THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

FOREST AND LAND USE MITIGATION AND ADAPTATION IN SRI LANKA

ASPECTS IN THE LIGHT OF INTERNATIONAL CLIMATE CHANGE POLICIES

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ABSTRACT

As a developing island nation, Sri Lanka is vulnerable to the possible impacts of climate change. The land use and forestry sector accounts for a large part of Sri Lanka's greenhouse gas emissions and can play a major part of Sri Lanka's strategy to mitigate and adapt to climate change. Data and information on land use and forests in terms of area extent and carbon stock variability between different ecosystems is limited in Sri Lanka. The research conducted and presented in this thesis was motivated by a shortage of data on these aspects.

The overall objective of this thesis is to primarily analyze environmental parameters and secondly to investigate livelihood aspects of forest and land use to evaluate the climate mitigation and adaptation potential in the land use and forestry sector in Sri Lanka. Specific objectives were to; investigate the environmental status and participatory views and aspirations on land use and forest cover change; estimate structural characteristics and above ground biomass carbon stocks for various forest ecosystems and land uses and to estimate a historical reference level to estimate the costs and earnings for implementation of reducing emissions from deforestation and forest degradation in Sri Lanka. An additional objective were to explore the potential of and barriers to including forests and land uses in climate mitigation schemes while securing multiple environmental and economical benefits for local land users. Data were collected during three periods of field work between 2006 and 2011 in different parts of Sri Lanka and consists of an assessment of soil and well water salinity, biomass carbon estimations as well as participatory assessments and spatial analysis of land use changes.

Results show that vulnerable coastal areas could be rehabilitated through Afforestation and Reforestation Clean Development Mechanism using coconut trees or homegardens. This is due to their multi-purposes and carbon sequestration potential as well as the role they play in environmental protection. Also, there is a large range in above ground biomass carbon stock between forest types and homegardens with a high variation of carbon stocks within forest types. This variation is due to the heterogeneity of forest ecosystems as well as different forest usage in the recent past causing variations in successions. Calculating carbon stock depends on the allometric equation used, included variables and adaptation to the specific life zone. Forest conservation policies have had a positive effect on forest cover through reduced encroachment and reduced illegal felling of timber in forests around two protected forest areas. Simultaneously the process has threatened the livelihoods of many local people around the forests. The forestry sector in Sri Lanka has a large mitigation potential, but reference level setting for reducing emissions from deforestation and forest degradation is hampered by erratic, few, and often incompatible forest inventories that lower the potential to describe past forest carbon content in a credible way. Accordingly, Sri Lanka needs further work and assistance in the form of technical advice and capacity-building for monitoring the nation's forest resource and the drivers of deforestation.

The findings presented in this thesis can contribute to a better understanding of potential options and approaches that Sri Lanka can use to realize its climate change mitigation and adaptation potential in the land use and forestry sector.

Keywords: Carbon stock, biomass, forest, land use, deforestation, Sri Lanka, REDD+, CDM

PREFACE

This thesis consists of a summary (Part I) and the following five appended papers (Part II), referred to by roman numerals in the text:

I. Mattsson, E., Ostwald, M., Nissanka, S.P., Holmer, B., Palm, M. 2009. Recovery of coastal ecosystems after tsunami event and potential for participatory forestry CDM – examples from Sri Lanka. Ocean and Coastal Management 52:1-9.
II. Mattsson, E., Persson, U.M., Ostwald, M., Nissanka, S.P. 2012. REDD+ readiness implications for Sri Lanka in terms of reducing deforestation. Journal of Environmental Management 100:29-40.
III. Mattsson, E., Ostwald, M., Wallin, G., Nissanka S.P. 2011. Estimating forest characteristics and biomass carbon stocks in Sri Lanka: uncertainties and research needs. Submitted to Journal of Sustainable Forestry.
IV. Lindström, S., Mattsson, E., Nissanka, S.P. 2011. Forest cover change in Sri Lanka: the role of small-scale farmers. Submitted to Applied Geography.
V. Mattsson, E., Ostwald, M, Nissanka, S.P. 2012. Exploring the future potential of homegardens as a multifunctional land use strategy in Sri Lanka with focus on carbon sequestration. Working paper.

All papers have been produced in collaboration with Department of Crop Science at the University of Peradeniya, Sri Lanka. Paper II and III were conducted in collaboration with the Department of Economics, the Department of Biological and Environmental Sciences at the University of Gothenburg, the Centre for Climate Science and Policy Research at Linköping University, and the Division of Resource Theory at Chalmers Technical University, Gothenburg. In paper II, Persson carried out the economical analysis. In paper IV, Lindström carried out the field measurements which were analyzed and written in collaboration with Mattsson. In all papers except paper IV, Mattsson carried out, analyzed and was operationally responsible for all field work.

The papers are reprinted with permission from the respective journals.

Other relevant publications by the author:

Näsström, R., Mattsson, E. 2011. Country Report Sri Lanka – Land use change and forestry at the national and sub-national level. FOCALI report 2011:04 (www.focali.se)

Westholm, L., Ostwald, M., Henders, S., Mattsson, E. 2011. Learning from Norway – A review of lessons learned for REDD+ donors. FOCALI report 2011:03 (www.focali.se)

Westholm, L., Henders, S., Ostwald, M., Mattsson, E. 2009. Assessing baseline and sustainable development in four case countries. Published in ETFRN Newsletter Issue No. 50, Forests and climate change: adaptation and mitigation.

Westholm, L., Henders, S., Ostwald, M., Mattsson, E. 2009. Assessment of existing global monitoring and financial instruments for carbon sinks in forest ecosystems – the issue of REDD. FOCALI Report 2009:01 (www.focali.se).

Biddulph, R., Westholm, L., Mattsson, E., Pettersson, J., Strömberg, J. 2009. Inception report: Making REDD work for the poor. FOCALI Report 2009:02 (www.focali.se).

Mattsson, E. 2008. Policy and monitoring aspects on avoided deforestation – towards a post 2012 climate regime. CSPR Report 2008:01, Centre for Climate Science and Policy Research, Norrköping, Sweden.

Submissions to the UNFCCC

Ostwald, M., Palm, M., Mattsson, E., Ravindranath, N.H. 2008. Land use and forest issues at COP13 in Bali, Dec 2007. CSPR Briefing 2008:01, Centre for Climate Science and Policy Research, Norrköping, Sweden.

Ostwald, M., Palm, M., Mattsson, E., Persson, M., Berndes. G., Amatayakul, W. 2007. Views on the implication of possibly changing the limit established for small-scale afforestation and reforestation clean development mechanism project activities. Submission to the UNFCCC Secretariat based upon call for submission.

Ostwald, M., Palm, M., Mattsson, E., Persson, M., Berndes, G., Amatayakul, W. 2007. Response to the call for public inputs on new procedures to demonstrate the eligibility of lands for afforestation and reforestation projects activities under the CDM. Submission to the UNFCCC Secretariat based upon call for submission.

TABLE OF CONTENTS

I. SUMMARY

II. PAPERS I–V

Part I

Summary

"Persons who love nature find a common basis for understanding people of other countries, since the love of nature is universal among men of all nations"

Dag Hammarskjöld

1. INTRODUCTION

Global climate change is one of the greatest scientific, environmental, economic and social challenges of our time. The average global surface temperature has risen by 0.74°C since the late 1800s and the best estimates from model projections show that the surface air temperature could rise another 1.8–4.0°C in the 21st century (Solomon et al., 2007). The current warming trend is expected to have severe global effects such as sea level rise, higher frequency of extreme weather events, freshwater shortages, changes in agricultural yields, and negative impacts on forest ecosystems (Schneider et al., 2007; Smith et al., 2009). Already in the late 1800s the Swedish scientist Arrhenius (1896) estimated that a doubling of carbon dioxide (CO_2) concentrations could cause an increase in temperature of 5–6°C, not far from recent estimates. In the 1970s and 1980s, it became known that land cover change alters surface albedo and that terrestrial ecosystems can act as sinks and sources of carbon and thus impact the global climate (Sagan et al., 1979; Woodwell et al., 1983). Increased human-induced pressure on Earth's biophysical systems, through, for example, land use change, biodiversity loss and ocean acidification could potentially reach critical thresholds and trigger feedback mechanisms where subsystems could shift into new states with negative consequences for humanity (Rockström et al., 2009). The escalating influence of humans on the global environment during the industrial-era with altered greenhouse gas (GHG) concentrations in the atmosphere makes it appropriate to supplement the present geological epoch Holocene with Antropocene as proposed by Crutzen and Stoermer (2000).

The role of land use and forests in climate change mitigation and adaptation is now widely recognized (Penman et al., 2003; Stern, 2007; Eliasch, 2008). Forests have an important role in the global carbon cycle. Deforestation and forest degradation accounts for about 6–18% of all GHG emissions (Van der Werf, 2009). Preventing carbon from being released from the forest carbon pools is therefore important to mitigate climate change. Over the last twenty years the political response to a changing climate has featured the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and its Kyoto Protocol in 1997. Emissions resulting from land use, land-use change and forestry (LULUCF) were included as a mitigation option in the project-based mechanisms of the Kyoto Protocol, Clean Development Mechanism (CDM) and Joint Implementation (JI). At the climate change negotiations in Cancún, 2010, reducing emissions from deforestation and forest degradation (REDD+) was established as an official element of a post-Kyoto Agreement after 2012 (UNFCCC, 2010).

As a developing island nation, Sri Lanka is vulnerable to the impacts of climate change in several ways. These ways include rising sea levels which could threaten human settlements and coastal ecosystems. More extreme weather events can increase both the frequency and intensity of floods, droughts and landslides. Declines in crop yields and changed distribution patterns of forests, could affect flora and fauna negatively (Somaratne and Dhanapala, 1996; Parry et al., 2007). The land use and forestry sector accounts for a large part of Sri Lanka's GHG emissions and can play a major part of Sri Lanka's strategy to mitigate and adapt to climate change. If planned and implemented properly, carbon mitigation activities from the land use and forestry sector can bring adaptive components such as continuity of forest ecosystems, biodiversity, watershed conservation and poverty alleviation. It is therefore important to identify strategies and approaches arising from increasing GHG emissions in this sector. Such insights are also needed to identify optimal technical and policy interventions for the future. In addition, information on forest status and trends is often restricted in many developing countries, including Sri Lanka, where the historical data and information on land use and forests in terms of area extent and carbon stock variability between different ecosystems is limited.

The research conducted and presented in this thesis was partly motivated by a shortage of data on these aspects in Sri Lanka that could inform the evolving discussions in the international climate policy arena to reduce emissions from land use and forestry activities in developing countries. This thesis fits well within the current dynamic phase in Sri Lanka where the issues relating to climate change mitigation and adaptation such as natural resources management, forest conservation and climate smart agriculture have become more prioritized within ministries, private business, organizations and academia (Chokkalingam and Vanniarachchy, 2011a). Little research has so far investigated the role of Sri Lankan forest based land use systems in relation to policies and measures to mitigate and adapt to climatic change. Accordingly, research findings and analysis relating to these issues are in demand.

1.1. Aims and objectives

The overall objective of this thesis is to primarily analyze environmental parameters and secondly, investigate livelihood aspects of forest and land use to evaluate the climate mitigation and adaptation potential in the land use and forestry sector at the local and national level in Sri Lanka.

The thesis takes as its departure point in paper I an assessment of impacts on and recovery of coastal ecosystems following the 2004 Sumatra-Andaman earthquake and the following tsunami in Hambantota district, investigating how participatory afforestation and reforestation Clean Development Mechanism can be an instrument to decrease vulnerability for local communities. Given the importance of robust land use management and polices that generate income and protection identified in paper I, this thesis proceeds in paper II to investigate the extent to which available data on forest cover and new in situ data on forest carbon stocks can be used to estimate the potential implications of REDD+ implementation in Sri Lanka. In paper III, structural characteristics of natural forests and variations in above ground biomass (AGB) carbon of various forest ecosystems are analyzed and the uncertainties of these estimates by using the most commonly used allometric equations are evaluated. In paper IV, forest cover change dynamics around two protected forest areas are analyzed to the light of small scale farmers' views and national forest policies. Paper V highlights the carbon stock potential of homegardens in relation to their multiple benefits and high acceptance among land users.

