastal vulnerability to natural hazards is the enforcement of a buffer zone.

The locations of the surveyed households were captured with a GPS device and entered into the GIS. It was therefore possible to determine the distance of the houses from the sea. The information from the questionnaires and the distance measurements served as input for the statistical analysis to identify the 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 all variables were not normally distributed, thus non-parametric statistical tests were used. After comparing the means of several variables with regard to different groups of households, respective tests were used to check if values between different groups differed significantly.

7.2 Methodology for 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 device during a detailed ground survey. The results were included in the GIS and first scanned visually to determine any linkages between the width and composition of the vegetation belt as well as 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 estuary with the sea up to the island of Pathamulla. In this area, the survey made use of the results of the land-cover classification (see section 5.4.1), which was linked to the household surveys.

Then, the southern part of the vegetation belt 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 a width of 300 m from the sea shore.

7.3 Results of the vulnerability assessment

7.3.1 Exposure

For the analysis of the influence of distance to the sea on water level and damage, the surveyed homesteads were first divided into two groups according to their distance from either the sea ("sea group"; 117 households) or the inlet ("inlet group"; 40 households) (Figure 7.1). In order to estimate the importance of the distance parameter, the homesteads of the interviewed households were stratified into five classes based on their distance from the sea. The classes had a width of 150 m each, except for the fifth, which contained every interviewed homestead located at a distance between 600 m and 958 m as the furthest recorded distance for a homestead within this survey. The flow depths decreased considerably with increasing distance from the sea which is logical and was expected (Table 7.2). The mean flow depth reported in the distance class 1 was 291 cm and 99 cm in class 5, with the overall average being 217 cm. The flow depths of the 5 distance classes were tested to be significantly different (ANOVA: p=0.000). The subsequent pairwise comparisons (with LSD) of the ANOVA (p=0.000) showed that the decrease in water level was mainly significant with regard to the first distance class in comparison to the other classes.

Table 7.2: Flow depth at the house for the sea group (houses close to the sea). (ANOVA: p=0.000; Kruskal-Wallis: p=0.000). 12 households were omitted due to missing data, 3 households were omitted due to obviously inaccurate data

Distance to sea in classes (m)	Mean flow depth (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 no data were 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 (Table 7.3) 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. Again, 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.

Table 7.3: 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: rs=-0.482, p=0.000). 5 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

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 channeling effect of the inlet. It is suggested that not only flow depth influences the damages, but also the energy of the waves, which is focused by the narrow inlet which thus contributes to the destructive force of the waves. A similar effect with regard to bays and estuaries was 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. 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: rs=-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 (Table 7.4). The relatively high value for class 4 is because one household reported extremely high damages. When this household was not considered in the analysis, the damages in class 4 decreased from 602,000 Sri Lankan Rupees (LKR) to 461,000 LKR. 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 of the surveyed households in 2004, i.e., poorer households tend to live closer to the sea and are thus more exposed to the impacts of coastal hazards. This statement is confirmed when looking only at the sea group (Spearman: rs=0.194; p=0.049), but also when taking all surveyed households into account (Spearman: rs=0.196; p=0.020).

Table 7.4: Mean overall financial damage by distance to the sea (ANOVA: p=0.003; Kruskal Wallis: p=0.000). 4 households were omitted due to missing data.

Distance to sea in classes (m)	Mean (LKR) (x1000)	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

7.3.2 Sensitivity

The extent and condition of coastal ecosystems is a major factor of sensitivity of coupled systems, therefore this aspect was analyzed separately (see section 7.4). 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. First, any differences with regard to the income of the groups before the tsunami were analyzed (Table 7.5 and 7.6). The analysis revealed that apart from households depending on labor, the total income of all occupational households was very similar at the time of the tsunami. When looking at income per capita, the analysis does not produce any significant results (p=0.434).

Table 7.5: Total income of households in the different occupational groups before the tsunami; Kruskal-Wallis test not significant (p=0.096). 17 households were omitted due to missing data.

Main income source of household	Mean (LKR)	N	Std. deviation
Fishery	13,367	39	12,666
Employed	15,439	38	18,154
Self-employed	16,746	20	16,845
Labor	7,675	16	4,553
Official	16,175	16	10,051
Pension/no job	15,927	11	20,986
Mean/total	14,284	140	14,910

Table 7.6: Income per capita of households in the different occupational groups before the tsunami; Kruskal-Wallis test not significant (p=0.434). 17 households were omitted due to missing data.

Main income source of household	Mean (LKR)	N	Std. deviation
Fishery	2,987	39	3,020
Employed	3,217	38	2,836
Self-employed	3,691	20	3,205
Labor	2,118	16	1,230
Official	3,315	16	1,883
Pension/no job	4,470	11	4,829
Mean/total	3,205	140	2,928

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.

7.3.3 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 (Table 7.7) 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 in 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 between the different occupational groups. The income of fishery and labor 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, in Table 7.8) and income per capita (p=0.048, not displayed) with employed households having ca. 4,600 LKR more and official households having 7,900 LKR more than the average household in this study. On the other hand, self-employed households had 4,300 LKR less and labor households had 7,500 LKR less than the average.

Table 7.7: Change in income between December 2004 (before the tsunami) and September 2007 between the different occupational groups; Kruskal-Wallis test significant (p=0.003). 17 households were omitted due to missing data.

Main income source of household	Mean (LKR)	N	Std. deviation
Fishery	96	39	5,853
Employed	5,207	38	12,656
Self-employed	-4,560	20	13,172
Labor	843	16	2,467
Official	5,065	16	8,542
Pension/no job	-2,381	11	9,796
Mean/total	1,277	140	10,169

Table 7.8: Mean of total income of households 2007 in 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 (in 1,000 LKR)	N	Std. deviation (x 1,000)
Fishery	14	40	12
Employed	21	38	22
Self-employed	12	23	7
Labor	9	16	5
Official	24	17	16
Pension/no job	15	12	18
Mean/total	16	146	16

Another analysis investigated connections between the occupational groups and the period without work after the tsunami. Households depending on fisheries had to spend 8 months on average without their main income, while this period was only 2.7

months for the other groups (Table 7.9). 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 finding 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 in the surveyed GN divisions decreased from 364 to 123 after the tsunami, i.e., 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.

Table 7.9: Mean period without work after the tsunami (in months) in the different occupational groups; ANOVA: p=0.001; Kruskal-Wallis test significant (p=0.000). Category "pension/no job" was not included in this analysis. 6 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
Labor	2.3	15	3.4
Official	1.1	17	1.8
Mean/total	4.3	140	6.8

When testing differences in financial help from the Sri Lankan Government by occupational groups, two main factors were observed (Table 7.10). While fishery households received 42 % more support than the average household of this study, labor households received 64 % less. Pairwise comparisons (with LSD test) showed significant differences for fishery (against employed, labor, official, and pension/no job households) and labor households (against fishery, employed, and self-employed households). The reason why fishermen received more money is 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. Instead, they had to look for new jobs or had to start working as a laborer on other boats. Other respondents mentioned that catches had decreased after the tsunami. This was due to an oversupply of small boats after the tsunami, which caused overexploitation in near-shore areas (De Silva and Yamao 2007; IRIN 2007; Sonvisen et al. 2006; BBC 2005). 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 for fishermen might be their particular exposure, as fishery 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).

Table 7.10: Financial support from the Sri Lankan government in the different occupational groups (ANOVA: p=0.001; Kruskal-Wallis: p=0.000). 2 households were omitted due to missing data.

Main income source of household	Mean (in 1,000 LKR)	N	Std. deviation (x 1,000)
Fishery	210	40	190
Employed	140	42	96
Self-employed	152	27	90
Labor	54	16	52
Official	130	17	91
Pension/no job	105	13	90
Mean/total	147	155	130

The low support for labor households is likely to be partly due to the fact that they suffered less financial damage than the other groups (Table 7.11). Their overall damage was roughly 24 % of the average of all surveyed households. The overall financial damage includes the damage to the house as well as the loss or destruction of other assets.

Table 7.11: Overall financial damage from the tsunami in the different occupational groups; (ANOVA: p=0.052; Kruskal-Wallis: p=0.000). 3 households were omitted due to missing data.

Main income source of household	Mean (in 1,000 LKR)	N	Std. deviation (x 1,000)
Fishery	666	41	513
Employed	682	42	635
Self-employed	600	27	339
Labor	178	15	132
Official	942	16	1,584
Pension/no job	413	13	501
Mean/total	619	154	707

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 5,000 LKR were chosen in order to have an equal number of cases per class. Class 5 includes all households with an income over 20,000 LKR. The same procedure was used for income per capita, where steps of 1,000 LKR were used, so that class 5 includes all households with a per capita income over 4,000 LKR.

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 could only be seen that all classes showed increases in income except the households with the highest income (over 20,000 LKR), which experienced losses of about 3,000 LKR (p=0.283 for all classes). The variable “time without work” also did not reveal 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). The same applies to the question whether the household managed to recover (yes/no).

When looking for correlations between income per capita and the variable “financial help from the government after the tsunami” it is noticeable that households with the lowest income (up to 1,000 LKR per household member) received about 190,000 LKR per household, which is 28 % more than the average of all surveyed households. The Kruskal-Wallis test gave a significance of p=0.017 for this analysis (Table 7.12).

Table 7.12: Financial support from the Sri Lankan government in the different income groups (based on income per capita of the household); Kruskal-Wallis test significant (p=0.017). 17 households were omitted due to missing data.

Income per capita classes (in LKR)	Mean (in 1,000 LKR)	N	Std. deviation (x 1,000)
0 - 1,000	191	24	82
1,001 – 2,000	136	36	93
2,001 – 3,000	122	25	102
3,001 – 4,000	142	23	101
> 4,000	156	32	213
Mean/total	149	140	131

One part of the questionnaire focused on drinking water supply of 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 3 households received their drinking water from a 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 (Table 7.13) Damages to wells and taps were then compared. While most affected households reported several damages at the same time for both sources, taps were mainly affected by the physical destruction of the structure. The share of wells without any damages was 30 % for wells, while 57 % of all taps were not affected by the tsunami.

Table 7.13: Type of damages to drinking water supply due to the tsunami. Multiple answers were permitted.

	Source of drinking water		
Damage type	Well	Tap	Total
None	12	65	77
Filled with debris	16	9	25
Salinization	20	15	35
Polluted by other contaminants	21	14	35
Destruction of structure	15	43	58

Significant differences between the water sources can be found when comparing the time the household had no proper water supply. While this was 1.6 months for taps, households depending on wells had to wait for 5.8 months until the water supply was properly restored (Kruskal-Wallis: p=0.003). The 9 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 9 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 water tankers, and the remaining 15 households were supplied from a public tap. The 2 other households had lost their private tap and also depended on a public tap.

Fourteen households reported that they received support for re-establishing their water supply, which is equal to 9.3 % of all households with information on water supply. 9 households received support from national or international NGO's, the other 5 were supported by the Sri Lankan government.

The questionnaire contained one question on protection measures taken by the household after the tsunami with regard to any future events. 30.6 % of the respondents (48 households) gave a positive reply. While most of the mentioned measures consisted of paying particular attention to any messages given on television, in the radio, or by the police, only very few people reported any concrete preventive measures taken after the event. One family built a two-storied house after the event in order to keep their valuables in a safe place and find shelter in case of an emergency. Households that mentioned protection measures, tended to be wealthier. While the average per-capita income (2004) of households without any measures was 2,700 LKR, this value was 4,200 LKR for households with prevention measures (p=0.002). This suggests that wealthier households in general have a higher awareness of the risk of natural hazards.

In addition to financial help from the government, the affected households generally received support from different sides. About 85 % of the surveyed households mentioned different types of support from national and international organizations. This support included kitchen equipment, food, medicine and the provision of fishing equipment or a new house. Very few households even received two new houses from different organizations. Help from friends, family, or neighbors also was an important aspect, as about 65 % of all households received some kind of informal support.

Finally, the question on the occurrence of other natural hazards in the region revealed that in general the study region is not very prone to hazardous events, as 69 % of the respondents did not mention any other hazards. The remaining households reported regular flooding, which mainly takes place along the inlet connecting the estuary with the sea. This flooding is due to the blocking of the estuary mouth by a sandbar and takes place during the rainy season. To avoid flooding consequences and to guarantee access to the sea for fishermen, the mouth is cleared regularly. As this flooding does not have any severe consequences, no preventive measures are taken by the affected households.

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 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 a width of 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. They also reported that the government particularly tried to relocate people formerly living very close to the coast.

7.4 Results of the vegetation survey

Figure 7.2 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 locations where only the foundation of a house was observed at the time of the survey. As the people had moved to other places, no questionnaires were conducted at these locations. The vegetation was dominated by coconut trees, *Pandanus*, and different shrub species in various associations. In some parts, there was hardly any vegetation left, and houses stood 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 more or less impassable vegetation cover.

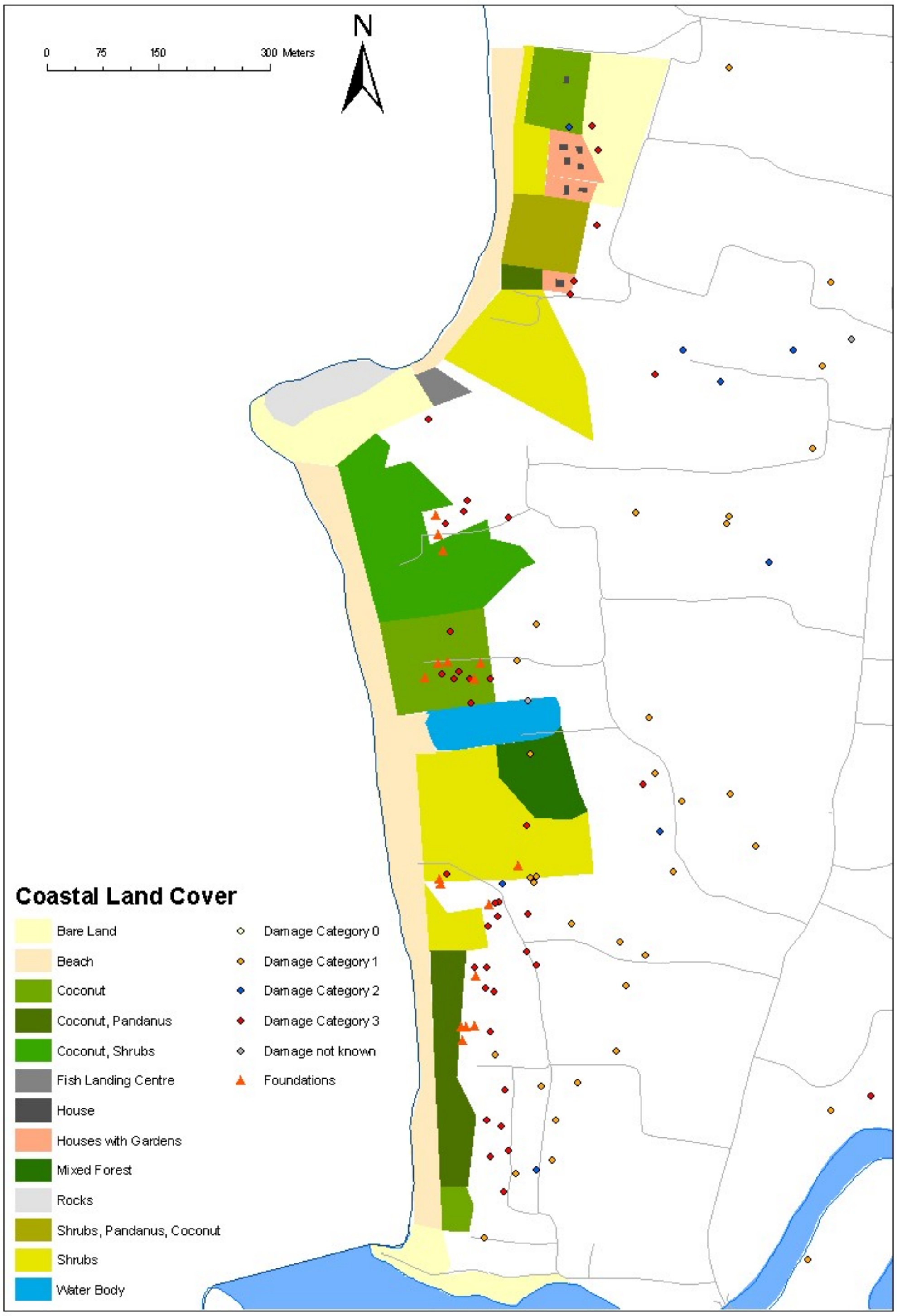

Figure 7.2: Coastal vegetation including the surveyed households divided into the different damage categories and mapped foundations.

In the considered subset of the vegetation survey, three different vegetation classes were defined based on visual inspection. The first section just north of the inlet consists of a belt of *Pandanus* backed by a loose coconut plantation with more or less no undergrowth (Figure 7.3). The width of this strip is between 30 and 50 m. The next section consists of only very few trees, but has a dense undergrowth of different shrubs with an overall density of 80 to 220 m (Figure 7.4). Finally, the main element of the third section again are 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 (Figure 7.5).

Figure 7.3: Example for vegetation class 1: belt of *Pandanus* in the front and loose coconut plantation without undergrowth behind.

Figure 7.4: Example for vegetation class 2: only few trees, but partly dense undergrowth of different shrubs (denser than classes 1 and 3).

Figure 7.5: Example for vegetation class 3: mainly coconut, with less *Pandanus* in the forefront (compared to class 1), but with denser undergrowth.

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 a linear ($F = ß_0 + ß_1 \cdot D$)[2] and an exponential model ($F = ß_0 \cdot e^{-ß_1 \cdot D}$) were compared within the range of the sampled data[3]. The analysis reveals 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 flow depths for the three vegetation classes at a distance of 0 m (Figure 7.6).

When applying the full linear model with V being the vegetation class, no significant interaction effect between the variables "vegetation class" and "distance to the sea" could 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 (Rothman 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 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 (Table 7.14). The results were stable under bootstrapping with 5,000 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 McCabe 2005; Garson 2009).

[2] F=Flow depth; D=Distance to the sea

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

Table 7.14: Linear regression model ($F = ß_0 + ß_1 \cdot D + ß_2 \cdot V$) 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	Standard error	Standardized coefficients	Sig.
	ß		$ß_s$	
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

In order to estimate the size of the vegetation effect at different distances from the sea, confidence bands were calculated. Figure 7.6 shows the 95 % confidence bands for the 3 vegetation classes and also confirms the differences between vegetation class 3 and the other two classes at all distances. The comparably large confidence intervals do not indicate real variations of the water level, but are due to limitations linked to estimates of flow depths by respondents.

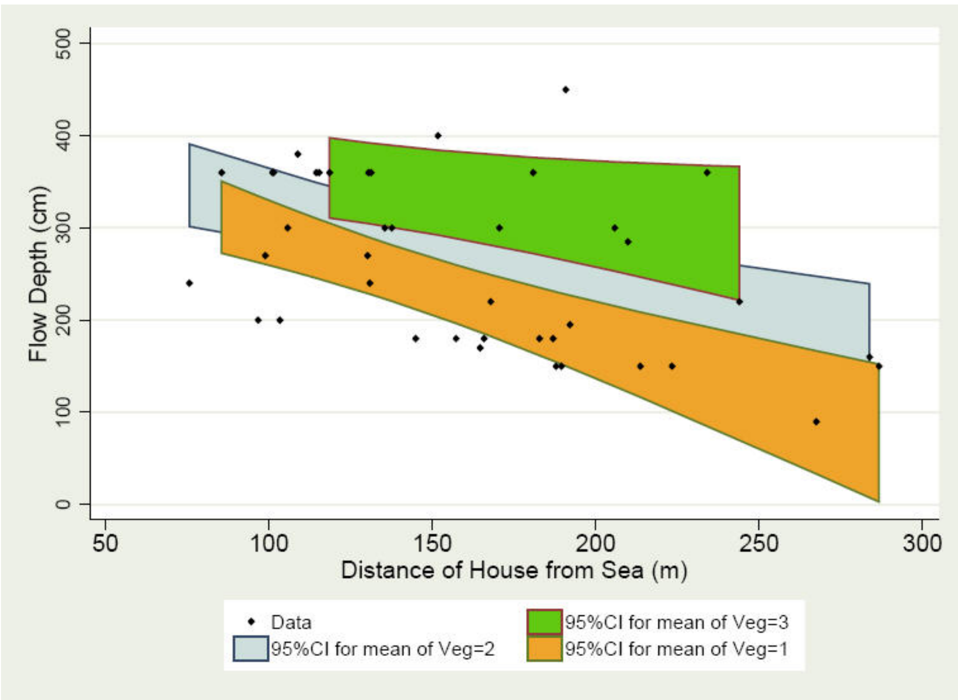

Figure 7.6: Results of the simple linear regression model with 95% confidence bands for the three vegetation classes. Class 3 shows clear differences compared to the other two classes.

In a second approach, the intercept of the linear model, i.e., the flow depth at distance zero for all vegetation classes, was set to 450 cm, which is a reasonable level 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 proves that the reduction of the water level with increasing distance from the sea was different for all three vegetation classes. Again, bootstrapping with 5,000 replications proved the stability of the results (Figure 7.7).

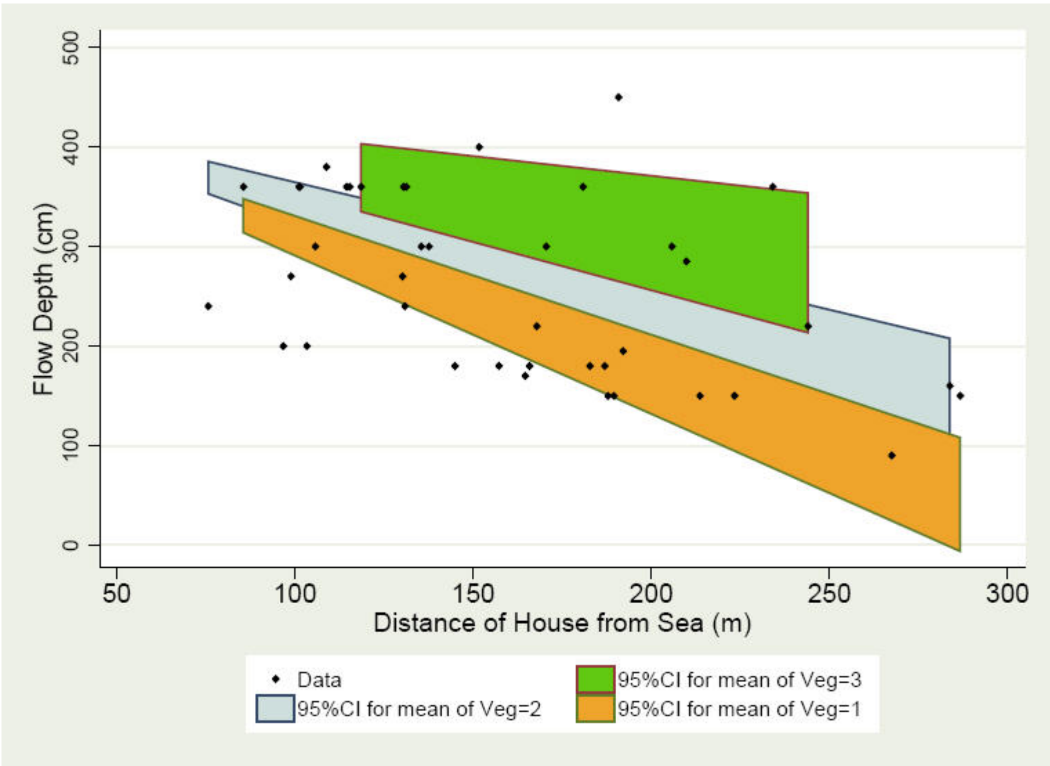

Figure 7.7: Results of the linear regression model with flow depth set to 450 cm right at the shore (distance to the coast = 0 m) with 95 % confidence bands for the three vegetation classes. Class 3 shows clear differences compared to the other two classes.

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 confirm the findings of the first model linked to flow depths. 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 the simpler model (Table 7.15). Clearly, these results are not independent from the first findings, but serve as an additional proof that the different vegetation classes had different effects on the impacts of the tsunami, i.e., on flow depth as well as on damage to the surveyed houses.

Table 7.15: 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	Standardized coefficients	Sig.
	ß	$ß_s$	
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 the protective effect of vegetation employed distance to the sea as the only adjusting factor. In reality, there are further factors that influenced the impacts of the tsunami waves, such as seafloor topography, particularly in near-shore areas (Chatenoux and Peduzzi 2005; Kumar et al. 2008), distance from the origin of the tsunami (Chatenoux and Peduzzi 2005), and further environmental parameters (Chatenoux and Peduzzi 2005; Kumar et al. 2008; Iverson and Prasad 2006; Baird et al. 2005). These factors were assumed to be homogenous in the study area and were therefore not included in the model. However, the generalization of the results is restricted to comparable situations. Generally, it is known that no observational study could ever prove cause-effect relations.

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. 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 (Figure 7.8). 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, the village is surrounded by a mangrove belt consisting only of *Rhizophora apiculata* with its extensive stilt roots. Although it is one of the few places in the study area with remaining natural vegetation, it was not possible to detect any protective effect through 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.