The specific research objectives of this thesis are to:

- Investigate the environmental status and participatory views and aspirations on land use and forest cover change (Papers I, IV).
- Estimate structural characteristics and above ground biomass carbon stocks for various forest ecosystems and land uses (Papers I–III, V)
- Estimate a historical reference level to estimate the costs and earnings for REDD+ implementation in Sri Lanka (Paper II)

- Explore the potential of and barriers to including forests and land uses in climate mitigation schemes while securing multiple environmental and economical benefits for local land users (Papers I–V)

This summary continues as follows: the background section offers an overview of land use and forests in the global climatic system, their role within the international climate negotiations and addresses methodological concerns in measuring forest carbon. The materials and methods section summarizes methods used in each of the appended papers followed by a summary of the results. The discussion section reviews the scope and limitations of the thesis and its implications for future research and policy agendas.

2. BACKGROUND

2.1. Land use and forests in the global climatic system

Ever since humans learned to manage and control fire and domesticated plants and animals, they have cleared forests to excerpt higher value from land. About half of the global terrestrial land surface has been converted or extensively modified by human activities over the last 10,000 years (Lambin et al., 2003). Forests play an important role in protecting watersheds, preserving biodiversity, preventing erosion and regulating the earth's climate and provide several economically and socially significant functions for sustaining life on earth. The United Nations Food and Agriculture Organization (FAO, 2005) defines forest as land with a tree canopy cover of more than 10%, trees higher than 5 meters and an area of more than 0.5 hectares (ha) unless it is predominantly under agricultural or urban land use. A reduction in forest area can happen through deforestation which is defined as "the conversion of forest to another land use or the long-term reduction of the tree canopy cover below the minimum 10% threshold". Natural disasters can also convert forests if they are unable to regenerate naturally. An increase in forest area can occur through management practices of afforestation, i.e. planting of trees on land that was not previously forested, or through natural expansion of forests. There is no change in forest area where a forest is cut down but replanted (reforestation), or where the forest grows back within a relatively short period (natural regeneration). Forest degradation is usually considered partial deforestation with tree crown cover greater than 10% remaining. These forest change dynamics are shown in Fig. 1. Proximate causes of deforestation are agricultural expansion (e.g. soybean, maize, wheat), wood extraction (e.g. logging or wood harvest for domestic fuel or charcoal), and infrastructure expansion such as road building and urbanization. Rarely is there a single direct cause for deforestation (Geist and Lambin, 2002) and the complexity between the different causes remains inadequately understood.

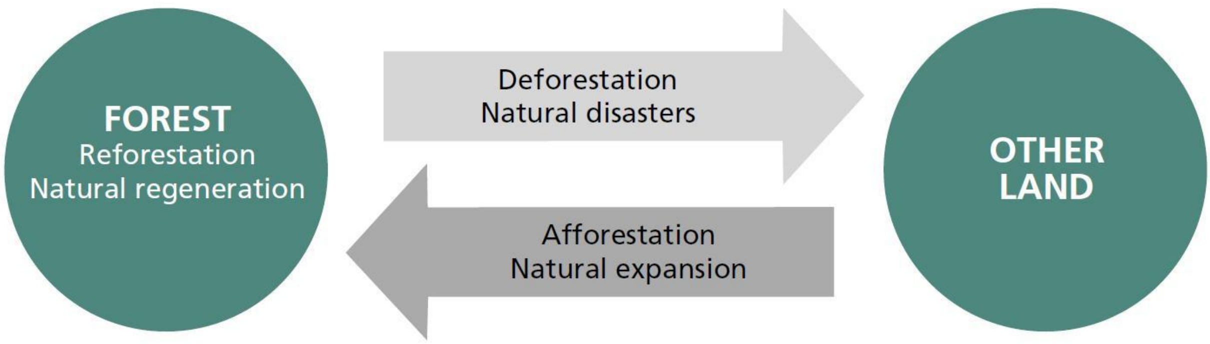


Fig. 1. Forest change dynamics (FAO, 2005).

The Earth's total forest area is 3.69 billion ha or 31% of global land area (FAO, 2011) whereas tropical forests accounts for about 44% of the global area and store 40–50% of the terrestrial carbon (Malhi and Grace, 2000; Lewis et al., 2009; FAO, 2011). During photosynthesis, trees assimilate CO_2 from the atmosphere and convert it to carbohydrates. Some of the carbohydrates are respired back to the atmosphere and the rest forms the biomass of the trees. When the plant material dies the carbohydrates are decomposed or is burnt and the carbon is released back into the atmosphere as CO_2 (Dixon et al., 1994; Malhi et al., 1999). Therefore, forests act as reservoirs and sinks or sources of GHGs, primarily CO_2 depending on factors such as forest age, biotic and abiotic disturbances and management regimes. Forests accumulate or release carbon through several reservoirs or carbon pools. The main carbon pools in tropical forest ecosystems are the living above and below ground biomass such as trunks, branches, leaves and roots and the necromass (dead wood and litter) and soil organic matter (SOM) (Penman et al., 2003). Tropical forests hold 56% of their carbon stored in their above and below ground biomass, 32% in SOM, 11% in dead wood and 1% in litter. Boreal forests on the other hand, store 20% in their above and below ground biomass, 64% in SOM, 10% in litter and 6% in dead wood (Pan et al., 2011). Apart from anthropogenic management processes, permafrost thawing and peatland fires where soil carbon is oxidized, much of the soil carbon are stored in the ground due to physical and chemical processes. As a result, soil carbon contributes less to sources and sinks of carbon from land use change than AGB carbon. AGB carbon is more easily affected by disturbance processes such as land conversion, fires, wind throw and pest outbreaks which tend to drive carbon out of the living biomass (Houghton, 2007).

The release of GHG emissions from land use activities accounted for roughly 20% of GHG emissions in the 1990s (IPCC, 2007). The majorities of these emissions came from deforestation and forest degradation in the tropics which is the main emission source in many developing countries (Stern, 2007). Since the 1960s, tropical forest loss has been high with large inter-annual and geographic variability (FAO, 2010a). A recent remote sensing based survey conducted by the United Nations Food and Agriculture Organization (FAO, 2011) estimates that global deforestation, mainly the conversion of tropical forests to agricultural land, averaged 15.2 million ha per year (Mha yr^{-1}) between 2000 and 2005. This estimate was partly offset by gains in forest area through afforestation and natural forest with 8.8 Mha yr^{-1} between 2000 and 2005. The net loss of forests (from forest land use to other land uses) accelerated, increasing from 4.1 Mha yr^{-1} per year between 1990 and 2000 to 6.4 Mha yr^{-1} between 2000 and 2005, although other estimates reported that forest loss slowed down during this period (FAO, 2010a). Emissions from deforestation averaged 1.6 gigatons of carbon per year (GtC yr^{-1}) during the 1990s (Solomon et al., 2007) although estimates during the period 2000–2010 report lower values of 1.1 GtC yr^{-1} (Friedlingstein et al., 2010) and 1.0 GtC yr^{-1} (Baccini et al., 2012), as a consequence of lower levels of forest loss and forest regrowth elsewhere. While emissions of CO_2 from fossil fuel combustion can be estimated with a relatively high degree of certainty (Rypdal and Winiwarter, 2001) emissions and removals related to tropical deforestation are highly uncertain, with estimates ranging from 0.5 to 2.7 GtC yr^{-1} (Solomon et al., 2007).

2.1.1. Uncertainties in measuring terrestrial carbon emissions

Variability in forest biomass is responsible for much of the uncertainty in current estimates of terrestrial carbon emissions (Houghton, 2007; Grassi et al., 2008). Biomass in tropical forests can be determined by various methods, for example, through field measurements, remote sensing, modeling, or by a combination of these (De Fries et al., 2006). A significant improvement in recent years has been the extension of satellite remote sensing and ancillary spatial data such that researchers can move beyond a focus on immediate forest loss (proximate causes) and attempt to understand the human and biophysical drivers of tropical deforestation (underlying drivers) (Chowdhury, 2006).

Accounting for emissions from land use and forestry related activities is complex due to several factors. These are mainly related to difficulties in deriving measurements for historical carbon content in land (setting reference levels), and the non-permanent nature of sequestration in trees and land use systems due to natural or human induced disturbances. There is also the possibility of creating displacement of emissions (leakage) if forest protection in one place pushes deforestation pressures elsewhere; which means that overall emissions would not be reduced (Wunder, 2008; Henders and Ostwald, 2012). Another uncertainty relates to the primary source for global information on forest resources; FAO Global Forest Resources Assessment (FRA). FAO FRA provides national forest carbon estimates of AGB carbon stocks for tropical forests and other wooded lands and is derived primarily from ground-based forest inventories conducted by the respective national institutions. However, the majority of existing forest inventories is inadequate, inconsistent, few in number and may not be representative of the country's forests as these inventories are designed to provide estimates of commercial timber volume (Brown, 1997; Gibbs et al., 2007; FAO, 2010b). Moreover, the definition of forest is ambiguous and may have changed over time.

2.2. Land use and forests in global climate policy

2.2.1. CDM

The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1992 with the objective of stabilizing GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (UNFCCC, 1992). All 194 parties to the UNFCCC are expected to count their emissions and removals from land use change and forestry in national inventories. In 1997 the Kyoto Protocol was adopted by the UNFCCC and it stipulates that Annex 1 countries (in essence the industrialized countries) with emission reduction commitments may count emissions and removals of GHGs deriving from certain direct human-induced land use change and forestry activities towards their overall reduction targets. In addition industrialized countries can count removals by sinks in project-based activities under two flexible mechanisms created by the Kyoto Protocol – Joint Implementation (JI) and the Clean Development Mechanism (CDM). JI refers to projects undertaken jointly by two Annex I countries whereas CDM allows industrialized countries with a GHG reduction commitment to invest in projects that reduce emissions in developing countries (non-annex 1 Parties) as an alternative to more expensive emission reductions in their own countries. At the seventh Conference of the Parties (COP 7) to the UNFCCC in Marrakesh in 2001, it was decided that only afforestation and reforestation (A/R) are eligible under the CDM in the Protocol's first commitment period (2008–2012). Forest carbon offsets from other LULUCF activities were excluded for several reasons, partly due to difficulties in measuring, reporting and verifying (MRV) the actual reductions from these activities. CDM project activities have to address a number of issues such as additionality, non-permanence, uncertainty, and the risk of creating leakage. In addition, there is a ceiling on the maximum number of credits that an Annex I party can obtain from A/R CDM projects. The forestry component of the CDM project portfolio has developed slowly and in February 2012 A/R projects comprised about 1% of the global CDM portfolio in terms of registered projects, or 36 projects (UNFCCC, 2012a). The slow start and low numbers of projects reflects the time it takes to develop and verify complicated forestry methodologies (Chokkalingam and Vanniarachchy, 2011b). Recently, the possibility of expanding the project types eligible under CDM to also include other LULUCF activities such as re-vegetation, forest management, cropland management, grazing land management, wetland management and soil carbon management in agriculture, has been discussed. Including additional LULUCF-based CDM types would offer a more holistic landscape-approach. Also, the sustainability element, which is one of the components that need to be delivered within CDM projects, is important within since it deals with the improvement of the natural resource base which is essential for sustainable livelihoods (Lindgren, 2011).

2.2.2. REDD+

Momentum to include a larger suite of forest carbon activities under the UNFCCC began at COP 11 in Montreal 2005, when Costa Rica, Papua New Guinea and eight other tropical nations called for the inclusion of reducing emissions from deforestation in developing countries (RED) under the UNFCCC (UNFCCC, 2005a). The COP established a two-year process to review relevant scientific, technical and methodological issues and consider possible policy approaches and positive incentives for RED. It also requested its technical group the Subsidiary Body for Scientific and Technological Advice (SBSTA) to evaluate the issue under the agenda item "Reducing emissions from deforestation in developing countries and approaches to stimulate action" and to report back at COP 13 on Bali.

Several workshops were held on methodological and financial issues on the topic over those two years and considerable progress was made. The scope was widened and forest degradation was added, hence RED became REDD. At COP 13 on Bali 2007, delegates agreed to include REDD in the UNFCCC framework under the Bali Action Plan, which addresses enhanced national and international action on climate change mitigation, including: "consideration of policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries" (UNFCCC, 2007). At COP 13, Norway and multi-lateral agencies supported REDD and readiness efforts and demonstration activities started in a number of developing countries with support from, for example, the newly established World Bank's Forest Carbon Partnership Facility (FCPF) and the UN-REDD programme. As deliberations moved forward on a REDD mechanism whereby developed countries would provide incentives through financial compensation to developing countries for climate change mitigation benefits from maintaining and enhancing forest biomass (i.e. carbon), three categories have emerged for what such a financing mechanism should cover: (1) reducing emissions from deforestation and forest degradation in developing countries (REDD); (2) conservation, sustainable management of forests, and (3) stock enhancement in addition to REDD (REDD+). The addition of the latter two comprise the plus as REDD became REDD+.

In 2010, at COP 16 in Cancún, Mexico, REDD+ was formally added into the climate change agenda within UNFCCC. It was decided that MRV elements for REDD+ as included in the Cancún Agreements are critical elements necessary for the successful implementation of any REDD+ mechanism: and that REDD+ should be initiated with current technical knowledge (UNFCCC, 2010). At COP 16, Parties also agreed that REDD+ should be developed in three phases: 1) REDD+ readiness development of national strategies or action plans; 2) implementation of policies and measures and 3) payment for performance on the basis of quantified forest emissions and removals. In 2011, at COP 17 in Durban, South Africa, Parties were again discussing issues relating to carbon emission accounting and MRV, particularly on whether to use Reference Emission Levels (RELs), which refer to the amount of gross emissions from a geographical area estimated within a reference time period (deforestation and forest degradation) or Reference Levels (RLs) which refer to the amount of net or gross emissions and removals from a geographical area estimated within a reference time period (see section 2.4) also including conservation and sustainable management of forests (UNFCCC, 2011a). Another important issue that was discussed was REDD+ finance, but no agreement was reached on this issue.

Since its inception, REDD+ has developed into one of the most prominent but also contentious issues on the international climate change agenda, receiving high attention not only from governments, but also from researchers, multilateral funds and organizations, NGOs, politicians and the private sector (Johns and Johnson, 2008; Westholm et al., 2009; Cerbu et al., 2010). This may be due to its apparently simple initial approach: to pay tropical forest countries to keep their forests standing. In the beginning, emission reductions from avoided deforestation were believed to be a relatively cheap, quick and feasible mitigation option, more readily available in the short term than reduction opportunities in other sectors (Stern, 2005). As the discussions have progressed and matured and their scope extended, multiple challenges have surfaced including how benefits from REDD+ should be distributed to forest communities and how to establish a structure of funding mechanisms that maintains environmental integrity. These concerns must be addressed in the context of low quality governance structures and weak tenure systems in many developing countries (Phelps et al., 2010).

Even where there is sufficient technical knowledge on MRV, many developing countries including Sri Lanka lack consistent data on forest trends and status because they have dysfunctional or non-existing inventories and monitoring systems. This is a barrier to initiating REDD+ as expressed in the Cancún Agreements. If REDD+ is going be equitable and yield significant emission reductions, these shortcomings must be addressed. This contribution contributes to the knowledge and understanding required to do that for Sri Lanka.

2.2.3. Other options

The issues and difficulties that have been raised regarding terrestrial carbon sinks are not new. Before the discussions on REDD+ were initiated, they were present in other arenas and the discussion on how forest-based schemes such as REDD+ can work in practice could be assisted by looking at similar mechanisms and initiatives already in place; such as the market for voluntary emissions reductions (VERs) for forest carbon credits that have developed in areas outside the regulated schemes at the international level. Most site-level voluntary projects now use several voluntary standards such as the Climate, Community and Biodiversity Standards (CCBS), Voluntary Carbon Standard (VCS) and the Plan Vivo for certification to ensure environmental and social credibility in forest projects as demanded by the buyers (Kollmuss et al., 2008). Experiences in the development of Afforestation/Reforestation (A/R) projects under the CDM can also generate lessons for a REDD+ mechanism, although there has been limited provisions for such projects so far.

2.2.4. Forest carbon activities in Sri Lanka

Sri Lanka has so far been involved only in a few forest carbon activities. One voluntary market project is currently under validation to the Plan Vivo standard (Plan Vivo, 2012) and seven A/R CDM projects have been initiated, but by the end of 2011 none had reached the validation and implementation phase (Chokkalingam and Vanniarachchy, 2011a). In October 2009, Sri Lanka was granted observer status on the Policy Board of the UN-REDD program (UN-REDD, 2009) which gave it access to networks and knowledge sharing. The UN-REDD program is supporting Sri Lanka with 4 million USD for its initial readiness activities and a REDD+ National Joint Program was set up in 2011 to assist in the development of an effective REDD regime and to contribute to reduction of emissions from deforestation and forest degradation from 2011–2014 (Bandaratillake, 2011). The National Joint Programme draft proposes to set up five demonstration projects in five districts to assess the emissions reduction impacts of forest-based livelihood development activities with the involvement of local stakeholders (ibid.). In UNFCCC deliberations, Sri Lanka has been one of the nations supporting the expanded focus of REDD+, highlighting the need for compensation to be provided for conservation and sustainable management of forest resources (UNFCCC, 2008). Sri Lanka also views remote sensing and satellite imaging as appropriate monitoring methodologies, while stressing the lack of resources for implementing such high-tech methodologies.

2.3. The forest transition

Countries that due to their size and their historical deforestation level have contributed only marginally to increased levels of GHG in the atmosphere have received less attention in the REDD+ literature than larger countries with high emissions from deforestation (e.g. Brazil, Indonesia, DR Congo). It will however be important to include smaller and therefore low emission countries like Sri Lanka in a REDD+ system to ensure a more equal distribution of possible REDD+ benefits. In addition to the risk of creating leakage, the total deforestation in all low emission countries combined might produce and add significant amounts of emissions to the atmosphere if they are left out from a REDD+ system. The diversity of country circumstances can be viewed in the context of forest transition theory (Mather, 1992), elaborated further in the framework of REDD+ by da Fonseca et al. (2007) and Griscom et al. (2009).

Forest transition theory suggests that initially a country has a high forest cover and low deforestation rate (HFLD) (Fig. 2). In order to foster economic development, countries start using their natural resource base in the form of timber and agricultural products, this often leads to a degradation of natural ecosystems, and the conversion of forest for expanded agricultural production (Angelsen, 2007). This eventually leads to high forest cover and high deforestation rate (HFHD). Further development can reinforce and accelerate deforestation as a result of advancing infrastructure development that yields better access to markets with increasing demand for forest goods, resulting in low forest cover and high deforestation rates (LFHD). As countries develop economically, forest cover stabilizes as a result of off-farm jobs which reduce the profitability of deforestation giving a low forest cover and low deforestation rate (LFLD). Similarly, forest scarcity increases the value of forest products which hinders further forest conversion yielding a low forest cover and a negative deforestation rate (LFND). These processes mark the forest transition from shrinking to expanding forest area, as has earlier occurred in boreal and temperate regions such as the United States and Europe. The forest transition may look different from country to country or from region to region and is influenced by national polices and economic forces. Essentially, seen through the lens of forest transition theory, REDD+ seeks policy interventions which will initiate forest transitions at a higher level of forest cover and thus bypass the high emission stages (Fig. 2). This requires broad policy reforms, solid MRV systems and changes in land tenure regimes (Sunderlin and Atmadja, 2009; Meyfroidt et al., 2011).

Some developing countries (e.g. India, China, Vietnam and Costa Rica) have over the last few years undergone a forest transition; they achieved reduced deforestation and are now demonstrating a net gain in forest cover. However, increase of forest area does not necessarily mean an improvement of forest quality since carbon stock increments and biodiversity recovery can be slow and it can also mean that the demand causing the domestic deforestation is moved to another nation (Meyfroidt et al., 2011). The long tradition of forest conservation in Sri Lanka together with the recent trends of declining forest loss have been reflected in the country's increasing engagement in the international REDD+ discussions, where Sri Lanka is supporting the expanded focus of REDD+, highlighting the need to compensate for conservation and sustainable forest management (SFM). This reflects a situation generally where the negotiation positions of the Parties within the UNFCCC reflect their respective interests as reflected in their respective positions on the forest transition curve (UNFCCC, 2011b). Countries which are not undergoing rapid deforestation and degradation have a strong incentive to argue for payments for work done to effectively manage and conserve forest stocks.

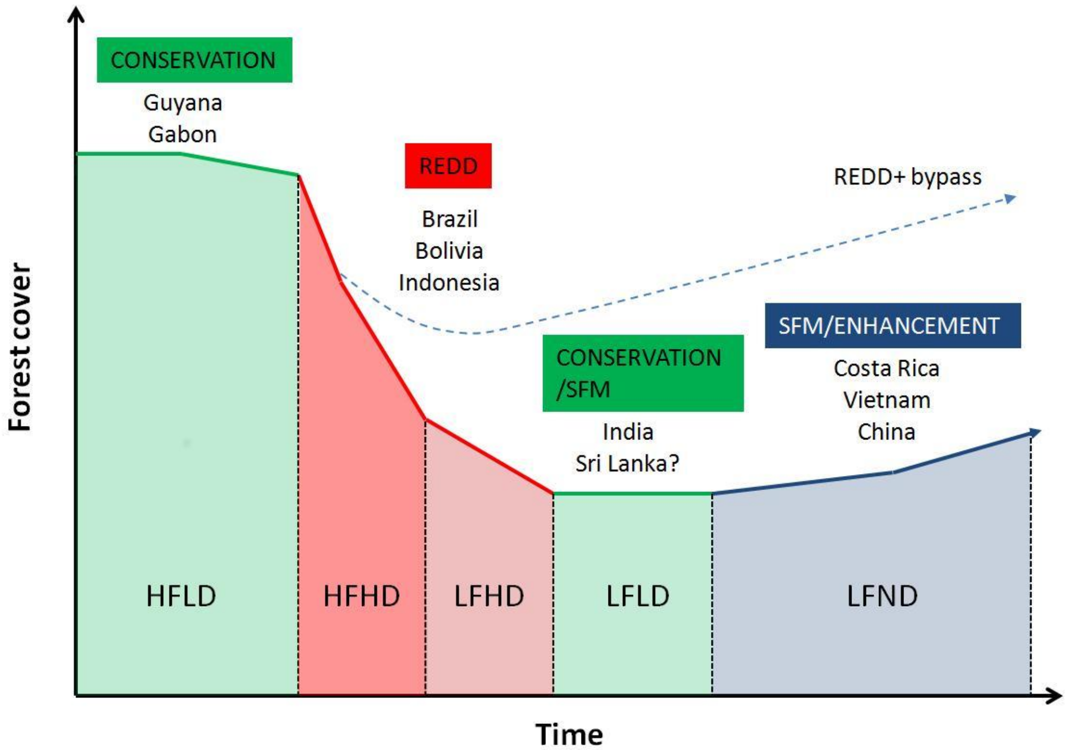


Fig. 2. Different stages in the forest transition. HFLD refers to high forest, low deforestation countries, HFHD are high forest, high deforestation countries, LFHD is low forest, high deforestation countries, LFLD refers to countries with low forest, low deforestation whereas LFND is low forest, no deforestation countries (Modified from Angelsen et al., 2009; Meyfroidt et al., 2011).

2.4. MRV and reference levels

Monitoring systems that measure, report and verify (MRV) changes in forest carbon stocks are key for the implementation of national REDD+ schemes. As mentioned in section 2.2.2., most developing countries have limited capacity for the sort of measuring and monitoring that is needed for participation in an international REDD+ system which will provide compensation for performance based action. MRV of carbon requires repeated ground-based data from field inventories as well as remote sensing techniques to monitor forest carbon stocks and establish reference levels. Capacity building support from developed to developing countries in terms of providing technical training methodologies, and knowledge sharing that help countries to strengthen their institutional and technical capacity could help to develop more robust, accurate and consistent monitoring systems (GOFC–GOLD, 2009; Herold, 2009).

Reference levels (RLs) or baselines are the benchmarks for assessing a country's performance in reducing emissions and describe the behavior, performance or quality under a business-as-usual (BAU) scenario. RLs can therefore be used to determine the effectiveness in terms of climate impact, cost efficiency and funds for the system (Angelsen et al., 2009), hence an agreed RL is fundamental for any performance based system such as REDD+. If the data on forest carbon stocks is incomplete, there are risks associated with how a RL is calculated and used. On the one hand there is the risk of giving too low acknowledgement for carbon saving and storing activities, such as by using very conservative numbers in the calculations (Mollicone et al., 2007). This could increase the risk for expansion of alternative land use practices that can generate more income than storing carbon in the forest. The net benefit and incentive for a country to participate is therefore reduced. On the other hand, there is the risk of creating carbon saving and storing schemes that in reality do not reduce the level of CO_2 in the atmosphere, either due to the fact that the action would have taken place anyway or that nations are being paid for doing nothing (Persson and Azar, 2007).