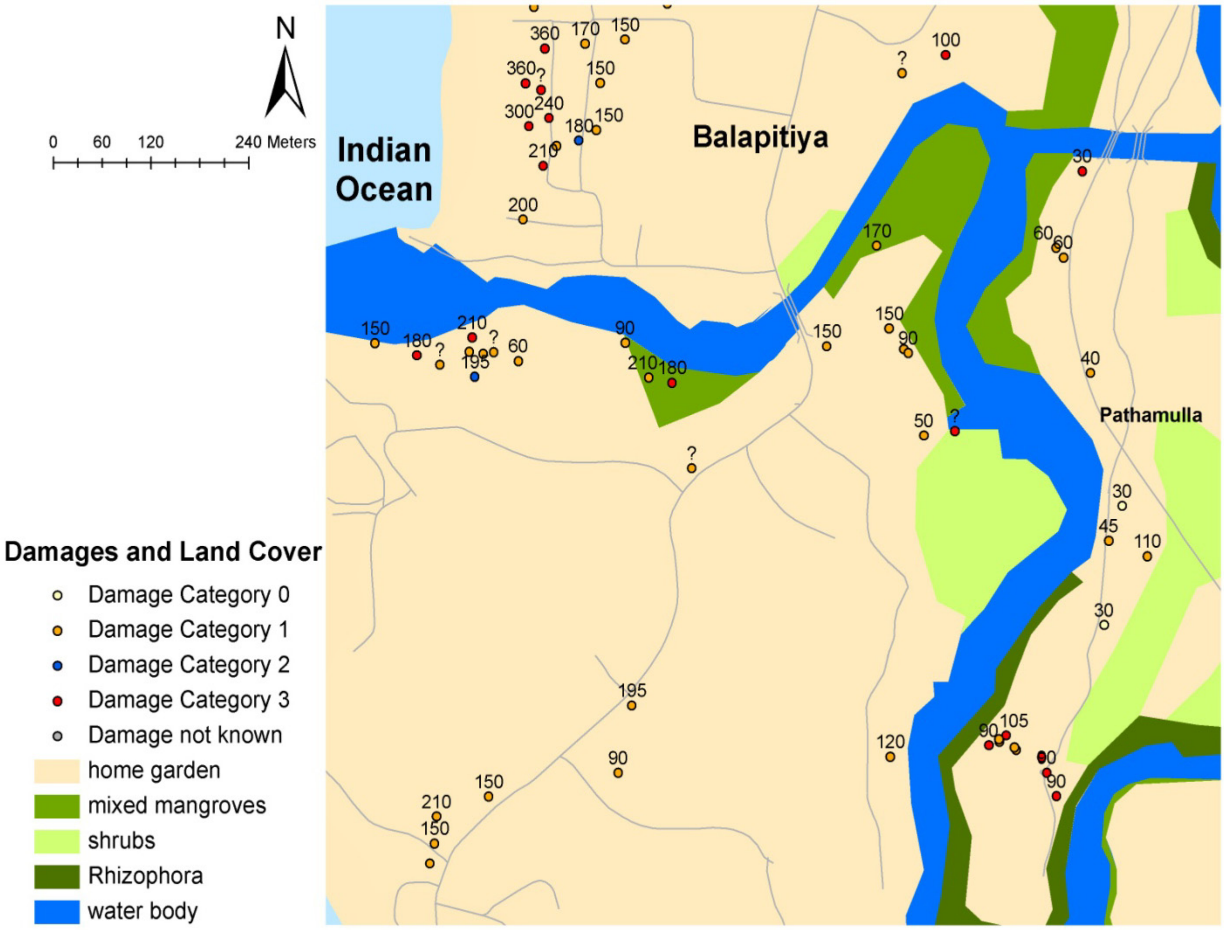

Figure 7.8: Overview of impacts of the tsunami along the inlet; numbers give the flow depth at the houses during the tsunami (in cm).

7.5 Discussion and conclusions

Referring to the ongoing discussion on the protective effects of coastal vegetation, one part of this study tried to determine whether this effect could be observed in a tsunami-affected area in southwestern Sri Lanka. As the region was homogeneous with respect to important factors such as coastal topography, simple models to test and estimate the protective effect of vegetation could be applied. Significant differences between the three analyzed vegetation classes were found with regard to their effects on flow depth at the surveyed houses and damages to the houses. The flow depth was significantly higher at houses behind the third vegetation class compared to the other two classes. 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. The decrease in flow depth with increasing distance from the sea was also slower behind this vegetation class. However, due to the given homogeneity in the study region, the results cannot be used as a general argument in favor of coastal vegetation as a protective shield against tsunami waves. Each location has to be analyzed independently in order to take into account 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 indicate potential protective effects of certain coastal ecosystems under specific conditions. Further extensive analyses should be conducted to find more evidence on this important issue for different locations. This could save lives and properties. On the other hand, the assumption of a protective effect of an ecosystem could lead to a false sense of security, as an ecosystem might not always provide the expected protection in case of a destructive natural hazard. For the small mangrove strip along the inlet, e.g., no protective effect could be identified from the damage analyses.

The use of the multidimensional vulnerability framework in combination with the Sustainable Livelihoods Framework proved to be useful for analyzing particular vulnerabilities of households in the study area. It is highly challenging 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 intends to go beyond the conservative categories of physical impact and physical as well as 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) indicates external socio-economic as well as biophysical influences on different scales, which have an impact on the 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 comprehensive way.

The results indicate that fishermen show a higher exposure than the other occupational groups as they live 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 flow depths, 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 not only 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 labor 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). Labor 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 water tankers.

The focus of the Turner framework is on coupled socio-ecological 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 have been criticized intensively particularly because of the uniform regulation of a buffer of 100 m, which did not take into account different aspects of exposure such as coastal topography or bathymetry (Ingram et al. 2006; Jayasuriya 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 the analysis, which proved the considerable reduction of the flow depth after the first 150 m from the shore (Table 7.2). However, the channeling 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 it 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 (Samaranayake 2006 pers. comm.; UDA 2006; IUCN 2007), is the establishment of various types of greenbelts along the coasts. The results of this study, corroborated by other research, indicate 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 neglect of other protective measures such as early warning systems in favor of greenbelts could further contribute to this development (Kerr and Baird 2007). 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.

8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary and conclusions

This study analyzed changes in land use and land cover as well as the vulnerability of a coastal community in southwestern Sri Lanka to natural hazards. The area around the small town of Balapitiya was affected by the tsunami in 2004, which caused extensive damages to houses, properties, and infrastructure. East of the town there is a brackish estuary (Maduganga), which is of high value due to its rich biodiversity and its contribution to local livelihoods through fishery and tourism. The areas north and east of the water body are mainly occupied by settlements and agricultural activities with cinnamon being the most important crop. The other areas are more urban with only small home gardens for personal use.

The study applied LUCC modeling and vulnerability assessment in a combined effort, as the two issues are closely linked to each other. Land use and land cover generally have a significant influence on the structure of the biophysical component of coupled socio-ecological systems. The biophysical component in turn is closely connected to the socio-economic subsystem through the provision of ecosystem services. Through this pathway, changes in land use and land cover have a direct impact on the vulnerability of coupled systems. Due to their complexity, both aspects require integrated and multidisciplinary approaches in order to analyze them in a comprehensive way.

Today it is widely accepted that LUCC are generally caused by a large set of proximate and underlying factors of different origins. Most ecosystems are more or less severely impacted by human influence, and human decision making is the major factor determining changes in land use and land cover. Decision making does not always follow the rules of purely rational behavior as assumed in most approaches. That is why most modeling efforts for simulating LUCC are not able to incorporate decision making in a realistic way. Due to their architecture, agent-based models (ABMs) are better suited to deal with this complex and important issue, in addition to further benefits. Therefore, it was decided to make use of LUDAS as a recently developed ABM for generating simulations of land cover and livelihoods under different policy scenarios.

The study supported the advancement of LUDAS through transferring and adapting it to a new socio-economic and biophysical setting.

Data for the simulation process were mainly collected through extensive household surveys using a structured questionnaire that focused on measuring access to the different asset categories of the Sustainable Livelihoods Framework. The surveys were complemented by visits to the agricultural plots of the households with surveys of agricultural practices, vegetation status mapping, RRA exercises, interviews with local and national experts and decision makers, and the analysis of secondary material such as statistics and government reports. Current land cover in the study area was analyzed by visual inspection of two Ikonos satellite images. Classification of land cover was based on the detailed knowledge of the study area and additional information from maps and aerial photographs, and complemented by ground truthing. Principal component analysis and cluster analysis resulted in a classification of the population in five different livelihood groups, three of which were used in the simulation process. Binary logistic regression analyses identified the socio-ecological determinants relevant for decision making on land use within the various livelihood groups.

The LUCC simulations reveal the impacts of changes in the selected external policy factors on human decision making with regard to land use and their implications for income generation. Access to agricultural subsidies and to agricultural extension services were identified as the most important policy factors for the area around Maduganga. The model thus analyzes scenarios of future development of land use and livelihoods based on changes in these factors. The values of the policy factors are defined by the user of the model. The simulations reveal that the impact of changes in the access to extension services is rather low, while better access to subsidies lowered the trend of decreasing income from agriculture and modified the development of mixed cinnamon and paddy areas. The results of the combined scenario, which assumed good access to both policy factors, are similar to those of the scenario with high access to subsidies without any extension services. This underlines the low impact of access to extension services on land use and livelihoods in the study area. However, most scenarios show large uncertainties, which increase towards the end of the 20-year simulation period. They can nevertheless be used to analyze general trends of future land use and livelihoods under different external conditions.

Overall, the simulations show a downward trend in the share of income from agricultural activities over the simulation period. Furthermore, the total of landholdings per household decreases, mainly due to declines in homestead area. It is suggested that this development is due to internal population growth, which leads to the division of landholdings into smaller pieces for subsequent generations.

The rather low impact of the selected policy factors on land use and income generation is due to current land use and the related livelihood strategies in the study area. The majority of the land around Maduganga is either occupied by homesteads or various agricultural uses with the exception of a few small spots along the estuary and the inlet, which still contain some mangroves or other more or less undisturbed vegetation (see section 5.4.1). With respect to ecological theories, the system in its current setting is assumed to be in a temporary stable state. Most theoretical approaches in ecology deny the existence of a so-called climax community, which is in perfect equilibrium and not subject to any further changes. These non-equilibrium theories describe ecosystems as complex adaptive systems that are influenced by multiple interactions on various temporal and spatial scales and that are open to external influences. Thus, they are subject to uncertainty, non-linearity, and complex dynamics. These aspects together with frequent disturbances prevent ecosystems from reaching a continuous climax state (Wallington et al. 2005; Scoones 1999). However, the system can still be in one of several possible states of temporary equilibrium (Pickett et al. 1992). This also applies to human-influenced ecosystems, which are becoming increasingly important in landscape ecology (Wu 2006). Therefore, this non-equilibrium approach can easily be transferred to the coupled socio-ecological system in this study.

The study area around Maduganga is in a temporary equilibrium, where no larger internal modifications can be expected, although smaller hierarchical components of the system can still be subject to changes. However, this does not imply that the system will never change again, but rather that changes have to be triggered by external influences. Such influences can be mainly of a political nature, e.g., changes in land-use planning, conservation efforts or other direct land-use related laws and regulations. Changes could also be triggered by policies that impact on livelihood strategies, although, for example, the simulations in this study reveal that the promotion of agricultural activities cannot be expected to have a major influence on land use and livelihoods. Economic aspects could affect the study region in form of a general economic downturn or through a strong decline or rise in cinnamon prices on the global market. Such macroeconomic disturbances would also impact on the vulnerability of livelihoods to further external shocks or hazards, as results of the vulnerability assessment in this study show.

The vulnerability assessment concentrates on the coastal strip around Balapitiya to evaluate the impacts of the tsunami and from the results assess the vulnerability of certain livelihood groups to future hazards. Data were again mainly collected through extensive household surveys. The locations of the surveyed households were captured with a GPS in order to analyze their exposure to the tsunami. Due to their importance, different ecosystem services, their disturbance through the impacts of the tsunami, and consequences for livelihoods were given particular attention.

The results show that labor and particularly fishery households were the most vulnerable to the impacts of the tsunami. Fishery households suffered the highest exposure to the energy of the waves, as they were living closest to the sea. They also had the greatest difficulties to recover after the event, because they had the longest period without work in the aftermath of the tsunami. They lost most of their working equipment and often did not receive adequate support from the government or from NGOs. Results also reveal the particular exposure of households along the inlet connecting the estuary with the sea, as the narrowing of the inlet intensified the forces of the waves.

The vulnerability assessment also included a detailed vegetation survey to analyze whether coastal vegetation had any protective effect. Simple linear regression models reveal significant differences between the three identified vegetation classes with regard to water level at the surveyed houses and damages to the houses.

The vulnerability assessment combined the utilization of two different frameworks for dealing with the complexity of coupled socio-ecological systems. The Turner framework provided the overall guidance for considering all relevant interactions and feedbacks of the various components of the social and the biophysical subsystems as well as influences from other hierarchical levels. The development of the survey and the indicators as well as the analysis of the collected data was guided by the exposure, sensitivity, and resilience of the system as the categories of vulnerability on the local level according to the Turner framework. The survey and indicator development also followed the asset categories of the Sustainable Livelihoods Framework in order to generate a comprehensive picture of livelihoods before and after the tsunami. This combined conceptual guidance facilitated the discovery of underlying vulnerabilities on the household level, which would not have been possible without a comprehensive assessment.

The results of the analysis show that most livelihood groups had managed to recover from the impact of the tsunami by the time of the survey, while for some groups the hazard caused a permanent shift in their livelihoods, as they did not succeed in returning to their previous income-generating activities. The assessment also reveals the importance of several ecosystem services for livelihoods, how the provision of these services can be affected by a hazard, and how the state of biophysical subsystems and thus their provision of services affect the vulnerability of communities to such hazards.

Vulnerability is basically a forward-looking approach to analyze the sensitivity and resilience of coupled systems to one or more potential hazards. This study, however, used an ex-post approach and conducted the vulnerability assessment after the hazard event had occurred. This approach improved the availability of quantifiable empirical data at the local level considerably and thus increased the accuracy of the assessment. The results help to identify certain elements of the coupled system such as livelihood groups, locations (e.g., along the inlet), and ecosystem services that proved to be severely affected by the tsunami. Thus, these elements can also be expected to be vulnerable to any upcoming similar events unless measures are taken to reduce this vulnerability.