As discussions have evolved and intensified, the proposals on how to set RLs have been greatly debated and developed. Most Parties to the UNFCCC support the position that reference levels should be based on historical emissions (UNFCCC, 2011a). The compensation reductions proposal presented in 2005 is based on the idea that nations would be compensated for reducing or halting their deforestation rate as compared with the BAU scenario of the reference level (Santilli et al., 2005). One argument against using this approach in isolation is that it would not provide significant incentives or rewards to countries with low historic deforestation rates. Other proposals therefore include modified systems that would reduce the impact of the most extreme yearly anomalies and systems that would provide incentives for countries with historically low deforestation rates (Mollicone et al., 2007; Strassburg et al., 2008). A mechanism based on two different schemes as proposed by Mollicone et al. (2007) can be used to account for preserved carbon: one for countries with high deforestation rates with the aim of reducing their rates and another scheme aimed at countries with low rates. Under this proposal, to generate credits a country's historical deforestation rate has to be weighted relative to the global average baseline. Countries with emissions higher than half the global average are rewarded for reducing emissions from forest conversion whereas countries with emissions less than half the global average baseline are rewarded for maintaining their carbon stock.

Most of the RL proposals thus deal with how to appropriate reward performance and give incentives to nations with varying historical forest records. These proposals rely more or less on historical emissions (Fig. 3) to form a historical baseline. Such data, based on data on forest emission changes in the recent past, require objective, science-based emissions and removals data over a recent historical period, which is a severe challenge for many countries. In addition to data a set of predefined rules such as a forest definition, scope (e.g. the number of included terrestrial carbon pools) and a reference period, must all be decided upon. Historical emissions estimates could contribute to the determination of a future BAU scenario (Meridian Institute, 2011) and could be projected with the help of extrapolations, and/or modeling and assumptions (Fig. 3). Future BAU scenarios are also useful for demonstration activities within a country to analyze and evaluate national REDD+ strategies and planning (Busch et al., 2011).

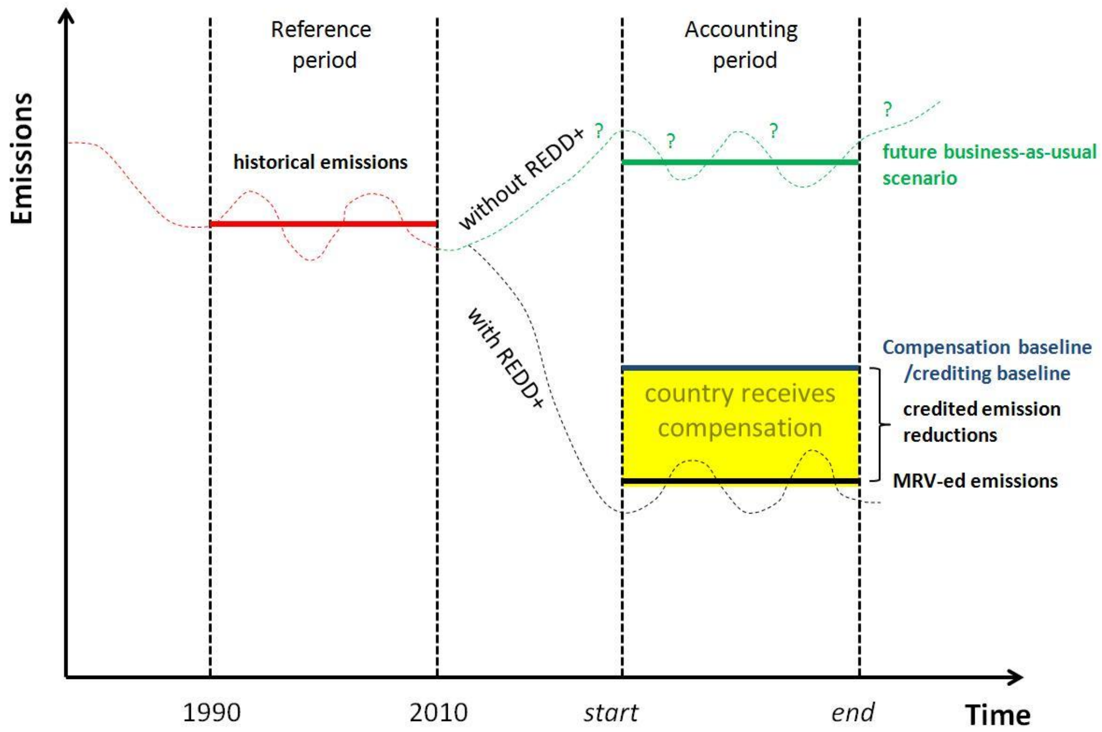


Fig. 3. Distinction between three different reference level concepts; historical emissions, future business-as-usual scenario and compensation baseline/crediting baseline. Modified from Busch et al. (2011).

In order to address many concerns in REDD+ such as leakage, equity and additionality the use of a Development Adjustment Factor (DAF) has been proposed. This would involve factoring in to the RL setting national circumstances such as GDP or position on the forest transition curve (Mather, 1992) population dynamics, road networks, market factors or governance indicators (Angelsen, 2009). This proposal also considers the UNFCCC principle of “common but differentiated responsibilities” allowing more generous RLs for poor countries striving for socio-economic development and stricter or more stringent targets for more developed countries. This also enables participation of HFLD countries through future projections.

Credits or rewards will be made against a *compensation* baseline or crediting baseline (Fig. 3) that will be decided in a political setting through negotiations (Angelsen, 2008). The difference between the actual carbon emission and the compensation baseline is where earnings or rewards will be generated. Hence, the compensation baseline might not be directly associated with measured or calculated carbon that is stored or emitted but will rather ensure that climate benefits are delivered and ensure effectiveness and could be adjusting for national circumstances. Setting the compensation baseline tighter than the BAU baseline will also reduce the number of credits brought to the market, thus reducing the risk of crowding out other mitigation activities.

2.4.1. Support options

There are several support options for national REDD+ readiness assessments focusing on RLs which countries could follow. The IPCC has developed Good Practice Guidelines (IPCC-GPG; Penman et al., 2003) for estimating national GHG emissions where key categories relevant for REDD+ are included. The guidelines provide methods at different levels of quality from a very coarse to a highly detailed assessment. These approaches range from

Tier 1: (simplest to use; globally available data), to
Tier 2: (nationally-derived data which allow for more precise estimates where changes in carbon stock are calculated), and
Tier 3: (high resolution methods specific for each country and repeated through time) (IPCC, 2006).

Emission categories with high influence on a country's GHGs should be estimated using detailed calculations and nationally developed models (i.e. Tier 2 and 3) (Penman et al., 2003) taking into account activity data (area changes), trends in activity data as well as emission factors (GHG emissions or removals per unit area. The IPCC reporting principles also emphasize that GHG reporting should be consistent, comparable, transparent, accurate, and complete (ibid.). Many developing countries do not currently have the capacity to produce national estimates to follow these reporting standards and with data requirements of Tier 2 or 3 methodologies (Herold, 2009). Tier 1 methodologies are already used in most countries' national communications to the UNFCCC and could be used as a first step while countries develop MRV systems to meet stricter requirements over time. In addition, the concept of *conservativeness* (Grassi et al., 2008) may provide flexibility in dealing with uncertain and incomplete data. Conservativeness in this context means that when the completeness or accuracy of estimates cannot be satisfactorily achieved, carbon stocks should not be overestimated. If this principle is followed, accurate estimates of carbon stocks will likely be achieved as MRV improve. Another international effort that provides guidance is the Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD, 2009) initiative. GOFC-GOLD has suggested a common time frame for setting a reference level from 1990 until 2005 partly since freely available remote sensing data exists for most developing countries within this timeframe making reference level establishment easier.

2.5. Study area

Sri Lanka is a tropical island located in the Indian Ocean, to the southeast of the Indian subcontinent and has an estimated population of 20.5 million (Department of Census and Statistics, 2010). It covers an area of approximately 65,610 km^2 between 5°54'–9°52'N and 9°39'–81°53E, which makes it approximately the same size as Ireland or Tasmania. Sri Lanka's total emissions of CO_2 amounted to 26 megatonnes (Mt) in 2005 excluding emissions from land use change and forestry. This amounts to only 0.07% of the world's total emissions. According to UNFCCC (2005) approximately 50% of the total Sri Lankan emissions in 1994 were derived from land use change and forestry. Sri Lanka's Gross Domestic Product (GDP) for 2010 was 106.5 billion USD in terms of purchasing power parity (PPP), which put the country in 69^{th} place globally. The agricultural sector accounts for only 12% of GDP, but employs 33% of the labor force (CIA, 2011). Production and export of agricultural products such as tea, rubber, coffee and sugar became important during the 1800s and 1900s and these are still central commodities. Similarly, the country has moved steadily towards an industrialized economy with the development of textiles, apparel, telecommunications, finance and food processing (Ministry of Finance, 2010).

Sri Lanka consists of a south-central mountainous area with elevations up to 2524 meters above sea level (m.a.s.l.) surrounded by a vast coastal plain below 500 m.a.s.l., where most forests and agricultural regions are located (Government of Sri Lanka, 2000). Sri Lanka has a tropical climate characterized by two major monsoon periods, the southwest monsoon from May to September (yala) and the northeast monsoon from December to February (maha). The country is divided into three climatic zones, based on the annual rainfall and its distribution: the dry zone (1250–1525 mm yr^{-1}) in the south-east and north, the intermediate zone (1525–2280 mm yr^{-1}) predominantly in the central parts, and the wet zone (2280–5100 mm yr^{-1}) in the southwest (Domrös, 1974). Due to the small variation in latitude the differences in temperature are mainly dependent on elevation with mean annual temperature from 26–28°C in areas below 150 m.a.s.l and 15–19°C in the upcountry region (Government of Sri Lanka, 2000).

Despite Sri Lanka's relatively small land area, its large variations in rainfall, altitude, and soil characteristics create forests of high diversity, ranging from wet evergreen to montane forests and vast areas of dry monsoon forests with high species diversity and endemicity. Eighty-five percent of the natural forests consist of dry-zone forests. Lowland rainforests and montane forests with higher biological diversity and higher levels of endemism are confined to small patches (Gunatilleke and Gunatilleke, 1990). Sri Lanka has lost more than 60% of its forest cover from about 80% in the late 1800s to 25% in early 2000 (FAO, 2010b). Deforestation has seriously diminished timber supplies, made soils less productive, water supply more erratic and floods more frequent and severe (Bandaratillake and Sarath Fernando, 2003). Major forest inventories of Sri Lanka have been carried out by Koelmayer (1957), Andrews (1961), Forest Department of Sri Lanka (FAO/GOSL, 1986), Legg and Jewell (1995) and Government of Sri Lanka (GOSL, 2000). Assessments of forest cover at the district level using Landsat data concluded that four districts in the north had showed forest decrease from 1992 to 2001, while several districts in the south-central region had undergone an increase in forest area during the same period (Ratnayake et al., 2002). The recently ended war between the government and the Liberation Tigers of Tamil Eelam (LTTE) has also contributed to deforestation by increasing the demand for timber construction and displacing settlements (White, 2006; Suthakar and Bui, 2008), although Gunawardane (2010) found an increase in total forest cover by 3.5% from 1992–2010 in five war-torn northern districts mostly due to natural regeneration. Recent trends from FAO FRA (2010b) also indicate that forest cover loss has decreased in recent years, although variations exist between districts.

Geographically, this thesis was carried out on local, regional and national level in Sri Lanka. Data for paper I was compiled in the dry coastal area of Hambantota district in the southeastern part of the country whereas data collection for papers II and III was conducted in several districts with different climate regimes and biomes ranging from the low elevation wet zone in the south, upland areas in the central region and dry, lowland areas in the north-central region. Fieldwork for paper IV was collected around one protected forest in the low elevation wet zone and around one protected forest in the central region whereas data material for paper V was collected at local level in the wet and dry zones. More information on specific study area characteristics can be found in the appended papers I-V.

3. MATERIAL AND METHODS

Several methods have been used to achieve the objectives of this thesis. Data were collected during three periods of field work between 2006 and 2011 in different parts of Sri Lanka. Extensive descriptions of measurement techniques, instrumentation, data analysis and location are described in detail in each of the appended papers. Below follows a description of the main methods employed in the field work including data analysis.

3.1. Environmental assessment of soil and well water salinity

An environmental assessment was conducted in Hambantota district in 2006 in order to evaluate the present status of soils, land and vegetation and to assess the recovery process 14 months after the tsunami event in 2004 (paper I). Following the guidelines provided in FAO (2005), soil samples were collated in 15 transects at 50–200 m from sea shore with 50–100 m intervals and three depths (0–10, 10–30 and 30–50 cm) in six land use ecosystems (natural forests, mangrove forests, homegardens, coconut plantations, casuarina plantations and paddy rice), that were inundated by sea water after the tsunami event. One reference sample per transect was also collected further inland on non-tsunami affected soil in order to distinguish the salinity difference between inundated and non-inundated sites. The samples were analyzed through electric conductivity measurements in the laboratory using the method described by Walkley and Black (1934). In addition, well water samples were collected in sandy soils within 200 m of the seashore at eight different locations spread along the coast. These measurements were carried out in order to acquire a complete picture of salinity levels further down in the soils. In all papers, field observations were made and documented by camera and Global Positioning System (GPS) to complement the other field methods.

3.2. Forest carbon and structural characteristics

Tree measurements were conducted in five different land use systems (casuarina plantations, coconut plantations, home gardens, natural dry forests, mangrove forests) in order to assess the carbon stock for each land use system (paper I). By collecting data on girths and number of stems of trees with girths greater than 10 cm in quadrates following Ravindranath and Premnath (1997), the AGB was estimated for land use and forest based systems in the tsunami affected areas. Predefined formulae from Ravindranath et al. (2000) were used to estimate the basal area used to calculate the biomass volume of the trees before accounting for a moisture content of 15% and that half of the dry matter in biomass consists of carbon (FAO, 1983). This method was originally designed for Indian natural forest and therefore there are some limitations in its application in Sri Lanka.

The field measurements collected in the second field visit presented in paper II and III were conducted in six different natural forest ecosystems (low-land, sub-montane, montane, moist monsoon, dry monsoon and open forests) based on spectral signatures in remote sensing imagery used in the two latest national forest inventories (Legg and Jewell, 1995; GOSL, 2000). In total, almost 20,000 trees were measured between November 2008 and August 2009 including forest plantations of pine, teak and eucalyptus, encompassing 233 single temporary inventory plots each 30x30 meters in size (Fig. 4 and 5). Two pan-tropical allometric equations and one volume equation were used (Brown et al. 1989; Luckman et al., 1997; Ravindranath and Ostwald, 2008) to estimate the AGB carbon stock (paper II). Only AGB was measured since it is the largest carbon pool in tropical forests and is most directly impacted by land conversion along with its feasibility to measure. It is also an obligatory category for countries wishing to engage in REDD+ (GOFC-GOLD, 2009). Using allometric equations and a volume equation as input for carbon stock required more input parameters than for the method applied in paper I. Apart from diameter at breast height (DBH), also tree height and species information were collected. Species information was used as input for assessing oven dry wood densities (Worthington, 1959; Reyes et al., 1992; Chave et al., 2009; ICRAF, 2010) and evaluating species distribution. Default ratios of below-ground biomass were added for all forest categories in order to compare our estimates with existing IPCC-GPG Tier 1 estimates (paper II) (IPCC, 2006). Allometric equations were applied to calculate the biomass of each tree. All trees in a single inventory plot were then added to acquire the total AGB carbon per plot for each forest type and subsequently up to hectare size. These carbon estimates were multiplied with the area information for each forest category found in the two latest national forest inventories conducted in 1992 and 1996 to get the total carbon stock for each natural forest ecosystem in Sri Lanka (paper II). This served as input to calculate a historical reference level from 1992–1996 to 2005–2010 taking into account the latest national estimates of forest cover reported the FAO (FAO, 2010b). Two remaining natural forest categories (riverine dry forests and mangrove forests) were not sampled. For riverine dry forests we applied the same AGB estimates as for dry monsoon forests based on similarity of forest characteristics. For mangrove forests, AGB estimates from Amarasinghe and Balasubramaniam (1992) were used.

Fig. 4. Measurement of diameter at breast height in a montane forest during the second field study.

Twelve inventory plots of homegardens were also measured (paper V) where eight plots were measured in randomly chosen homegardens in dry zone areas (Hambantota district and Anuradhapura district) and four in randomly chosen wet zone homegardens within the Kandy district. Given the lack of a standard approach and available allometric equations to estimate carbon stock for homegardens and agroforestry systems, the pan-tropical allometric equations by Brown et al. (1989) and Chave et al. (2005) were applied, using the same approach as in papers II–III. Based on the field measurements and available homegarden area information from 1992 and 2005, the total AGB carbon content was estimated for homegardens on a national level 1992–1996–2005–2010. These estimates were compared with the area extent and total carbon stock of eight natural forest categories for the same years.

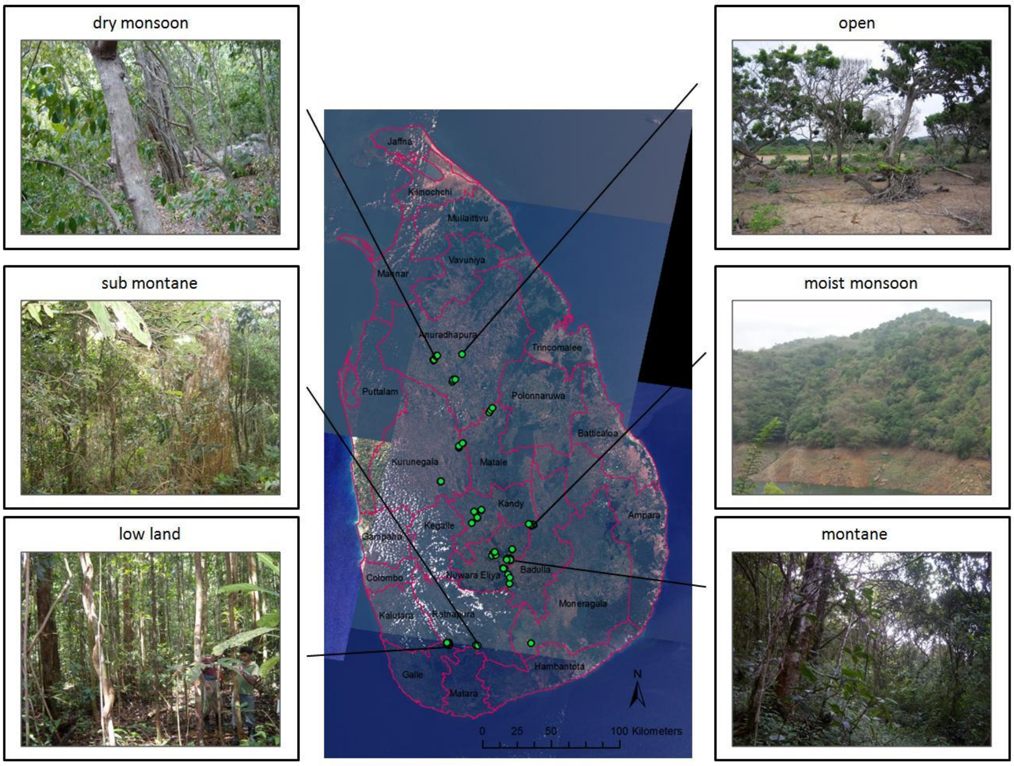


Fig 5. Field inventory locations in six different natural forest ecosystems sampled between November 2008 and August 2009.

The analysis was extended (paper III) to include more allometric equations in order to evaluate and discuss the accuracy and variation of different pan-tropical equations on AGB carbon stocks between different life zones (Holdridge, 1967) since no allometric relationships have been developed specifically for Sri Lankan natural forests. The parameters of DBH, tree height, species information and numbers of trees were used to analyze structural characteristics, relationships and allometry between forest types as well as forest plantations (paper III).

3.3. Participatory assessment

24 questionnaire interviews containing structured and open-ended questions were conducted with land users around different land use systems in Hambantota district (paper I). The purpose was to obtain a comprehensive picture of respondents' land use management, the effects of the 2004 tsunami they experienced and of their aspirations and expectations in relation to future land use management.

Structured interviews were carried out with 32 households divided equally between the two study areas: Kanneliya Forest Reserve and Knuckles Conservation Forest (paper IV). The purpose of the interviews was to acquire information on land users' relationships with the forests, current and historical land use practices and their views of changes in forest cover in relation to changes in forest conservation and management policies. Moreover, seven interviews were conducted with key informants with the purpose of acquiring viewpoints on forest cover change in relation to forest dependency of local land users.

3.4. Spatial analyses

Forest and land use changes were classified through remote sensing analyses and Geographic Information Systems (GIS) to obtain information about changes between 1984 and 2003/2010 around and within the protected forest buffer zones in Kanneliya Forest Reserve and Knuckles Conservation Forest (paper IV). Land use maps from 1984 were used to estimate the historical extent of different land uses, natural forests and households and two sets of satellite imagery acquired from Google Earth were used to visually classify recent changes in forest cover, land use and demographic changes. The land use maps from 1984 were coarser in resolution and more generalized than the satellite images and consequently the land use analysis for 1984 became more simplified than the recent visually interpreted satellite images. The differences in resolution, visibility, (e.g., due to cloud cover) and temporal scale of the satellite images caused difficulties when analyzing changes around villages in Knuckles that was covered by two different set of images from 2003 and 2010 respectively; the older image containing no clouds but having course resolution and the newer image having high resolution but high percentage of clouds. As a result, the interpretation of forest cover and land use were based on what could be visualized in the older satellite image from 2003 while the satellite image with better resolution was used to verify these results, although cloud coverage prevented this approach from being applied to the whole area. Land use changes were subsequently compared and validated with field observations and the respondent's views of utilization of their lands historically to find similarities and differences to acquire a more holistic picture of change. Also as a complement, GPS coordinates and photos acquired in field were used as a ground truthing method to fill gaps relating to unidentified land use. To get a sense of the population increase, the numbers of households were calculated visually for the two years. The exact increase in numbers of households for each village should be taken with care since not all households might have been marked in the original land use maps but yield a general sense of the demographic changes in the two study areas and the indirect consequences on land use change.

4. RESULTS

4.1. Environmental assessment of soil and well water salinity

Out of 150 soil samples taken on tsunami inundated land, eight samples, all collected on mangrove forests and rice fields, had values more than 4 milli Siemens per cm (mS cm^{-1}) which is the saline/non-saline boundary according to United States Department of Agriculture (Tanji, 1990). Most of the remaining samples had values well below the saline threshold value and were within the same range as the reference samples. The soil type affected conductivity levels, where silty-clayish soils in coconut and rice fields in general had higher conductivity values than sandy soils, due to fast leaching of salt in sandy soils whereas smaller porous volumes in silty-clayish soils resulted in slower leaching. Higher conductivity levels in mangrove forests are probably a result of their location close to ocean and lagoons and the constant exchange of tidal water (paper I).

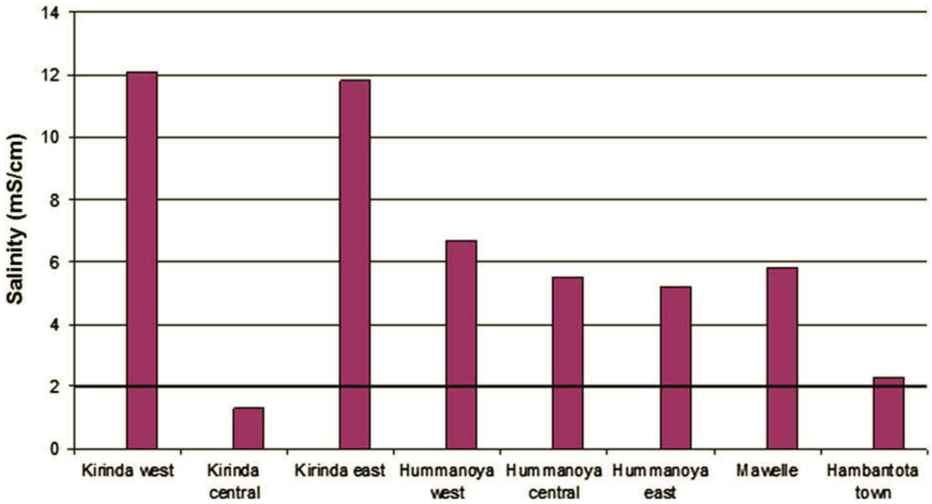


Fig. 6. Salinity from wells in tsunami affected areas of Hambantota district within 200 m distance range from the seashore. The thick line at 2 mS/cm is representing the maximum accepted value for clean water according to FAO (2005).