The parallel implementation of the LUCC modeling and the vulnerability assessment proved to be a meaningful approach. While the vulnerability assessment focused on livelihoods and ecosystem services in the coastal system at Balapitiya, the LUCC modeling ensured that socio-economic, political, and ecological factors in the area around Maduganga, which forms the immediate hinterland of Balapitiya, as well as their impacts on the coastal strip, were also taken into account. The LUCC scenarios provide an outlook on how land use and livelihoods might change. Together with the vulnerability assessment, the combined results can be used for deducing policy recommendations for the resilience and the sustainability of the study system in general. The analysis for the LUCC simulations show that population pressure on the coastal system can be expected to increase due to a loss of importance of agricultural activities, migration to urban areas, the growing importance of tourism along the coastal strip, and the general trend of a growing population. This will contribute to a higher exposure of people to sea-related hazards, as they will also occupy areas close to the sea, and might also increase the pressure on the different types of coastal vegetation. The results of this study show that coastal vegetation in general had a significant impact on the energy of the tsunami waves. Furthermore, the remaining mangroves along the inlet and the estuary provide valuable services for people living around them. This especially applies to fishermen, as mangroves serve as nurseries for fishes and other marine organisms, e.g., shrimps, which are important for income generation around the estuary. The value of mangroves for livelihoods has been recognized in that area and efforts for their protection are underway. The fishermen suffered most from the impacts of the tsunami. Their livelihoods could be in further danger due to increasing pollution of the estuary and coastal waters. The government is currently making the first efforts to promote agriculture in general and cinnamon plantations in particular by providing subsidies for fertilizer. However, an increase in fertilizer and pesticide application might lead to a further deterioration of the water quality in the estuary, which was already identified as one of the main threats in that area (CCD 2004b). It would result in a reduction in fish and shrimp stocks, while at the same time due to population growth more people will rely on this resource for their livelihoods. In the immediate coastal area, deterioration of water quality is expected as a result of population pressure and subsequent economic activities and discharge of pollutants from the estuary. The provision of marine organisms is already hampered by overexploitation as too many people fish in the coastal waters.

An important advantage of the combined approach was that data collection and analysis of secondary material could be conducted in a combined effort. Furthermore, results of the land-cover classification for the simulation process could also be used for the vulnerability assessment, and the design of the questionnaire was identical in some parts, as both were related to the Sustainable Livelihoods Framework and analyzed similar livelihoods. Altogether, the questionnaire for the vulnerability assessment benefited from the experiences with the questionnaire for the LUCC modeling. Another advantage was the combined utilization of expert knowledge. Both scientific issues require a detailed knowledge of the relevant subcomponents of the coupled system and of relevant external factors influencing human decision making and vulnerability on the local level. The parallel approach ensured a comprehensive analysis of all relevant aspects of importance for livelihoods and vulnerability in the study area.

8.2 Recommendations for further research

Prior to this study, LUDAS was developed and applied for an upland watershed in central Vietnam (Le 2005). Due to its early development stage and the complexity of integrated LUCC modeling including the realistic simulation of human decision making, the approach will be subject to continuous verification. The generic modeling framework and many elements of the operational model can still be used when applying LUDAS in a new region. However, certain modifications may be necessary to adapt the model to the socio-economic and biophysical situation in the target region. The area selected for this study provided a different biophysical and socio-economic setting than the study area in Vietnam. The biophysical environment is strongly influenced by human activities, and the extent of more or less undisturbed ecosystems is very low. Additionally, the observations reveal that livelihoods in the Sri Lankan study area depend much less on land-based activities. The results of the simulations with the two selected external policy factors show that internal agent-driven changes are only of minor importance for changes in land use and land cover in such a system, which is in a temporary equilibrium state. A comparison of the first two applications of LUDAS shows that the model in its current version is mainly to be used in areas with remaining natural or semi-natural vegetation that is under pressure of being modified or converted to another land cover due to human activities. However, it was proven that there is no internal need and only few possibilities for additional LUCC in the area around Maduganga. On the other hand, the simulations reveal meaningful differences between the behavior and income-generating activities of the various livelihood groups. For the application of LUDAS in a similar setting, first the model should be modified in such a way that it focuses more on the livelihoods of different groups rather than just concentrating on land-use related issues. In this regard, the impact of potential external disturbances, which are out of the control of the local people, on livelihoods and land use, should be analyzed. The major goal of these analyses would be to reveal the threshold beyond which the resilience of the system is exceeded, the equilibrium collapses, and the system or subcomponents of the system shift into another regime with serious consequences for livelihoods.

With regard to the area around Maduganga estuary, these potential external disturbances could be mainly of an economic or political nature. While the policy factors used for the simulations did not cause great changes in land use, major political developments related to land-use planning could result in changes in land use and land cover. Such modifications could be, for example, large-scale regulations related to a zoning of the area around Maduganga or the enforcement of regulations for the protection of certain areas. A zoning plan for Maduganga was developed in 2006 (CRMP 2006), but had not yet been implemented at the time of the survey. In the same year, Maduganga was also declared as a sanctuary, which is supposed to enhance the protective status of the area. However, this development had not yet shown any consequences, which was also due to difficulties in enforcing the regulations (Ratnayake 2006 pers. comm.).

Regional economic changes could impact on the system in two ways. A general economic downturn with a subsequent loss of employment opportunities would lead to more people relying increasingly on livelihood activities depending on the direct provision of ecosystem services such as agriculture, fishery, or tourism. This development would increase pressure on the biophysical subsystems in the study area, although it is not likely to cause a shift of the whole system. However, it could threaten the livelihoods of the households relying on ecosystem services. Tourism is already on the rise in this area due to the scenic attractiveness of the estuary and is beginning to cause difficulties between people generating income through tourism activities and other people, particularly fishermen. The increasing pressure on ecosystem services could be further intensified by population growth, which is about 1 % in the Galle district.

Another economic influence could result from a severe global drop in cinnamon prices, as cinnamon is the most important export product in this area. This would be likely to lead to a considerable disturbance of many livelihoods around

Maduganga, and might eventually lead to changes in land use with a significant reduction in the cinnamon area. The global financial crisis in 2008 and 2009 had already resulted in a sharp decline of prices for several Sri Lankan export commodities including cinnamon (CBSL 2008; Seneviratne et al. 2009; The Colombo Times 2009).

In addition to this stronger focus on livelihoods, there are further methodological options with regard to decision making, economic aspects, biophysical features, and validation strategies to enhance the ability of LUDAS to provide a more realistic description of LUCC in coupled socio-ecological systems. These options were discussed by Le (2005). As outlined above, LUDAS should be adapted to other biophysical and socio-economic settings, either with a particular focus on LUCC or on further aspects influencing decision making and livelihoods of different social groups in the study region under consideration.

The need for adaptation of the methodology to other geographical settings also applies to the vulnerability assessment as the second major research component of this study. It is expected that the combination of the different frameworks as guiding principles for the design of the vulnerability assessment in general and of the indicator development in particular can serve as a universal approach for conducting comprehensive assessments in various socio-economic and biophysical environments. Nevertheless, indicators and tools for analyzing the linkages between the different components of the coupled system and the overall vulnerability of the system always have to be adapted to the particular conditions in the respective study area. Furthermore, different hazards require different tools and methodologies, particularly with regard to describing the impact of the hazard and the exposure of the components of the system to these impacts. This task becomes a major challenge when dealing with the vulnerability to multiple hazards instead of focusing only on one specific hazard.

This study aimed at conducting a vulnerability assessment as comprehensive as possible. However, due to the complexity of coupled socio-ecological systems the consideration of all relevant aspects on all scales is nearly impossible (Turner et al. 2003b). Therefore, future assessments should aim to include further political and socio-economic aspects particularly on higher hierarchical scales such as the national or the international level, and to analyze how they impact on the local system.

Due to the above-described importance of ecosystem service provision when characterizing the vulnerability and resilience of coupled socio-ecological systems and the disregard of these interlinkages in many approaches, this aspect has to be given major consideration in upcoming vulnerability assessments. This applies particularly with regard to non-provisioning services, which are difficult to capture and to quantify. This study identified the protective function of coastal vegetation as one ecosystem service with a potential to influence the vulnerability and resilience of the coupled system. The study applied detailed vegetation surveys together with linear regression models to identify the linkages between vegetation and damages. However, other ecosystem services will require other tools and methodologies of analysis that have to be developed as place-based studies on the basis of secondary data and consideration of the particular conditions in the study area.

The vulnerability assessment conducted in this study applied an ex-post approach that analyzed the impacts of a past event in order to identify vulnerabilities to similar future hazards. In a next step, the indicator set should be advanced such that it can also be applied in an ex-ante vulnerability assessment. This approach will require a modification of the analyzed parameters, as characteristics and impacts of the hazard will not be available for investigation. Instead, the analysis should put an even stronger focus on socio-economic characteristics and on the importance of various ecosystem services for local livelihoods. It would also be of particular relevance to analyze how external parameters such as national policies can modify the vulnerability of different components of the system.

By simulating LUCC with an ABM under different policy scenarios and assessing the vulnerability of a coupled socio-ecological system to natural hazards, this study employed two different but nevertheless conceptually linked research approaches. Both topics benefited from the detailed knowledge of important aspects of social, political, economic, and ecological origin influencing the structure and function of the system in the study area. Thus, it was possible to develop livelihood profiles and depict connections between the socio-economic and the biophysical components of the system under consideration in a particularly accurate and detailed way. Due to the described conceptual linkages between LUCC modeling and vulnerability assessments, the combination of the two research fields helps to generate important knowledge for the sustainable development of coupled socio-ecological systems. However, further efforts should link vulnerability assessments to advanced LUCC models. Combined analyses could, for example, assess the impacts of simulated LUCC changes on the provision of ecosystem services and the overall vulnerability of the coupled system. It should also be tested if and how agent-based approaches could be used to simulate the vulnerability of certain components of coupled systems under specific hazard conditions and external parameters. In a next step, the same methodology could be used to analyze the impacts of various measures to increase the adaptive capacity of the system (Downing and Ziervogel 2004; Patt and Siebenhüner 2005; Acosta-Michlik 2005). It is expected that these efforts will result in a variety of different approaches, all of which are suited for particular situations and hazards. Particularly the differentials in the characteristics of hazards will influence the design of the ABM and the analyzed parameters. Rapid onset hazards such as tsunamis, storm surges, or earthquakes create only short-term impacts (however, with long-term consequences), while creeping hazards such as impacts of climate change, food insecurity, and economic shocks reveal their impacts on the system over a long time period.

When incorporated into decision-making processes, the realistic simulation of LUCC and its effects on livelihoods can support the development of a sustainable management of natural resources, ecosystem services, and livelihoods. Ensuring at the same time that the coupled socio-ecological system is resilient to various types of external disturbances, the combination of both research fields can significantly contribute to the sustainable development of communities and their environment.

9 REFERENCES

Acosta-Michlik L (2005) Intervulnerability assessment – shifting foci from generic indices to adaptive agents in assessing vulnerability to global environmental change. Report on a Project of the Advanced Institute on Vulnerability to Global Environmental Change

Adger WN (2000) Social and ecological resilience: are they related? in: Prog Hum Geog 24(3):347-364

Adger WN, Brooks N, Bentham G, Agnew M, Eriksen S (2004) New indicators of vulnerability and adaptive capacity. Technical Report 7, Tyndall Centre for Climate Change Research.

Adger WN, Hughes PT, Folke C, Carpenter SR, Rockström J (2005) Socio-ecological resilience to coastal disasters. Science 309:1036-1039

Adger WN (2006) Vulnerability. Global Environ Chang 16:268-281

Aeron-Thomas M (2003) Integrated coastal zone management in Sri Lanka. Improving policy-livelihood relationships, Policy Review Paper 4, UK Department for International Development

Affeltranger B, Bogardi J, Renaud F (2005) Living with water. In: United Nations (ed) Know risk. Geneva, pp 258-261

Agarwal C, Green GM, Grove JM, Evans TP, Schweik CM (2002) A review and assessment of land-use change models: dynamics of space, time, and human choice. Gen. Trch. Rep. NE-297, U.S. Department of Agriculture, Forest Service, Northeastern Research Station

Alcamo J, Busch G (2005) Global land scenarios. Update - Newsletter of the International Human Dimensions Programme on Global Environmental Change, 03/2005, pp10-11

Alcamo J, Kok K, Busch G, Priess JA, Eickhout B, Rounsevell M, Rothman DS, Heistermann M (2006) Searching for the future of land: scenarios from the local to global scale. In: Lambin EF, Geist HJ (eds.) Land-use and land-cover change – local processes and global impacts. Springer, Berlin Heidelberg New York, pp 137-155

Alongi DM (2002) Present state and future of the world’s mangrove forests. Environ Conserv 29(3):331-349

Alwang J, Siegel PB, Jorgensen SL (2001) Vulnerability: a view from different disciplines. Social Protection Discussion Paper Series, The World Bank

Amarasinghe MD (2004) Current status of mangroves and other coastal wetlands in Sri Lanka. In: IUCN Sri Lanka (ed) Wetland conservation in Sri Lanka. Proceedings of the National Symposium on Wetland Conservation and Management, Sri Lanka

Anderies JM, Janssen MA, Ostrom E (2004) A framework to analyze the robustness of social-ecological systems from an institutional perspective. in: Ecol Soc 9(1): 18 [online]. http://www.ecologyandsociety.org/vol9/iss1/art18/

Anderson JR, Feder G (2007) Agricultural extension. Handbook of Agricultural Economics 3:2343-2378

Angelsen A, Kaimowitz D (1999) Rethinking the causes of deforestation: lessons from economic models. World Bank Res Obser 14(1):73-98

Annan K (2003) Message for the international day for disaster reduction 8 October 2003. http://www.unisdr.org/eng/public_aware/world_camp/2003/pa-camp03-sg-eng.htm. Cited 29 Oct 2007

Appanah S (2005) Assessment of forestry-related requirements for rehabilitation and reconstruction of tsunami-affected areas of Sri Lanka. Mission Report 10-24 March 2005, Food and Agriculture Organization of the United Nations

Axelrod R (2003) Advancing the art of simulation in the social sciences. in: Japanese Journal for Management Information Systems 12(3), special issue on agent-based modeling

Backhaus K, Erichson B, Plinke W, Weiber R (2006) Multivariate Analyseverfahren – Eine anwendungsorientierte Einführung. Springer, Berlin Heidelberg

Baird AH, Campbell SJ, Anggoro AW, Ardiwijaya RL, Fadli N, Herdiana Y, Kartawijaya T, Mahyiddin D, Mukminin A, Pardede ST, Pratchett MS, Rudi E, Siregar AM (2005) Acehnese reefs in the wake of the Asian Tsunami. Curr Biol 15:1926-1930

Baird AH (2006) Myth of green belts. Samudra 44:14-19

Baird AH, Kerr AM (2008) Landscape analysis and tsunami damage in Aceh: comment on Iverson and Prasad (2007). Landscape Ecol 23(1):3-5

Bambaradeniya CNB, Ekanayake SP, Kekulandala LDCB, Fernando RHSS, Samarawickrama VAP, Priyadharshana TGM (2002) An assessment of the status of biodiversity in the Maduganga mangrove estuary. Occasional Papers of IUCN Sri Lanka No.1, Colombo, The World Conservation Union.