While the soil samples featured low levels of conductivity, seven out of eight wells for drinking purposes were contaminated with salt, i.e. >2.0 mS/cm (Fig. 6) (FAO, 2005). It is therefore possible that the sandy soil conditions facilitated salt-contaminated water to go through the porous sand layers and infiltrate the groundwater table. Improving the water quality through pumping out groundwater had in some cases been successful, but dumping well water nearby and over-pumping might have worsened the conditions (paper I).

4.2. Forest carbon and structural characteristics

Dry natural forests had the largest AGB carbon stock followed by coconut plantations, casuarina plantations, homegardens and mangrove forests (paper I). These results were mainly explained by stem thickness and spatial density of trees. The AGB carbon stock estimates for different land uses and forests in Hambantota district should be considered an indication rather than a quantifiable result owing to the low rate of tree sampling in a limited number of plots.

The resulting average carbon stock value (above and below ground biomass) from 1992 to 2010 is 120–130 tonnes of carbon per hectare (tC ha^{-1}) for eight natural forest ecosystems using all three allometric equations (paper II). The total carbon stock for eight natural forest categories was estimated at 267 MtC in 1992, declining to 249 MtC in 1996, 210 MtC in 2005 and 204 MtC in 2010 (Table 1).

Table 1. Carbon stock estimates in above- and below-ground biomass carbon showing total (MtC), per hectare (tC ha^{-1}), forested area (1000 ha) and range (tC/ha^{-1}) of the eight different Sri Lankan forest ecosystems from 1992 to 2010 using Tier 2 data from our inventory campaign.

Tier 2 estimates – inventory campaign 2008–2009

Forest ecosystem	1992		1996		2005		2010		range (tC ha^{-1})
	MtC	Ha	MtC	Ha	MtC	Ha	MtC	Ha	
Lowland rainf.	31	142	27	124	20	93	19	86	203–225
Sub-montane	12	69	11	66	10	59	10	58	159–172
Montane	0.1	3	0.1	3	0.1	3	0.1	3	43–50
Moist monsoon	33	244	30	222	24	180	23	170	125–139
Dry monsoon	173	1094	163	1028	141	892	136	858	153–162
Open forests	13	464	14	472	14	489	14	500	26–31
Mangrove	0.7	9	0.8	10	1.0	12	1.1	13	35–149
Riverine	4	23	3	18	2	12	1	10	153–162

	1992			1996			2005			2010			range (tC ha^{-1})
	MtC	tC ha^{-1}	Ha	MtC	tC ha^{-1}	Ha	MtC	tC ha^{-1}	Ha	MtC	tC ha^{-1}	Ha	
Total	267	130	2048	249	128	1943	210	122	1740	204	120	1698	120–130

The total carbon loss for eight natural forest ecosystems was 18 MtC between 1992 and 1996 and 45 MtC between 1996 until 2010 assuming a BAU scenario based on the forest cover change rates from 1992-1996 until 2005-2010 using national reported values to the FAO FRA (FAO, 2005; FAO 2010b). In terms of annual emissions from deforestation this translates to 17 $MtCO_2$ yr^{-1} between 1992 and 1996 and 12 $MtCO_2$ yr^{-1} between 1996 and 2010, which are both around half of the 27.9 $MtCO_2$ in total Sri Lankan CO_2 emissions from forest and other land use systems in 1994 (UNFCCC, 2005b). Large variations exist in total above and below ground biomass carbon stock for different forest types, where dry monsoon forest holds a substantial amount due to its large area (Fig. 7).

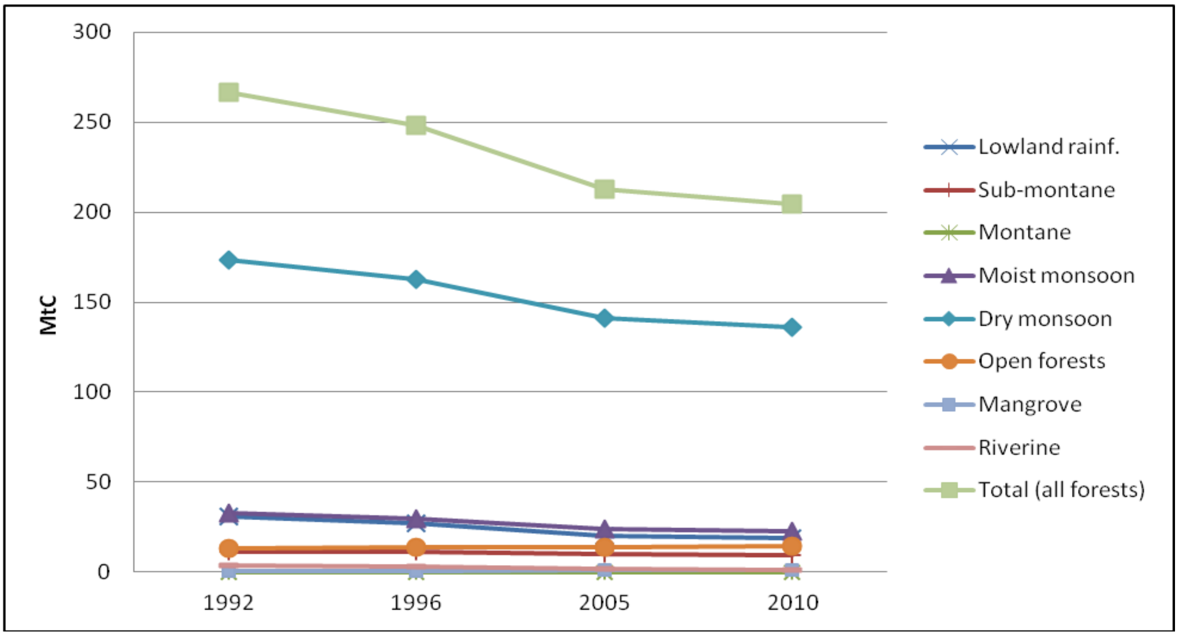
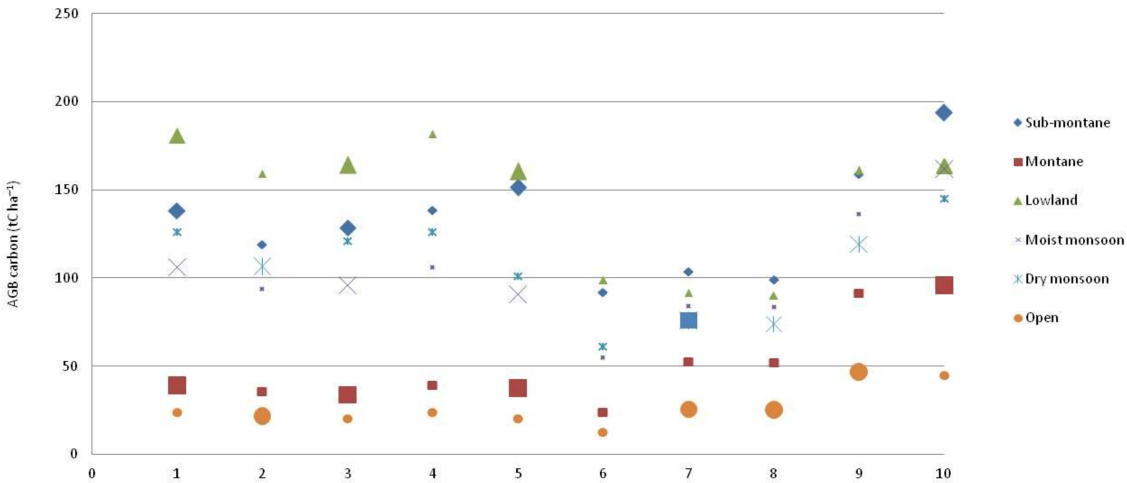


Fig. 7. Total above and below ground biomass carbon content for eight different Sri Lankan forest categories and total carbon content for all eight combined forest types.

In paper III, the mean AGB carbon was estimated at 22–181 tC ha^{-1} in six natural forest types, lower than the figures presented in paper II due to the exclusion of below ground biomass and a different set of allometric equations. Four hundred and thirty-four different tree species were identified. In terms of structural characteristics it was found that tree density was highest in moist monsoon forests and lowest in open forests, where all natural forests had higher densities than managed plantation forests. Forest types containing trees with a greater DBH or basal area have taller trees at any given diameter, a finding which is supported by Feldpausch et al. (2011) and vary by forest type due to several environmental parameters and disturbance regimes. Diameter size distributions also showed that a large share of the trees in each forest ecosystem are in the 3–10 cm DBH range, declining toward higher diameter size classes, while the trees in plantation forest categories were distributed between 10–20 cm. On the other hand, there is large variation between forest types on AGB distribution with respect to diameter size classes. An evaluation of the variation of dry-weight wood densities showed a total range of 0.29–1.32 g cm^{-3} between measured tree species. The occurrence of many hardwood species in, e.g., dry monsoon forests yield a higher mean dry-weight wood density whereas in other forest types such as sub-montane forests the occurrence of lighter softwood species yield lower mean values.



	Allometric equation	Variables			Restrictions	Source
		DBH	height	density		
1	$Y = \exp(-2{,}4090+0{,}9522\times\ln(D^2\times H\times S))$	x	x	x	moist life zone (1500 mm < rainfall < 4000 mm), DBH > 5 cm	Brown et al., 1989
2	$Y = \exp(-2{,}187+0{,}916\times\ln(D^2\times H\times S))$	x	x	x	dry life zone (rainfall < 1500 mm)	Chave et al., 2005
3	$Y = \exp(-2{,}977+\ln(D^2\times H\times S))$	x	x	x	moist life zone (1500 mm < rainfall < 4000 mm)	Chave et al., 2005
4	$Y = (0.0899((D^2)^{0.9522})\times(H^{0.9522})\times(S^{0.9522}))$	x	x	x	n/a	Luckman et al., 1997
5	$Y = \exp(-3.1141+0.9719\times\ln(D^2)H))$	x	x		moist life zone (1500 mm < rainfall < 4000 mm)	Brown et al., 1989
6	$Y = \exp(-3{,}3012+0{,}9439\times\ln(D^2H)$	x	x		wet life zone (1500 mm < rainfall < 4000 mm)	Brown et al.,1989
7	$Y = 34.4703 - 8.0671\times(D)+0.6589\times(D^2)$	x			dry life zone (rainfall < 1500 mm), DBH > 5 cm	Brown et al., 1989
8	$Y = \exp(-1.996+2.32\times\ln(D))$	x			dry transition to moist life zone (rainfall > 900 mm), DBH 5–40 cm	Brown, 1997
9	$Y = 10\wedge(-0.535+\log_{10}(\pi\times r^2))$	x			dry life zone (rainfall < 900 mm), DBH 3–30 cm	Brown, 1997
10	$Y = \exp(-2.134+2.530\times\ln(DBH))$	x			moist life zone (1500 mm < rainfall < 4000 mm), DBH < 80 cm	Brown, 1997

Fig. 8. Comparison of mean above ground biomass carbon estimates for ten pan-tropical allometric equations (1–10). *Y* is biomass (in kg), *D* stem diameter at breast height (cm), *H* tree height (m), *S* wood density (g cm^{-3}), and *r* stem radius. Estimates presented in large symbols are values especially representative of the forest ecosystem based on the life zone.

Ten commonly used pan-tropical allometric equations found in the literature (Brown et al., 1989; Brown, 1997; Luckman et al., 1997; Chave et al., 2005) were used to estimate mean AGB carbon stocks for the six forest ecosystems (paper III). These equations were developed for forests in wet, moist, or dry life zones and yield large variations in estimated AGB carbon stocks even within the same forest types. The choice and relationship of input variables (i.e. DBH, height, and wood density) influenced the carbon estimates shown in Fig. 8. Overall, allometric equations including only DBH tend to yield either higher or lower carbon stocks than do those equations also incorporating height and wood density.

AGB carbon stock in the sampled dry zone homegardens (paper V) range from 10–55 tC ha^{-1} with a mean value of 35 tC ha^{-1} (stdev 24) whereas carbon stock in the sampled wet zone homegardens range from 48–145 tC ha^{-1} with a mean value of 87 tC ha^{-1} (stdev 42). Tree density per hectare ranged from 338 in the dry zone homegardens and 2108 trees in wet zone home gardens which are reflected in the higher carbon stock estimates within the wet zone homegardens. The total carbon stock value in homegardens was 50 MtC (1992), 53 MtC (1996), 60 MtC (2005) and 63 MtC for 2010 (Fig. 9). It was shown that homegardens have an important share of carbon in the natural forest ecosystem, increasing from almost one sixth in 1992 to almost one fifth in 2010.

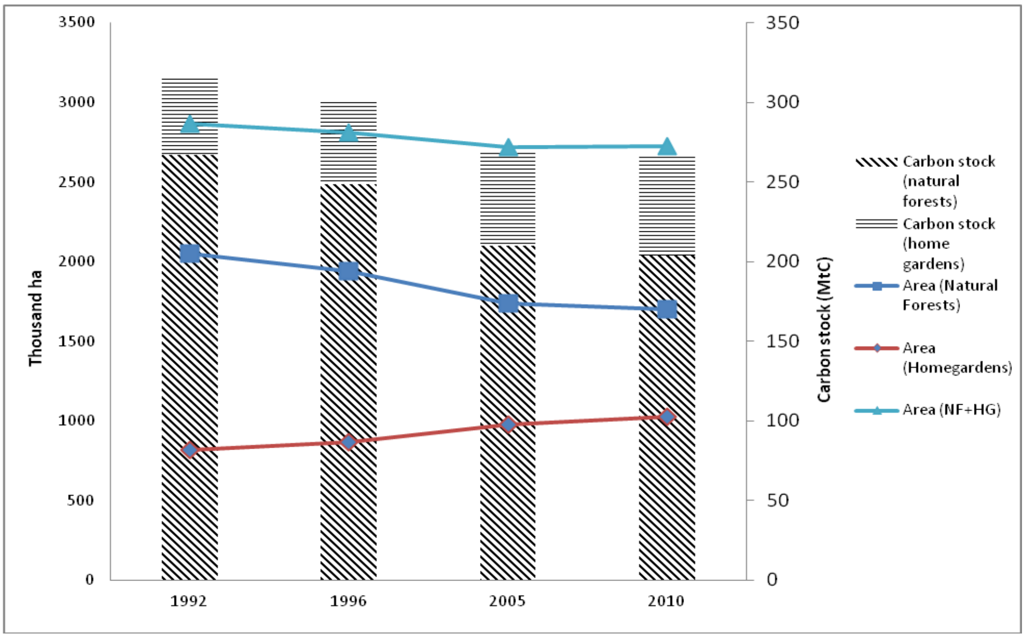


Fig. 9. Area change for homegardens, natural forests and total above ground biomass carbon content for homegardens and natural forests 1992–2010.

4.3. Participatory assessment

The main outcome (paper I) was the respondents feeling of vulnerability that the tsunami had caused even though present vegetation had mitigated the destruction of inland land use systems. People described the tsunami as having triggered demand for other land use practices, either by expanding present land uses or establishing new ones. However, lack of investment capital and land availability were seen as impediments to such changes. Given the results of the environmental assessment and tree measurements, coconut plantations appear to be the most suitable plantation option for A/R CDM establishment since they are important for livelihoods, the trees are salt tolerant and can grow on sandy soils and have a high carbon stock. Home gardens and *Casuarina equisetifolia* could also be considered appropriate options as they are multipurpose trees. However, the Casuarina has less beneficial attributes: it has poor copping ability, invasiveness and it is owned by the state, so may be less favorable for local communities. Mangrove rehabilitation is another alternative, and could potentially play a key role in terms of protection and improving environmental and human sustainability. On the other hand it was shown that carbon sequestration potential from mangroves is low and there are few potential places in the district where mangrove regeneration activities could be established.

Similar findings from the interviews in paper I, were made in paper IV, where lack of income constrained land users from expanding their land, although the major constraints were of a legal nature since many lived adjacent to the protected forest boundaries. As a result, about half of the respondents resorted to the natural forest to earn extra incomes. Cultivation of cash crops in high demand, predominantly tea and pepper, had increased in both study areas. However, demarcations of forest boundaries had restricted traditional land use practices, especially in Knuckles Conservation Forest, causing income reductions for many villagers and consequent emigration, which in turn allowed natural forest regeneration. Key informants in paper IV argued that forest boundary demarcation around the study areas had been successful in the sense that encroaching of forest and land illegal logging activities had reduced. Overall, institutional factors such as lack of policies, weak governance structures and lack of enforcement were underlying drivers that have caused forest cover loss in Sri Lanka. Land allocation for villagers was suggested as one future measure since rural communities would then have better incentives to look after their lands sustainably. Measures taken by the Forest Department in these areas included conservation through natural regeneration and afforestation activities which on the other hand generated little benefit for the local communities. Moreover, income activities such as non-timber forest products (NTFP) can provide an important source of income and thereby constitute an incentive for the participation of local communities in conservation activities.

4.4. Spatial analyses

Land use changes from 1984 until 2003 and 2010 were observed in both study areas, especially around Kanneliya Forest Reserve where the cultivation of tea or other land under cultivation has expanded into previously natural forest land with a resulting forest area decrease around all villages (paper IV).

In Knuckles Conservation Forest, the patterns in land use changes are more variable, resulting in forest decline around two villages and forest cover increase for two other villages (Fig. 10). Also, infrastructural development and household increase are observed in both study areas.

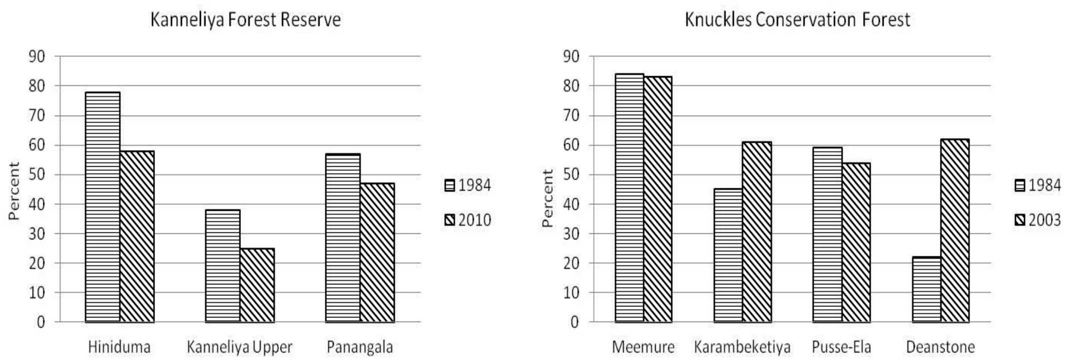


Fig. 10. Forest cover around three buffer zone villages in Kanneliya Forest Reserve 1984 and 2010 and in four buffer zone villages in Knuckles Conservation Forest 1984 and 2003.

5. DISCUSSION

5.1. Carbon offset potential

A/R CDM could potentially be established in Hambantota district in the form of tree plantations or homegardens, given the prospects for sustainable development in the area due to the multiple purposes of these land use systems and their potential in providing ecosystem services and protection. Also, with investments coming from an Annex 1 country, the barrier of investment costs, as expressed by interviewees, would be eliminated for the land users. Such activities may, however, be constrained by the small sizes of the land that each land owner possesses and could be cost ineffective since buyers may not be available for small carbon volumes. Chokkalingam and Vanniarachchy (2011a) report that the potential of A/R CDM is low in Sri Lanka. This is due to financial constraints as a result of small land areas in the country (by which is meant less than 200 hectares) of potential project developers or due to the fact that potential lands were reforested prior to the eligible start dates for A/R CDM projects (31 December, 1989). However, by aggregating or bundling land areas together in which several projects of the same and different sectors are brought together to form a single CDM project without the loss of the distinctive characteristics of each project activity, such projects would be more viable, although such methodologies have yet to be approved by the UNFCCC (UNFCCC, 2004; UNFCCC, 2012b). The increasing focus on REDD+ (as well as the voluntary offset markets) as a mitigation option could also be a viable alternative to generate income for the local land users in Hambantota district and for Sri Lanka in general, since surrounding natural forests can be protected while increasing the commercial value of forest plantations and homegardens. However, this requires secure tenure rights for the local communities if they are to gain from such a scheme. Also, homegardens are regarded as an agricultural system but may together with A/R CDM be folded into REDD+ as it develops. The assessment of homegardens in paper V shows the potential of using homegardens for future land use planning/strategies with its multiple benefits including carbon sequestration potential. In terms of rehabilitation of degraded lands, the incentives from carbon offset projects could be one viable option to explore further.

5.2. Hurdles for accurate assessment of forest carbon and characteristics

Based on the results in this thesis Sri Lanka's forest sector faces several challenges, not least in forest monitoring, reporting and verification. Even though the technical capacity and skills to initiate REDD+ exist within the scientific community and non-governmental organizations (NGOs) on a global scale, the lack of forest data and capacity to readily monitor changes in the last two decades pose a challenge to many developing countries like Sri Lanka. The average carbon stock of 120–130 tC ha^{-1} (paper II) was found to be lower than earlier IPCC-GPG Tier 1 estimates while a large carbon stock range was observed between forest types. Carbon density variations are therefore an outstanding methodological issue that could affect the level of quantified emission reductions and payments in a REDD+ system. More information on forest carbon stocks in suitable stratified uniform classes is therefore crucial for guiding the design and implementation of suitable mitigation policies.

As an integral part of future national forest inventories, a comprehensive biomass inventory is needed, covering all Sri Lankan forest ecosystems to assess the forest carbon stock, complemented by remote sensing to assess forest area changes. To be financially sustainable, such an assessment could also include parameters covering biological aspects and silvicultural parameters. This could give information that could be used to assess and pinpoint important areas for biodiversity and ecosystem protection, water table assessment as well as identifying areas where intensified agriculture and tree planting schemes could be promoted. Such an assessment would benefit by following generic guidelines (e.g. IPCC GPG; Penman et al., 2003) with improved accuracy towards higher tier levels as more information become available and would thus be more comparable between nations. Moreover, there are data and information challenges due to specific national environmental circumstances that have to be taken into account. This includes many different forest ecosystems and complex topography in the landscape, which makes it challenging to accurately estimate forest carbon stocks in situ. The AGB carbon is here estimated as being with the range 22–181 tC ha^{-1} (paper III), emphasizing a high diversity of AGB carbon stocks in natural forest ecosystems in Sri Lanka, with a very high variation of carbon stocks also within forest types despite statistical differences. To further evaluate the carbon stock potential in Sri Lankan forests, it would be useful to estimate the amount of carbon that could be stored in a forest i.e. the natural carbon carrying capacity (CCC) but with respect to anthropogenic land use activity suggesting an optimal manageable carbon carrying capacity. Additional research and data would be needed for such an approach, since the calculations are challenging and rely on empirical data (Mackey, 2008).

The structural characteristics of various forest types also showed that many forests are degraded due to environmental factors and human disturbance regimes. This implies further need for knowledge about the spatial variations of forest density. No conclusions can be drawn in this study as to which allometric equation best captures the actual AGB carbon stocks in Sri Lankan forests. However, given the large variation in structure between forest ecosystems and the fact that allometric equations including DBH yield both lower and higher AGB carbon estimates, attention should focus on differences in allometry and on calculating AGB carbon using the DBH, height, and wood density variables. Developing location-specific allometric relationships confined to the national or sub-national scale, subdivided into life zones or forest ecosystems, could be justified, as generalized pan-tropical equations may not adequately represent all forest types.

The degraded nature of many forest sites and large variation in biomass stocks and between forest types and districts open up for options such as nested approaches to implement REDD+ (Pedroni et al., 2009). Such an activity could include enhanced carbon sequestration at site-levels, but require suitable policy guidance, to address leakage and facilitate national monitoring (Chokkalingam and Vanniarachchy, 2011a).