Barbier EB (2007) Valuing ecosystem services as productive inputs. Econ Policy 22 (49):177-229

Barrett CB, Reardon T, Webb P (2001) Nonfarm income diversification and household livelihood strategies in rural Africa: concepts, dynamics, and policy implications. Food Policy 26:315-331

Batty M, Torrens PM (2001) Modeling complexity: the limits to prediction. Working Paper Series, Paper 36 – Oct 01, Centre for Advanced Spatial Analysis, University College London

BBC (2005) Tsunami fishermen struggle to cope. British Broadcasting Corporation. 30/12/2005. http://news.bbc.co.uk/1/hi/world/south_asia/4534868.stm. Cited 23 Sep 2008

Becchetti L, Castriota S (2007) Microcredit as a recovery tool: positive effects on a sample of Sri Lankan MFI borrowers hit by the tsunami. XVI International Tor Vergata Conference on Banking and Finance, Centre for Economic and International Studies, Università degli Studi di Roma, 5-7 December 2007

Berkes F, Colding J, Folke C (2003) Introduction. In: Berkes F, Colding J, Folke C, (eds) Navigating social-ecological systems – building resilience for complexity and change. Cambridge University Press, Cambridge, pp1-29

Birkhaeuser D, Evenson RE, Feder G (1991) The economic impact of agricultural extension: a review. Econ Dev Cult Change 39(3):607-650

Birkmann J (2006) Measuring vulnerability to promote disaster-resilient societies: conceptual frameworks and definitions. In: Birkmann J (ed) Measuring vulnerability to natural hazards – towards disaster resilient societies. United Nations University Press, Tokyo, pp9-54

Birkmann J, Wisner B (2006) Measuring the un-measurable – the challenge of vulnerability. Source 05/2006, United Nations University, Institute for Environment and Human Security, Bonn

Birkmann J, Fernando N (2008) Measuring revealed and rmergent vulnerabilities of coastal communities to tsunami in Sri Lanka. Disasters 32(1):82-104

Block S, Webb P (2001) The dynamic of livelihood diversification in post-famine Ethiopia. Food Policy 26:333-350

Blyth MJ (2005) Learning from the future through scenario planning. http://www.fourscenes.com.au/LearningFromScenarios0305.pdf. Cited 25 Aug 2009

Bohle HG (2001) Vulnerability and criticality. In: Update - Newsletter of the International Human Dimensions Programme on Global Environmental Change, 02/2001

Bonabeau E (2002) Agent-based modeling: methods and techniques for simulating human systems. P Natl Acad Sci USA 99(3):7280-7287

Braimoh A (2004) Modeling land-use change in the Volta basin of Ghana. Ecology and Development Series, No.14, Cuvillier Verlag, Göttingen.

Briassoulis H (2000) Analysis of land use change: theoretical and modeling approaches. In: Loveridge S (ed) The web book of regional science. Regional Research Institute, West Virginia University. http://www.rri.wvu.edu/regscweb.htm. Cited 25 Feb 2008

Brown DG, Walker R, Manson SM, Seto K (2004) Modeling land use and land cover change. In: Gutman G, Janetos A, Justice C, Moran E, Mustard J, Rindfuss R, Skole D, Turner II BL (eds) Land change science: observing, monitoring, and understanding trajectories of change on the earth's surface. Kluwer Academic Publishers, Dodrecht, pp395-409

Brown DG (2006) Agent-based models. In: Geist HJ (ed) Our earth's changing land: An encyclopedia of land-use and land-cover change, vol. 1 (A-K). Greenwood Press, Westport, London, pp7-13

Buchenrieder G (2003) Overview of poverty impacts of and policy options for non-farm rural employment. In: Proceedings of the Mini-Symposium on "Poverty impacts and policy options of non-farm rural employment", 25th International Conference of Agricultural Economists (IAAE) on "Reshaping agriculture's contributions to society", Durban, 16-22 August 2003

Cahn M (2002) Sustainable livelihoods approach: concept and practice. Devnet Conference 2002 – Contesting development: pathways to better practice, Institute of Development Studies, Massey University, 5-7 December 2002

Calder IR (2005) Blue revolution – integrated land and water resource management. 2nd edn. Earthscan, London

Campbell B Sayer JA, Frost P, Vermeulen S, Pérez MR, Cunningham A, Prabhu R (2001) Assessing the performance of natural resource systems. Ecol Soc 5(2):22 [online]. http://www.ecologyandsociety.org/vol5/iss2/art22/

Cannon T, Twigg J, Rowell J (2003) Social vulnerability, sustainable livelihoods and disasters. Report to DFID, Conflict and Humanitarian Assistance Department (CHAD) and Sustainable Livelihoods Support Office.

Cardona OD (2003) The need for rethinking the concepts of vulnerability and risk from a holistic perspective: a necessary review and criticism for effective risk management. In: Bankoff G, Frerks G, Hilhorst D (eds) Mapping vulnerability: disasters, development and people. Earthscan, London, pp37-51

Carpenter S, Walker B, Anderies JM, Abel N (2001) From metaphor to measurement: resilience of what to what? Ecosystems 4:765-781

Carpenter SR, Bennett EM, Peterson GD (2006) Scenarios for ecosystem services: an overview. Ecol Soc 11(1):32. [online]. http://www.ecologyandsociety.org/ vol11/iss2/art32/

Carr DL (2004) Proximate population factors and deforestation in tropical agricultural frontiers. Popul Environ 25(6):585-612

Castella J-C, Tran Ngoc Trung, Boiussau S (2005) Participatory simulation of land-use changes in the northern mountains of Vietnam: the combined use of an agent-based model, a role-playing game, and a geographic information system. Ecol Soc 10(1):27. [online]. http://www.ecologyandsociety.org/vol10/iss1/art27/

Castle CJE, Crooks AT (2006) Principles and concepts of agent-based modelling for developing geospatial simulations. Working Paper Series, Paper 110 – Sep 06, Centre for Advanced Spatial Analysis, University College London

CBSL (2008) Annual report 2008. Central Bank of Sri Lanka, Colombo

CCD (no year) Sri Lanka's mangroves. Colombo

CCD (2004a) Revised coastal zone management plan Sri Lanka. Coast Conservation Department, Colombo

CCD (2004b) Coastal environmental profile – Maduganga special management area Sri Lanka. Coast Conservation Department, Colombo

CCD (2005) Special area management plan for Maduganga estuarine lagoon. Coast Conservation Department, Colombo

CEA (2005) Environmental atlas of Sri Lanka. Central Environmental Authority, Battaramulla

CEA, Arcadis Euroconsult (1999) Wetland atlas of Sri Lanka. Central Environmental Authority, Arcadis Euroconsult, Colombo

Chambers, R, Conway GR (1991) Sustainable rural livelihoods: practical concepts for the 21st century. IDS Discussion Paper 296, Institute of Development Studies

Chang SE, Eeri M, Adams BJ, Alder J, Berke PR, Chuenpagdee R, Ghosh S, Wabnitz C (2006) Coastal ecosystems and tsunami protection after the December 2004 Indian Ocean Tsunami. Earthq Spectra 22(S3):863-887

Chatenoux B, Peduzzi P (2005) 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

Chhabra A, Haberl H, Braimoh A (2005) Multiple impacts of land-use/cover change. Update - Newsletter of the International Human Dimensions Programme on Global Environmental Change, 03/2005, p12

CIA (2008) The 2008 world factbook. Central Intelligence Agency. https://www.cia.gov/library/publications/the-world-factbook/. Cited 22 July 2008

Clark WC, Dickson NM (2003) Sustainability science: the emerging research program. P Natl Acad Sci USA 100(14):8059-8061

Clark WC (2007) Sustainability science: a room of its own. P Natl Acad Sci USA 104(6):1737-1738

Clemett A, Senaratna S, Banda R (2004) Can coastal zone management in Sri Lanka sustain local livelihoods and ecosystems? Improving policy-livelihood relationships, Policy Process Analysis Paper 2, UK Department for International Development

Cochard R, Ranamukhaarachchi SL, Shivakoti GP, Shipin OV, Edwards PJ, Seeland KT (2008) The 2004 Tsunami in Aceh and southern Thailand: A review on coastal ecosystems, wave hazards and vulnerability. Perspect Plant Ecol 10:3-40

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:253-260

CPA (2006) Reflections on tsunami one year on: lessons to be learnt. Discussion Paper, The Centre for Policy Alternatives, Colombo

Crawford IM (1997) Marketing research and information systems. Marketing and Agribusiness Texts, No. 4. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/docrep/W3241E/w3241e00.HTM. Cited 6 Feb 2008

Crawford TW, Messina JP, Manson SM, O'Sullivan D (2005) Complexity science, complex systems, and land-use research. Environ Plann B 32:792-798

CRMP (2006) Report of the Maduganga zoning study. Coastal Resources Management Project, Colombo

Crutzen PJ, Stoermer EF (2000) The „Anthropocene". Global Change Newsletter, No. 41, The International Geosphere–Biosphere Programme (IGBP), pp17-18

Crutzen PJ (2006) The “Anthropocene”. in: Ehlers E, Krafft T (eds): Earth System Science in the Anthropocene - Emerging Issues and Problems. Springer, Berlin Heidelberg New York, pp13-18

Cutter SL, Boruff BJ, Shirley WL (2003) Social vulnerability to environmental hazards. Soc Sci Quart 84(2):242-261

Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J (2008) A place-based model for understanding community resilience to natural disasters. Global Environ Chang 18:598-606

Dahdouh-Guebas F, Jayatissa LP, Di Nitto D, Bosire JO, Lo Seen D, Koedam N (2005) How effective were mangroves as a defence against the recent tsunami? Curr Biol 15(12):R443-R447

Danielsen F, Sorensen MK, Olwig MF, Selvam V, Parish F, Burgess ND, Hiraishi T, Karunagaran VM, Rasmussen MS, Hansen LB, Quarto A, Suryadiputra N (2005) The Asian tsunami: a protective role for coastal vegetation. Science 310:643

Das S, Vincent JR (2009) Mangroves protected villages and reduced death toll during Indian super cyclone. P Natl Acad Sci USA 106(18):7357-7360

DCS (2001) Census of population and housing 2001. Department of Census and Statistics. Colombo

DCS (2004) Announcement of the official poverty line. Department of Census and Statistics, Colombo. http://www.statistics.gov.lk/poverty/index.htm. Cited 23 July 2008

DCS (2005a) Census of buildings and persons affected by the tsunami – 2004 – Balapitiya DS Division, Galle District. Department of Census and Statistics, Colombo

DCS (2005b) Preliminary statistics of the census of buildings and persons affected by the tsunami – 2004 – Galle District. Department of Census and Statistics, Colombo

DCS (2007) Statistical abstract 2007. Department of Census and Statistics, Colombo. http://www.statistics.gov.lk/Abstract_2006/abstract2006/index.htm. Cited 22 July 2008

Dent JB, Edwards-Jones G, McGregor MJ (1995) Simulation of ecological, social and economic factors in agricultural systems. Agr Syst 49:337-351

De Silva DAM, Yamao M (2007) Effects of the tsunami on fisheries and coastal livelihood: a case study of tsunami-ravaged southern Sri Lanka. Disasters 31(4):386-404

De Silva G (2005) Mangroves as a tsunami buffer - Is it a myth? http://www.wildasia.net/main.cfm?page=article&articleID=183. Cited 23 Dec 2008

DFID (2001) Sustainable livelihoods guidance sheets. Department for International Development, London

Dominey-Howes D, Papathoma M (2007) Validating a tsunami vulnerability assessment model (the PTVA model) using field data from the 2004 Indian Ocean tsunami. Nat Hazards 40(1):113-136

Downing T, Ziervogel G (2004) Toolkit for vulnerability and adaptation training. Stockholm Environment Institute, Oxford

Downing TE, Aerts J, Soussan J, Barthelemy O, Bharwani S, Ionescu C, Hinkel J, Klein RJT, Mata LJ, Martin N, Moss S, Purkey D, Ziervogel G (2005) Integrating social vulnerability into water management. SEI Working Paper and Newater Working Paper No. 4, Stockholm Environment Institute, Oxford

Eastwood R, Lipton M, Newell A (2010) Farm size. Handbook of Agricultural Economics 4:3323-3397

Edmonds C (2002) The role of infrastructure in land-use dynamics and rice production in Viet Nam's Mekong river delta. ERD Working Paper Series No. 16, Economic and Research Department, Asian Development Bank

Ellis F (2000) Rural livelihoods and diversity in developing countries. Oxford University Press, Oxford

EM-DAT (2010) The OFDA/CRED international disaster Database – www.emdat.net – Université catholique de Louvain – Brussels – Belgium

Etienne M, Cohen M, Le Page C (2003) A step-by-step approach to building land management scenarios based on multiple viewpoints on multi-agent system simulations. Jasss 6(2). [online]. http://jasss.soc.surrey.ac.uk/6/2/2.html

FAO (2001) Forest resources of Sri Lanka – country report. The Forest Resources Assessment Programme, Food and Agriculture Organization of the United Nations. Rome. http://www.fao.org/docrep/007/ad678e/AD678E00.htm. Cited 22 May 2007

FAO (2005) Global forest resources Assessment 2005 – Sri Lanka country report. Country Report 123, Forestry Department, Food and Agriculture Organization of the United Nations, Rome

Few R (2003) Flooding, vulnerability and coping strategies: local responses to a global threat. Progress in Development Studies 3(1):43-58

Flint EP, Richards JF (1991) Historical analysis of changes in land-use and carbon stock of vegetation in South and Southeast Asia. Can J Forest Res 21:91-110

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global consequences of land use. Science 309:570-574

Folke C, Carpenter S, Walker B, Scheffer M, Elmqvist, T, Gunderson L, Holling CS (2004) Regime shifts, resilience, and biodiversity in ecosystem management. Annu Rev Ecol Evol S 35:557-581

Folke C (2006) Resilience: the emergence of a perspective for social-ecological systems analyses. Global Environ Chang 16:253-267

Gallopin GC (2006) Linkages between vulnerability, resilience, and adaptive capacity. Global Environ Change 16:293-303

Garson GD (2009) Statnotes: topics in multivariate analysis. http://faculty.chass.ncsu.edu/garson/PA765/statnote.htm. Cited 09 July 2009

Geist H, McConnell W, Lambin EF, Moran E, Alves D, Rudel T (2006) Causes and trajectories of land-use/cover change. In: Lambin EF, Geist HJ (eds) Land-use and land-cover change – local processes and global impacts. Springer, Berlin Heidelberg, pp41-70

Geoghegan J, Pritchard Jr L, Ogneva-Himmelberger Y, Chowdhury RR, Sanderson S, Turner II BL (1998) "Socializing the pixel" and "pixelizing the social" in land-use and land-cover Change. In: Liverman D, Moran EF, Rindfuss RR, Stern PC (eds) People and pixels - linking remote sensing and social science. National Academy Press, Washington, pp51-69

Geoghegan J, Villar SC, Klepeis P, Menodza PM, Ogneva-Himmelberger Y, Chowdhury RR, Turner BL II, Vance C (2001) Modelling tropical deforestation in the southern Yucatán peninsular region: comparing survey and satellite data. Agr Ecosyst Environ 85:25-46

Gibson CC, Ostrom E, Ahn TK (2000) The concept of scale and the human dimensions of global change: a survey. Ecol Econ 32:217-239

GLP (2005) Science plan and implementation strategy. Global Land Project, IGBP Report No. 53/IHDP Report No. 19, Stockholm

Gobin A, Campling P, Feyen J (2002) Logistic modelling to derive agricultural land use determinants: a case study from southeastern Nigeria. Agr Ecosyst Environ 89:213-228

GTZ (2005) Linking poverty reduction and disaster risk management. German Technical Cooperation, Eschborn

Haggith M, Muetzelfeldt RI, Taylor J (2003) Modelling decision-making in rural communities at the forest margin. Small-scale Forest Economics, Management and Policy 2(2):241-258

Harada K, Kawata Y (2004) Study on the effect of coastal forest to tsunami reduction. Annuals of the Disaster Prevention Research Institute Kyoto University 47C:273-279

Henrickson L, McKelvey B (2002) Foundations of "new" social science: institutional legitimacy from philosophy, complexity science, postmodernism, and agent-based modeling. P Natl Acad Sci USA 99(Suppl.3):7288–7295

HIC (2005) Impact of tsunami on lives by DS Divisions – Galle District. Humanitarian Information Centre for Sri Lanka. http://www.humanitarianinfo.org/srilanka/catalogue/Files/Map%20Centre/Thematic%20Maps/Sectoral%20Maps/LK0078_galle%20Tunami_Impact_07July.pdf. Cited 9 Dec 2008

Holling CS (1973) Resilience and stability of ecological systems. Annu Rev Ecol Syst 4:1-23

Hoogeveen J, Tesliuc E, Vakis R, Dercon S (2004) A guide to the analysis of risk, vulnerability and vulnerable groups. World Bank Policy Research Working Paper

Huigen MGA (2003) Agent based modelling in land use and land cover change studies. Interim Report, International Institute for Applied Systems Analysis, Laxenburg

Huigen MGA (2004) First principles of the MameLuke multi-actor modelling framework for land use change, illustrated with a Philippine case study. J Environ Manage 72:5-21

IMF (2008) World economic outlook database. International Monetary Fund. http://www.imf.org/external/pubs/ft/weo/2008/01/weodata/index.aspx. Cited 23 July 2010

Ingram JC, Franco G, Rumbaitis-del Rio C, Khazai B (2006) Post-disaster recovery dilemmas: challenges in balancing short-term and long-term needs for vulnerability reduction. Environ Sci Policy 9:607-613

IRIN (2007) Sri Lanka: fishing industry still lacks large tonnage boats. Integrated Regional Information Networks, UN Office for the Coordination of Humanitarian Affairs. 21/06/2007. http://www.irinnews.org/Report.aspx?ReportId=72857. Cited 15 Oct 2008

IUCN (2000) Conservation management plan for ten selected mangrove habitats south of Colombo, Sri Lanka. The World Conservation Union, Forest Department under the Ministry of Forestry & Environment, Colombo

IUCN (2005) Rapid environmental and socio-economic assessment of tsunami-damage in terrestrial and marine coastal ecosystems of Ampara and Batticaloa districts of eastern Sri Lanka. The World Conservation Union

IUCN (2007) Technical guidelines for the establishment of a coastal greenbelt. The World Conservation Union, Sri Lanka Country Office

Iverson LR, Prasad AM (2007) Using landscape analysis to assess and model tsunami damage in Aceh province, Sumatra. Landscape Ecol 22(3):323-331

Jayasuriya S, Steele P, Weerakoon D, Knight-John M, Arunatilake N (2005) 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

Jayatissa LP, Dahdouh-Guebas F, Koedam N (2002) A review of the floral composition and distribution of mangroves in Sri Lanka. Bot J Linn Soc 138:29-43

Jäger J (2006) Sustainability science. in: Ehlers E, Krafft T (eds) Earth system science in the Anthropocene - emerging issues and problems. Springer, Berlin Heidelberg New York, pp19-26

Karunathilake KMBC (2003) Status of mangroves in Sri Lanka. Journal of Coastal Development 7(1):5-9

Kates RW, Clark WC, Corell R, Hall JM, Jaeger CC, Lowe I, McCarthy JJ, Schellnhuber HJ, Bolin B, Dickson NM, Faucheux S, Gallopin GC, Grübler A, Huntley B, Jäger J, Jodha NS, Kasperson RE, Mabogunje A, Matson P, Mooney H, Moore III B, O'Riordan T, Svedin U (2001) Environment and development: sustainability science. Science 292:641-642

Kathiresan K, Bingham BL (2001) Biology of mangroves and mangrove ecosystems. Adv Mar Biol 40:81-251

Kathiresan K, Rajendran N (2005) Coastal mangrove forests mitigated tsunami. Estuar Coast Shelf S 65(3):601-606

Kathiresan K, Rajendran N (2006) Reply to 'Comments of Kerr et al. on ''Coastal mangrove forests mitigated tsunami''' [Estuar. Coast. Shelf Sci. 65 (2005) 601-606]. Estuar Coast Shelf S 67(3):542

Kerr, AM, Baird AH, Campbell SJ (2006) Comments on "Coastal mangrove forests mitigated tsunami" by K. Kathiresan and N. Rajendran [Estuar. Coast. Shelf Sci. 65 (2005) 601-606]. Estuar Coast Shelf S 67(3):539-541

Kerr AM, Baird AH (2007) Natural barriers to natural disasters. BioScience 57(2):102-103

Klepeis P, Turner II BL (2001) Integrated land history and global change science: the example of the southern Yucatán peninsular region project. Land Use Policy 18:27-39

Kumar CS, Murugan PA, Krishnamurthy RR, Batvari BPD, Ramanamurthy MV, Usha T, Pari Y (2008) Inundation mapping - a study based on December 2004 tsunami hazard along Chennai coast, southeast India. Nat Hazard Earth Sys 8(4):617-626

Lacambra C, Spencer T, Moeller I (2008) Tropical coastal ecosystems as coastal defences. In: ProAct Network: The role of environmental management in disaster risk reduction and climate change adaptation – annex I, case studies, pp1-22

Lambin EF, Turner II BL, Geist HJ, Agbola SB, Angelsen A, Bruce JW, Coomes OT, Dirzo R, Fischer G, Folke C, Homewood PSGK, Imbernon J, Leemans R, Li X, Moran EF, Mortimore M, Ramakrishnan PS, Richards JF, Skanes H, Steffen W, Stone GD, Svedin U, Veldkamp TA, Vogel C, Xu J (2001) The causes of land-use and land-cover change: moving beyond the myths. Global Environ Chang 11:261-269

Lambin EF, Geist HJ, Lepers E (2003) Dynamics of land-use and land-cover change in tropical regions. Annu Rev Environ Resour 28:205-241

Lambin EF, Geist H, Rindfuss RR (2006) Introduction: local processes with global impacts. In: Lambin EF, Geist HJ (eds) Land-use and land-cover Change – local processes and global impacts. Springer, Berlin Heidelberg, pp1-8

Laney RM (2004) A process-led approach to modeling land change in agricultural landscapes: a case study from Madagascar. Agr Ecosyst Environ 101:135-153

Latief H, Hadi S (2006) Thematic Paper: The role of forests and trees in protecting coastal areas against tsunamis. FAO Conference Coastal protection in the aftermath of the Indian Ocean tsunami: what role for forests and trees? 28-31 August, 2006, Khao Lak, Thailand

Le QB (2005) Multi-agent system for simulation of land-use and land cover change: a theoretical framework and its first implementation for an upland watershed in the central coast of Vietnam. Ecology and Development Series No. 29, Cuvillier Verlag, Göttingen

Le QB, Park SJ, Vlek PLG, Cremers AB (2008) Land-use dynamic simulator (LUDAS): a multi-agent system model for simulating spatio-temporal dynamics of coupled human-landscape system. I. Structure and theoretical application. Ecol Inform 3(2):135-153

Le QB, Park SJ, Vlek PLG (2010) Land use dynamic simulator (LUDAS): a multi-agent system model for simulating spatio-temporal dynamics of coupled human-landscape system. 2. Scenario-based application for impact assessment of land-use policies. Ecol Inform 5(3):203-221

Lenton TM, van Oijen M (2002) Gaia as a complex adaptive system. Philos T Roy Soc B 357:683-695

Lesschen JP, Verburg PH, Staal SJ (2005) Statistical methods for analysing the spatial dimension of changes in land use and farming systems. LUCC Report Series 7, Land-Use and Land-Cover Change (LUCC) Project, International Human Dimensions Programme on Global Environmental Change (IHDP), International Geosphere-Biosphere Programme (IGBP)

Ligtenberg A, Wachowicz M, Bregt AK, Beulens A, Kettenis DL (2004) A design and application of a multi-agent system for simulation of multi-actor spatial planning. J Environ Manage 72:43-55

Limburg KE, O'Neill RV, Costanza R, Farber S (2002) Complex systems and valuation. Ecol Econ 41:409-420

Liu PLF, Lynett P, Fernando H, Jaffe BE, Fritz H, Higman B, Morton R, Goff J, Synolakis C (2005) Observations by the international tsunami survey team in Sri Lanka. Science 308:1595

Liu J, Dietz T, Carpenter SR, Alberti, M, Folke C, Moran E, Pell AN, Deadman P, Kratz T, Lubchenco J, Ostrom E, Ouyang Z, Provencher W, Redman CL, Schneider SH, Taylor WW (2007) Complexity of coupled human and natural systems. Science 317:1513-1516

Lowry K, Pallewatte N, Dainis AP (1999) Policy-relevant assessment of community-level coastal management projects in Sri Lanka. Ocean Coast Manage 42:717-745

Luers AL, Lobell DB, Sklar LS, Addams CL, Matson PA (2003) A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. Global Environ Chang 13:255-267

MA (2005) Ecosystems and human well-being: current state and trends: findings of the condition and trends working group. Millennium Ecosystem Assessment, Island Press, Washington, DC

Macal CM, North MJ (2006) Tutorial on agent-based modeling and simulation Part 2: how to model with agents. in: Proceedings of the 2006 Winter Simulation Conference, Monterey, 3-6 December 2006, pp73-83

Makoka D, Kaplan M (2005) Poverty and vulnerability – An interdisciplinary approach. MPRA Paper No. 6964, Munich Personal RePEc Archive