5.3. Importance of participatory evaluation and management

This thesis demonstrates that it is important to consider participatory approaches, both in coastal management planning (as highlighted in paper I), and in forest management (as highlighted in paper IV). Land users and community members often have rich knowledge and are the direct users of the resources. Thus, involving and taking into account local communities' aspirations in decision making processes can provide avenues for sustainable management of local resources. Hence, with local ownership there is greater incentive to ensure long-term survival of resources (Chhatre and Agrawal, 2009). However, as was seen in paper IV, there is a lack of approaches to evaluate participatory forest management for many areas, and the dynamic role between top-down approaches and bottom-up approaches to assess sustainable forest management needs to be explored further.

With the possibility of new flows of money targeted for forest conservation, the role of participatory approaches could further be tested. REDD+ implementation will for example place new demands on national forest administrators. They will need to set up data for reference levels, elaborate carbon forest management plans and establish MRV at the national level. These demands will imply high costs for a national system where institutions at the state level system would have an advantage due to economies of scale, harmonization and streamlined organizations. These steps could further discourage decentralized forest governance with local participation (Phelps, 2010).

5.4. MRV limitations and challenges

Uncertainties abound in the methods used in papers I–III and V to estimate AGB carbon stocks. These include environmental parameters not accounted for, errors in inventory protocol, insufficient sampling, and omitting other forest carbon pools (roots, woody debris, litter and SOM). In addition, as found in paper III, carbon stocks depend on the allometric equation used, included variables, and adaptation to the specific life zone. Inconsistent methodologies used in earlier national forest inventories may also have resulted in uncertain forest area estimations which have also affected the accuracy of our results. However, using a standard methodology, integrating several approaches to establish a BAU reference level and estimating the costs and earnings in the context of REDD+ has never before been tested on Sri Lanka. Given the current policy development both internationally and in Sri Lanka it is important to analyze the prospects of REDD+ with available data and to highlight the present barriers and opportunities for formulating effective REDD+ policies.

One initial intention for parts of this thesis was to use Landsat imagery to map changes in forest cover on a national level from 1990–2000–2005 that could be used to give more accurate information on changes in forest cover changes used to construct a historical reference level. However, cloud cover coverage (often more than 15%) in all multi-date images as well as the abundance of mosaic land uses such as homegardens prevented this approach from being pursued with high accuracy and confidence. Hot-spot analyses of forest cover changes using high resolution images with complementary information from available historical land use maps as applied in paper IV are more straight forward. These approaches could be applied further to distinguish district level variations in forest area changes, and can be complemented with participatory approaches to assess drivers of forest cover changes.

Carbon mitigation instruments, such as REDD+, do not necessarily have to rely on the most advanced techniques in terms of remote sensing. It is crucial that any system to be used on a national level, with its specific natural circumstances, is based on available, feasible, reliable and transparent techniques and methods that can be used in any country with tropical forest and further be comparable between nations (GOFC-GOLD, 2009). On the other hand, Sri Lanka is a small country and start up costs setting up resources to use remote sensing might be high. Costs for setting up field inventories can be accomplished for relatively low costs since methodologies exist and personnel from e.g. academia or relevant ministries can be trained with relatively few resources. New remote sensing approaches (such as satellite LiDAR and radar) that have high accuracy and are designed specifically for vegetation structure measurements can however have a large role to play in coming years but is presently associated with high costs. Such estimations could be carried out on a pan-tropical level and serve as input for carbon density variations to be used for developing countries with small costs (Baccini et al., 2012).

As underscored in papers II and III the observer status in the UN-REDD programme could initiate and bring more capacity development and technical expertise to Sri Lanka. In addition a new forest map is currently being finalized by the Forest Department using 23.5 m resolution IRS (Indian Remote Sensing) images with ground truthing by district Forest Department forest officers. This information can yield new and accurate information on the national forest cover. In addition, updated biomass estimates and new information on land use and forestry sector has been finalized for the Second National Communication for submission to the UNFCCC but results are not yet available (Bandaratillake, 2011; Chokkalingam and Vanniarachchy, 2011a). This information can facilitate detailed follow up studies on this topic in a few years time as more consistent data will become available to allow more accurate estimates on Tier 3 level to estimate reference levels and the associated costs and earnings for REDD+ in Sri Lanka.

5.5. Way forward for Sri Lanka and tropical developing nations – REDDy or not?

The negotiations within UNFCCC on REDD+ will leave many important decisions about policies and measures for the implementation of REDD+ up to individual countries. Sri Lanka will likely have to set up a national-level monitoring and accounting system for carbon emissions or sequestration in forests in order to receive compensation for reductions below an agreed reference emission level. Paper II highlighted and identified such barriers and potentials and concluded that a large mitigation potential exists in the forestry sector with potential monetary gains to be made if implementation costs are kept low and if future carbon compensation levels exceed current carbon prices.

Although the causes of deforestation were addressed in paper II and IV, improved understanding of the primary and underlying drivers of deforestation on a sub-national scale is needed, especially given that recent reports have shown a decrease in forest cover for certain districts whereas other districts have experienced an increase in net forest cover (Ratnayake et al., 2002; Gunawardane et al., 2010). To assess and account for drivers of deforestation more information on macro and micro-economics is needed including in relation to commodity and input prices and agricultural operating costs as well as international trade. To further address principal and underlying drivers of forest loss, a multi stakeholder approach and coordination among ministries and organizations involved in land use decisions and implementation is needed.

Many institutional challenges lie ahead for the implementation of a possible REDD+ scheme. One challenge relates to a lack of financial resources and personnel, restricting monitoring and enforcement of protected areas as discussed in paper IV. The importance of forest conservation in Sri Lanka has resulted in ambitious forest laws, but these are weakly enforced due to low institutional capacity, also underlined in paper IV. These are barriers that require substantial coordination involving key stakeholders and local land users and where the role of a decentralized forest management should further be explored. Even though Sri Lanka is in a dynamic process and currently holds an active stance on issues relating to natural resource management, the Sri Lankan Government has yet to recognize the forestry sector as a potentially important element in its climate mitigation and adaptation strategy. In the second national communication to the UNFCCC reference to the forestry sector has a minor role in the overall climate change activities reported (Chokkalingam and Vanniarachchy, 2011a).

Previous international and national efforts to address and prevent deforestation failed mainly due to the fact that little attention was paid to weak forestry governance and threats outside the forestry sector (Lele et al., 2000; Sunderlin and Atmadja, 2009). REDD+ has emerged as an incentive for forest protection and improved forest management in the tropics. REDD+ contain new features and departures from earlier efforts in valuing forest carbon, payments will be based on performances, unprecedented money is involved, and some of failures of previous policies are taken into account. Many caveats however remain and there is a risk that mistakes from the past may nevertheless be repeated. Current REDD+ readiness plans do not sufficiently address political and economical drivers of deforestation and it is not clear how new money will yield planned results (Davis et al., 2009). Implications of the forest transition and how to address strengthened tenure rights are other concerns not yet properly addressed. In the end opposing political wills and social movements may determine the success or otherwise of REDD+ (Sunderlin and Atmadja, 2009).

Carbon mitigation strategies within the land use and forestry sector will require different approaches and activities from country to country due to different environmental conditions, land use management and political settings. Few one-size-fits-all solutions exist. Moreover, emission reductions within the LULUCF sector are not a solution to the overall problem with increasing levels of GHGs in the atmosphere. However, they can make an important contribution while countries agree on stricter targets on an international level to cut emissions stemming from fossil fuels.

6. CONCLUSIONS

The findings presented in this thesis can contribute to a better understanding of potential options and approaches that Sri Lanka can use to realize its climate change mitigation and adaptation potential in the land use and forestry sector. The results from this study have also highlighted some of the mechanisms behind tropical deforestation, for example the drivers and underlying causes of deforestation in Sri Lanka, especially at a local level. The methods used have brought evidence for monitoring forest carbon stocks and have provided input for methodological and technical issues experienced on the ground.

The following main conclusions can be drawn from this thesis:

- Land has recovered significantly after the tsunami event. Reforestation through planting of coconut trees or homegardens could be implemented under the ambit of afforestation and reforestation Clean Development Mechanism. This is due to their potential to contribute to sustainable development to local livelihoods and their multi-purpose role producing food, fibre and fuel, their carbon sequestration potential as well as the role they play in environmental protection (Papers I and V).

- From a national point of view, there is a large carbon mitigation potential in the forestry sector in Sri Lanka given that annual emissions from deforestation were 17 Mt CO_2 yr^{-1} between 1992 and 1996 and 12 MtCO_2 yr^{-1} between 1996 and 2010. This constitutes around half of the total CO_2 emissions in Sri Lanka (Paper II).

- Average above and below ground biomass carbon is 120–130 tC ha^{-1} in six Sri Lankan natural forest types, a lower uncertainty span than earlier IPCC Tier 1 estimates. On the other hand there is a large range in above ground biomass carbon stock between forest types (22–181 tC ha^{-1}) with a very high variation of carbon stocks also within forest types. This variation is due to the heterogeneity of forest ecosystems as well as different forest usage in the recent past causing variations in successions. Calculating carbon stock also depends heavily on the allometric equation used, included variables (where more variables yields more homogeneous results), and adaptation to the specific life zone (Papers II–III).

- Reference level development for REDD+ in Sri Lanka is hampered by erratic, few, and often incompatible forest inventories that lower the potential to describe past forest carbon content in a credible way. Accordingly, Sri Lanka needs further work and assistance in the form of technical advice and capacity-building for monitoring the nation's forest resource and the drivers of deforestation. The process is also likely to include synergies with other national development and environmental goals. In addition, taking into account local communities' aspirations and needs in decision making processes can provide avenues for sustainable management of local resources (Papers II–IV).

- Forest conservation policies have had a positive effect on forest cover through reduced encroachment and reduced illegal felling of timber in forests around the two protected forest areas; Kanneliya Forest Reserve and Knuckles Conservation Forest. Simultaneously the process has threatened the livelihoods of many local people around the forests. Involving local communities in forest management as in the case of Kanneliya Forest Reserve has likely been less detrimental for peripheral communities' livelihoods since they take part in the decision making processes, even though problems of population pressure and shortage of land occur (Paper IV).

7. FUTURE RESEARCH

A lot of progress has been made on methodological development in recent years with regard to measuring and monitoring carbon stocks under various land uses. However, as highlighted in this thesis, forestry data are lacking in many developing countries. For Sri Lanka, consistent long term field measurements with data parameters such as allometric equations, wood density, growth and regrowth patterns, volume tables, biomass expansion factors for tree species are often fragmented, do not exist, or if they do exist are not necessarily comparable. More research on developing sound inventory methods that include these parameters is needed. Pilot activities in different forest types and tenure regimes could give more information and experience in how to best address methodological challenges, to assess whether emissions reduction schemes are financially viable and if so how forest carbon emissions reductions can be achieved. Accounting for the drivers of change and the role of local communities in forest and land use management is more intricate and requires a multi-disciplinary approach incorporating knowledge from natural science, social science and economics. Integrated research is also important to improve understanding of the relationship between, e.g., forest cover change, agriculture, bioenergy demands and food security while delivering multiple benefits in terms of climate change adaptation and mitigation.

An ever-increasing demand from the developed and the developing world, especially for food and bioenergy requires large areas of lands for the production and will probably continue to be a major driver of forest loss. If more food and bioenergy is to be produced while keeping virgin forests intact, one solution that requires more attention is expanding farmland into degraded ecosystems. This type of expansion in combination of rehabilitation of degraded ecosystems would require more know-how and hence more investments into integrated research are needed. Also, more attention could be paid to agroforestry land use systems which combine trees and farming through intercropping while improving the carbon sequestration potential and providing important ecosystem services such as fuelwood supply and nitrogen fixing. These types of land uses are often located adjacent to or nested in natural forests. More research is required on integrating multiple land uses in a full carbon/landscape approach discussed under REDD++. An underlying need is also to integrate different sectors and break up the isolation between forest and agriculture.

Over the next year, the experiences from this thesis will be used for continued research in Sri Lanka. The idea is to examine which methods and approaches can be used to further investigate whether and how locally accepted land use systems can be extended spatially to serve multiple purposes, such as environmental protection, increased productivity, secured income and carbon sequestration. This project is intended to provide a better understanding of the different potential ways to reach sustainability in land use planning. By using local peoples' and stakeholders views on possible land uses, together with my own empirical research findings, it may be possible to establish better knowledge, higher land use based production and disaster management strategies for local communities. The expected outcome will include a first assessment of how multi-functional land uses could be allocated optimally according to land users' needs and how resources can be used in the most desirable way at the local level.

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