Malanson GP (1999) Considering complexity. Ann Assoc Am Geogr 89(4):746-753

Malthus T (1798) An essay on the principle of population. London

Mamiit RJ, Wijayaweera K (2006) The economic value of coastal ecosystems in reducing tsunami impacts: the case of mangroves in Kapuhenwala and Wanduruppa, Sri Lanka. Paper presented at the 3rd World Congress of Environmental and Resource Economists, Kyoto, Japan

Manassrisuksi K, Weir M, Hussin YA (2001) Assessment of a mangrove rehabilitation programme using remote sensing and GIS: a case study of Amphur Khlung, Chantaburi province, Eastern Thailand. Paper presented at the 22nd Asian Conference on Remote Sensing, 5-9 November 2001, Singapore

Manson SM (2001) Simplifying complexity: a review of complexity theory. Geoforum 32(3):405-414

Manson SM (2004) Boundedly rational land-use strategies and the local dimensions of human vulnerability and resilience in the Yucatán Peninsula. In: Proceedings of the 2004 Meeting of the Latin American Studies Association, Pittsburgh

Manson SM (2005) Agent-based modeling and genetic programming for modeling land change in the southern Yucatan peninsular region of Mexico. Agr Ecosyst Environ 111:47-62

Manson SM (2006) Bounded rationality in agent-based models: experiments with evolutionary programs. Int J Geogr Inf Sci 29(9):991-1012

Manson S, O'Sullivan D (2006) Complexity theory in the study of space and place. Environ Plann A 38:677-692

Manson SM, Evans T (2007) Agent-based modeling of deforestation in southern Yucatán, Mexico, and reforestation in the Midwest United States. P Natl Acad Sci USA 104(52):20678-20683

Marre K, Renaud F (2010) Differentials in impacts and recovery in the aftermath of the 2004 Indian Ocean tsunami: local examples at different scales in Sri Lanka. In: Brauch H-G, Oswald Spring Ú, Mesjasz C, Grin J, Kameri-Mbote P, Chourou B, Dunay P, Birkmann J (eds) Coping with global environmental change, disasters and security—threats, challenges, vulnerabilities and risks. Hexagon series on human and environmental security and peace, vol. 5, Springer, Berlin Heidelberg New York

Mascarenhhas A, Jayakumar S (2008) An environmental perspective of the post-tsunami scenario along the voast of Tamil Nadu, India: role of sand dunes and forests. J Environ Manage 89:24-34

Massel SR, Furukawa K, Brinkman RM (1999) Surface wave propagation in mangrove forests. Fluid Dyn Res 24:219-249

Mather AS (2006) Driving forces. In: Geist HJ (ed) Our earth's changing land: an encyclopedia of land-use and land-cover change, vol. 1 (A.K). Greenwood Press, Westport, London, pp179-185

Matthews RB, Polhill JG, Gilbert N, Roach A (2005) Integrating agent-based social models and biophysical models. In: Zerger A, Argent RM (eds) MODSIM 2005 International congress on modelling and simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, pp1617-1623

Mazda Y, Magi M, Kogo M, Hong PN (1997) Mangroves as a coastal protection from waves in the Tong King delta, Vietnam. Mangroves and Salt Marshes 1:127-135

McConnell WJ, Sweeney SP, Mulley B (2004) Physical and social access to land: spatio-temporal patterns of agricultural expansion in Madagascar. Agr Ecosyst Environ 101:171-184

McFadden L, Green C (2007) Defining 'vulnerability': conflicts, complexities and implications for coastal zone management. J Coastal Res, SI 50 (Proceedings of the 9th International Coastal Symposium):120–124

McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ Urban 19(1):17-37

Menard S (2001) Applied logistic regression analysis, 2nd edn. Sage University Papers Series on Quantitative Applications in the Social Sciences, 07-106, Sage Publications, Thousand Oaks

Metzger MJ, Rounsevell MDA, Acosta-Michlik L, Leemans R, Schröter D (2006) The vulnerability of ecosystem services to land use change. Agr Ecosyst Environ 114:69-85

Ministry of Disaster Management (2005) Towards a safer Sri Lanka – A road map for disaster risk management. Colombo

Moore DS, McCabe GP (2005) Introduction to the practice of statistics. Palgrave Macmillan, Hampshire

Munich Re (2007) TopicsGeo – natural catastrophes 2006 – analyses, assessments, positions. Munich

Mustard JF, De Fries RS, Fisher T, Moran E (2004) land use and land cover change pathways and impacts. In: Gutman G, Janetos AC, Justice CO, Moran EF, Mustard JF, Rindfuss RR, Skole D, Turner II BL, Cochrane MA (eds) Land change science: observing, monitoring and understanding trajectories of change on the earth's surface. Kluiwer Netherlands, Dordrecht Boston London, pp411-429

Nagayets O (2005) Small farms: current status and key trends. Information Brief prepared for the Future of Small Farms Research Workshop, Wye College, 26-29 June 2005

Nassauer JI, Corry RC (2004) Using normative scenarios in landscape ecology. Landscape Ecol 19:343-356

Nelson A (2000) Analysis of accessibility, transport networks, and travel time information. International Center for Tropical Agriculture, Cali

Nguyen TG, de Kok JL (2007) Systematic testing of an integrated systems model for coastal zone management using sensitivity and uncertainty analysis. Environ Modell Softw 22:1572-1587

O'Brien K, Leichenko R, Kelkar U, Venema H, Aandahl G, Tompkins H, Javed A, Bhadwal S, Barg S, Nygaard L, West J (2004) Mapping vulnerability to multiple stressors: climate change and globalization in India. Global Environ Chang 14:303-313

Olsen S, Sadacharan D, Samarakoon JI, White AT, Wickremeratne HJM, Wijeratne MS (1992) Coastal 2000 – recommendations for a resource management strategy for Sri Lanka's coastal region. Coast Conservation Department, Coastal Resources Management Project, Coastal Resources Centre (University of Rhode Island)

O'Neill RV, Johnson AR, King AW (1989) A hierarchical framework for the analysis of scale. Landscape Ecol 3(3-4):193-205

Orland B, Budthimedhee K, Uusitalo J (2001) Considering virtual worlds as representations of landscape realities and as tools for landscape planning. Landscape Urban Plan 54(1-4):139-148

Panabokke CR (1996) Soils and agro-ecological environments of Sri Lanka. Natural Resources Energy & Science Authority, Colombo

Park SJ, van de Giesen N, Vlek PLG (2003) Optimum spatial scale for modelling land-use change processes in a savanna landscape in northern Ghana. J Korean Geogr Soc 40:221.241

Parker DC, Manson SM, Janssen MA, Hoffmann MJ, Deadman P (2003) Multi-agent systems for the simulation of land-use and land-cover Change: a review. Ann Assoc Am Geogr 93(2):314-337

Parker DC, Hessl A, Davis SC (2008) Complexity, land-use modelling, and the human dimension: fundamental challenges for mapping unknown outcome spaces. Geoforum 39:789-804

Parkinson S, Ramírez R (2006) Using a sustainable livelihoods approach to assessing the impact of ICTs in development. Journal of Community Informatics 2(3). [online]

Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability - contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Patt A, Siebenhüner B (2005) Agent-based modeling and adaptation to climate change. Vierteljahreshefte zur Wirtschaftsforschung 74(2):310-320

Peterson GD, Cumming GS, Carpenter SR (2003) Scenario planning: a tool for conservation in an uncertain world. Conserv Biol 17(2):358-366

Pickett STA, Parker VT, Fielder P (1992) The new paradigm in ecology: implications for conservation biology above the species level. In: Fielder P, Jain S (eds) Conservation biology: the theory and practice of nature conservation. Chapman and Hall, New York, pp65-88

Polsky C, Schröter D, Patt A, Gaffin S, Martello ML, Neff R, Pulsipher A, Selin H (2003) 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

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

Ramankutty N, Achard F, Alves D, Turner II BL, DeFries R, Goldewijk KK, Graumlich L, Reid SR (2005) Global changes in land cover. In: Update - Newsletter of the International Human Dimensions Programme on Global Environmental Change, 03/2005, pp4-5

Ramankutty N, Graumlich L, Achcard F, Alves D, Chhabra A, DeFries RS, Foley JA, Geist H, Houghton RA, Goldewjik KK, Lambin EF, Millington A, Rasmussen K, Reid RS, Turner II BL (2006) Global land-cover Change: recent progress, remaining challenges. In: Lambin EF, Geist HJ (eds) Land-use and land-cover change – local processes and global impacts. Springer, Berlin Heidelberg, pp9-39

Ramsar (2003) Information sheet on Ramsar wetlands – Maduganga. Ramsar Convention on Wetlands. http://www.wetlands.org/reports/ris/2LK003en.pdf. Cited 12 Nov 2010

Raven PH (2002) Science, sustainability, and the human prospect. Science 297:954-958

Reardon T (1997) Using evidence of household income diversification to inform study of the rural nonfarm labor market in Africa. World Dev 25(5):735-747

Renaud FG (2006) Environmental components of vulnerability. In: Birkmann J (ed) Measuring vulnerability to natural hazards. United Nations University Press, Tokyo, pp117-127

Richards JF (1990) Land transformation. In: Turner BL II, Clark WC, Kates RW, Richards JF, Mathews JT, Meyer WB (eds) The earth as transformed by human action: global and regional changes in the biosphere over the past 300 years. Cambridge University Press, Cambridge, pp163-178

Rindfuss RR, Turner II BL, Entwisle B, Walsh SJ (2004a) Land cover / use and population. In: Gutman G, Janetos AC, Justice CO, Moran EF, Mustard JF, Rindfuss RR, Skole D, Turner II BL, Cochrane MA (eds): Land change science – observing, monitoring and understanding trajectories of change on the earth's surface. Kluwer Academic Publishers, Dordrecht, pp351-366

Rindfuss RR, Walsh SJ, Turner II BL, Fox J, Mishra V (2004b) Developing a science of land change: challenges and methodological issues. P Natl Acad Sci USA 101(39):13976-13981

Rindfuss RR, Entwisle B, Walsh SJ, Mena CE, Erlien CM, Gray CL (2007) Frontier land use change: synthesis, challenges, and next steps. Ann Assoc Am Geogr 97(4):739-754

Rotmans J (2002) Scaling in integrated assessment: problem or challenge? Integrated Assessment 3(2-3):266-279

Rothman KJ, Greenland S, Lash TL (2008) Modern epidemiology. Lippincott Williams & Wilkins, Philadelphia

Samaranayake RADB (2000) Sri Lanka's agenda for coastal zone management. EEZ Technology, pp15-17

Samaranayake RADB (2006) Pre-and post-tsunami coastal planning and land-use policies and issues in Sri Lanka. In: Proceedings of the Workshop on Coastal Area Planning and Management in Asian Tsunami-affected Countries. Bangkok, Thailand, 27-29 September 2006. RAP Publication (FAO), no. 2007/06, Food and Agriculture Organization of the United Nations, pp167-198

Samaratunga PA, Marawila D (2006) Rural land sector in Sri Lanka: major characteristics, determinants and implications for land policy. Research Studies: Agriculture Economic Policy Series, No. 7, Institute of Policy Studies, Colombo

Schneiderbauer S, Ehrlich D (2004) Risk, hazard and people's vulnerability to natural hazards – a review of definitions, concepts and data. Joint Research Centre, European Commission, Luxembourg

Schwamborn R, Saint-Paul U (1996) Mangroves – forgotten forests? Natural Resources and Development 43/44:13-36

Schwarze S (2004) Determinants of income generating activities of rural households – a quantitative study in the vicinity of the Lore-Lindu national park in central Sulawesi/Indonesia. Dissertation, University of Göttingen

Scoones I (1998) Sustainable rural livelihoods – a framework for analysis. IDS Working Paper 72, Institute of Development Studies

Scoones I (1999) New ecology and the social sciences: what prospects for a fruitful engagement? Annu Rev Anthropol 28:479-507

Seneviratne AK, Abayawickrama MRR, Perera CS, Madampe MKDN (2009) Impact channels in Sri Lanka. 3rd China-ASEAN Forum on Social Development and Poverty Reduction, 4th ASEAN+3 High-Level Seminar on Poverty Reduction, and Asia-wide Regional High-level Meeting on The Impact of the Global Economic Slowdown on Poverty and Sustainable Development in Asia and the Pacific, 28-30 September 2009, Hanoi

Serneels S, Lambin EF (2001) Proximate causes of land-use change in Narok district, Kenya: a spatial statistical model. Agr Ecosyst Environ 85:65-81

Siegel PB (2005) Using an asset-based approach to identify drivers of sustainable rural growth and poverty reduction in Central America: a conceptual framework. World Bank Policy Research Working Paper 3475

Smit B, Wandel J (2006) Adaptation, adaptive capacity and vulnerability. Global Environ Chang 16:282-292

Smith DR, Gordon A, Meadows K, Zwick K (2001) Livelihood diversification in Uganda: patterns and determinants of change across two rural districts. Food Policy 26:421-435

Sonvisen SA, Pajot G, Anmarkrud T (2006) Survey of fisheries rehabilitation in Sri Lanka. Norwegian College of Fishery Science, Food and Agriculture Organization of the United Nations

Staal SJ, Baltenweck I, Waithaka MM, deWolff T, Njoroge L (2002) Location and uptake: integrated household and GIS analysis of technology adoption and land use, with application to smallholder dairy farms in Kenya. Agr Econ 27:295-315

Steffen W, Sanderson A, Tyson PD, Jäger J, Matson PA, Moore III B, Oldfield F, Richardson K, Schellnhuber HJ, Turner II BL, Wasson RJ (2005) Global change and the earth system – a planet under pressure, 2nd Printing. Springer, Berlin Heidelberg

Sudmeier-Rieux K, Ash N (2009) Environmental guidance note for disaster risk reduction - healthy ecosystems for human security. The World Conservation Union, Gland

Swart RJ, Raskin P, Robinson J (2004) The problem of the future: sustanability science and scenario analysis. Global Environ Chang 14:137-146

The Colombo Times (2009) How the global economic crisis affects Sri Lanka. 26 February, 2009. http://www.thecolombotimes.com/business-news/2753-how-the-global-economic-crisis-affects-sri-lanka.html. Cited 4 Mar 2010

Thywissen K (2006) Components of risk – a comparative glossary. Source 02/2006, United Nations University, Institute for Environment and Human Security, Bonn

Tilakaratna G, Wickramasinghe U, Kumara T (2005) Microfinance in Sri Lanka: a household level analysis of outreach and impact on poverty. Research Studies: Poverty and Social Welfare Series No.7, Institute of Policy Studies. Colombo

Townsley P (1996) Rapid rural appraisal, participatory rural appraisal and aquaculture. FAO Fisheries Technical Paper 358. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/DOCREP/006/W2352E/W2352E00.HTM. Cited 6 Feb 2008

Turner II BL, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley L, Kasperson JX, Luerse A, Martello ML, Polsky C, Pulsipher A, Schiller A (2003a) A framework for vulnerability analysis in sustainability science. P Natl Acad Sci USA 100(14):8074-8079

Turner II BL, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley N, Hovelsrud-Broda GK, Kasperson JX, Kasperson RE, Luers A, Martello ML, Mathiesen S, Naylor R, Polsky C, Pulsipher A, Schiller A, Selin H, Tyler N (2003b) Illustrating the coupled human-environment system for vulnerability analysis: three case studies. P Natl Acad Sci USA 100(14):8080-8085

Turner II BL, Lambin EF, Reenberg A (2007) The emergence of land change science for global environmental change and sustainability. P Natl Acad Sci USA 104(52):20666-20671

Twigg J (2001) Sustainable livelihoods and vulnerability to disasters. Disaster Management Working Paper 2/2001, Benfield Greig Hazard Research Centre, London

UDA (2006) A basic guide to design and planting of coastal green belts in Sri Lanka. Urban Development Authority, Colombo

UNDP (2004) Reducing disaster risk – a challenge for development. United Nations Development Programme, Bureau for Crisis Prevention and Recovery, New York. http://www.undp.org/cpr/disred/rdr.htm. Cited 26 Sep 2008

UNDP (2007a) Human development report 2007/08. United Nations Development Programme, New York

UNDP (2007b) Measuring human development – a primer. United Nations Development Programme, New York

UNEP (2001) Sri Lanka: state of the environment 2001. United Nations Environment Programme, Pathumthani

UNEP (2003) Sri Lanka environmental profile. United Nations Environment Programme. http://www.unep.net/profile/index.cfm. Cited 22 May 2007

UNEP (2005) After the tunami – rapid environmental assessment. United Nations Environment Programme. http://www.unep.org/tsunami/tsunami_rpt.asp. Cited 23 Sep 2008

UNEP, MENR (2005) Sri Lanka – post-tsunami environmental assessment. United Nations Environment Programme, Ministry of Environment & Natural Resources of Sri Lanka

UNEP (2007) Global environment outlook GEO 4 – environment for development. United Nations Environment Programme

UNEP-WCMC (2006) In the front line: shoreline protection and other ecosystem services from mangroves and coral reefs. United Nations Environment Programme, World Conservation Monitoring Centre, Cambridge

UN/ISDR (2004) Living with risk. A global review of disaster reduction initiatives. United Nations/International Strategy for Disaster Reduction, Geneva

UN/ISDR (2005) Hyogo framework for action 2005-2015: building the resilience of nations and communities to disasters. World Conference on Disaster Reduction, 18-22 January 2005, Kobe, Hyogo

UNHCHR (2006) The human right to adequate housing. Fact Sheet No.21, Office of the High Commissioner for Human Rights. http://www.unhchr.ch/html/menu6/2/fs21.htm. Cited 3 Oct 2008

Valiela I (2006) Global coastal change. Blackwell Publishing, Malden Oxford Carlton

Valiela I, Bowen JL, York JK (2001) Mangrove forests: one of the world's threatened major tropical environments. BioScience 51(10):807-815

Veldkamp A, Lambin EF (2001) Editorial – predicting land-use change. Agr Ecosyst Environ 85:1-6

Veldkamp A, Verburg PH, Kok K, De Koning GHJ, Priess J, Bergsma AR (2001) The need for scale sensitive approaches in spatially explicit land use change modeling. Environmental Modeling and Assessment 6:111-121

Verburg PH, Soepboer W, Veldkamp A, Limpiada R, Espaldon V, Mastura SSA (2002) Modeling the spatial dynamics of regional land use: the CLUE-S model. Environ Manage 30(3):391-405

Verburg PH, de Groot WT, Veldkamp A (2003) Methodology for multi-scale land-use change modelling: concepts and challenges. In: Dolman AJ, Verhagen A, Rovers CA (eds) Global environmental Change and land use. Kluwer Academic Publishers, Dordrecht, pp17-51

Verburg PH, Schot P, Dijst M, Veldkamp A (2004) Land use change modelling: current practice and research priorities. GeoJournal 61(4):309-324

Verburg P, Kok K, Veldkamp T (2005) Pixels or agents? – modelling land-use and land-cover change. In: Update - Newsletter of the International Human Dimensions Programme on Global Environmental Change, 03/2005, pp8-9

Verburg PH, Kok K Pontius Jr.RG, Veldkamp A (2006) Modeling land-use and land-cover change. In: Lambin EF, Geist HJ (eds) Land-use and land-cover change – local processes and global impacts. Springer, Berlin Heidelberg, pp117-135

Vermaat JE, Thampanya U (2006) Mangroves mitigate tsunami damage: a further response. Estuar Coast Shelf S 69(1-2):1-3

Vermaat JE, Thampanya U (2007) Erratum to "Mangroves mitigate tsunami damage: a further response" [Estuar. Coast. Shel Sci. 69 (1-2) (2006) 1-3]. Estuar Coast Shelf S 75(4):564

Villagrán De León JC (2006) Vulnerability – a conceptual and methodological review. Source 04/2006, United Nations University, Institute for Environment and Human Security, Bonn

Villagrán De León JC (2008) Rapid assessment of potential impacts of a tsunami - lessons from the port of Galle in Sri Lanka. Source 09/2008, United Nations University, Institute for Environment and Human Security, Bonn

Vitousek PM (1994) Beyond global warming: ecology and global change. Ecology 75(7):1861-1876

Vitousek PM, Mooney HA, Lubchenko J, Melillo JM (1997) Human domination of earth's ecosystems. Science 277:494-499

Vlek PLG (2005) Nothing begets nothing – The creeping disaster of land degradation. InterSecTions 01/2005, United Nations University, Institute for Environment and Human Security, Bonn

Vogel C, O'Brien K (2004) Vulnerability and global environmental change: rhetoric and reality. In: Aviso – An Information Bulletin on Global Environmental Change and Human Security, No. 13, Global Environmental Change and Human Security (GECHS)

Walker B, Carpenter S, Anderies J, Abel N, Cumming G, Janssen M, Lebel L, Norberg J, Peterson GD, Pritchard R (2002) Resilience management in social-ecological systems: a working hypothesis for a participatory approach. Conserv Ecol 6(1):14. [online]. http://www.consecol.org/vol6/iss1/art14/

Walker B, Holling CS, Carpenter SR, Kinzig A (2004) Resilience, adaptability and transformability in social-ecological systems. Ecol Soc 9(2):5. [online]. http://www.ecologyandsociety.org/vol9/iss2/art5/

Wallington TJ, Hobbs RJ, Moore SA (2005) Implications of current ecological thinking for biodiversity conservation: a review of the salient issues. Ecol Soc 10(1):15. [online]. http://www.ecologyandsociety.org/vol10/iss1/art15/

Walsh SJ, Crews-Meyer KA (2002) Linking people, place, and policy – a GIScience approach. Springer, Berlin Heidelberg

Walsh SJ, Bilsborrow RE, McGregor SJ, Frizzelle BG, Messina JP, Pan WKT, Crews-Meyer KA, Taff GN, Baquero F (2003) Integration of longitudinal surveys, remote sensing time series, and spatial analyses – approaches for linking people and place. In: Fox J, Rindfuss RR, Walsh SJ, Mishra V (eds) People and the environment – approaches for linking household and community surveys to remote sensing and GIS. Kluwer Academic Publishers, Norwell Dordrecht, pp91-130

Walsh SJ, Messina JP, Mena CF, Malanson GP, Page PH (2008) Complexity theory, spatial simulation models, and land use dynamics in the northern Ecuadorian Amazon. Geoforum 39:867-878

Wang L, Sousa WP, Gong P (2004) Integration of object-based and pixel-based classification for mapping mangroves with IKONOS imagery. Int J Remote Sens 25:5655-5668

Weng Q (2002) Land use change analysis in the Zhujiang delta of China using satellite remote sensing, GIS and stochastic modelling. J Environ Manage 63:273-284

Wetland Conservation Project (1997) Wetland site report & conservation management plan Maduganga estuary. Central Environmental Authority, Euroconsult. Colombo

Wijetunge JJ (2006) 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

Wilson MA, Costanza R, Boumans R, Liu S (2005) Integrated assessment and valuation of ecosystem goods and services provided by coastal systems. In: Wilson JG (ed) The intertidal ecosystem: the value of Ireland's shores. Royal Irish Academy, Dublin, pp1-24

WRI (2003) Earth trends country profiles – coastal and marine ecosystems Sri Lanka. World Resources Institute. http://earthtrends.wri.org/country_profiles/index.php?theme=1. Cited 6 Feb 2009

Wu J, David JL (2002) A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. Ecol Model 153:7-26

Wu J, Marceau D (2002) Modeling complex ecological systems: an introduction. Ecol Model 153:1-6

Wu J (2006) Landscape ecology, cross-disciplinarity, and sustainability science. Landscape Ecol 21:1-4

Yanagisawa H, Koshimura S, Goto K, Miyagi T, Imamura F, Ruangrassamee A, Tanavud C (2009) The reduction effects of mangrove forest on a tsunami based on field surveys at Pakarang Cape, Thailand and numerical analysis. Coastal and Shelf Science 81:27-37

Young OR, Berkhout, F, Gallopin GC, Janssen MA, Ostrom E, van der Leeuw S (2006) The globalization of socio-ecological systems: an agenda for scientific research. Global Environ Chang 16:304-316

ACKNOWLEDGMENTS

The writing of this thesis was a lengthy and sometimes difficult process, which taxed the patience of my personal environment (colleagues, friends, and family). This process probably would have taken even longer without the great help and support of many people, and I want to take this opportunity to express my gratefulness to them. First, I would like to thank Dr. Günther Manske, who established my contact to UNU-EHS and who gave me the chance of joining the Doctoral Program at ZEF. In this regard, I also highly appreciate the support of Prof. Janos Bogardi, who offered me the opportunity to conduct my research at UNU-EHS. I benefited immensely from fruitful scientific discussions, logistic support, and the splendid view of my office window to the Rheinaue and the Siebengebirge.

My gratitude goes to ZEF and UNU-EHS for the financial and logistic support and to Prof. Paul Vlek and Prof. Eckart Ehlers for supervision of my thesis and for their scientific advice. I am deeply grateful to Dr. Fabrice Renaud and Dr. Quang Bao Le for their dedicated academic support. Their advice was of immense importance for my scientific development and for the quality of my work. They always believed in me (at least, they promised to do so…), although there were periods when this trust must have been a difficult challenge for them. Both spent a lot of time discussing my questions with me, although they were busy with thousands of other things at the same time. I am also very grateful to Guido Lüchters for his very helpful statistical advice. I would like to thank Rosemarie Zabel, Doris Fuß and Karin Hagedorn-Mensah at ZEF and the whole team at UNU-EHS for their great administrative support.

My field work in Sri Lanka was facilitated through the logistic support of the International Water Management Institute (IWMI) and their willingness to host me while I was in Colombo. I am deeply grateful to IWMI for giving me this opportunity and to the staff at IWMI (and Prasad in particular) for their support and for the helpful and interesting scientific and private discussions. I also thank the Small Fishers Federation for their support during my scoping mission and the Joint Research Centre of the European Commission for providing me with the Ikonos satellite images. My sincere thanks also go to my colleagues Adelina, Alexander, Marion, and Xiaomeng in our office 2722 for their great companionship and for interesting and valuable scientific discussions.

I benefited greatly from the local support during my field research in Ambalangoda. My special thanks go to my assistants Danushka, Dimuthu, Lucky, Nilu, Nuwan, and Samudra, who did a great job collecting all the necessary information together with me, although life with me surely was not always easy. I also thank Ranjith and Nalini at the Sumudu Guesthouse for making my stay there so enjoyable.

This long process was particularly difficult for my family, who had to bear my moods and had to listen to all my complaints. I highly appreciate the patience, trust, and love of my parents and wish to thank them for their support. Finally, my deepest gratefulness goes to my wife Sylvia, who suffered most during this time, and who always believed in me and strengthened my power with her love, encouragement, patience, and care. Furthermore, I also thank her for reading all my work and providing me with very helpful comments and ideas.