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The Potential of Reducing Emissions from Deforestation and Degradation (REDD) in Western Ghana

by

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Only when the last tree has died, the last river has been poisoned and the last fish has been caught will we realize that we cannot eat money.

Cree proverb

Abstract

Forest ecosystems are rich in carbon and deforestation is causing about 18 % of global anthropogenic greenhouse gas emissions. Therefore, strategies for reducing emissions from deforestation and degradation (REDD) are explored within the United Nations Framework Convention on Climate Change (UNFCCC) for mitigating climate change. Pilot activities have been initiated in Ghana and other tropical forest countries in order to test the implementation of strategies for REDD at the national and local level. This study explores the potential of REDD in Western Ghana by quantifying the carbon emissions from forest and land cover changes over a period of 21 years using Landsat images from 1986 and 2000 and ASTER images from 2007. The land cover of the satellite images was classified according to the FAO Land Cover Classification System (LCCS) using ground truth data for the classification of the ASTER image and data that was visually sampled within the satellite scenes for the classification of the Landsat images. The supervised Maximum Likelihood classification achieved an average producer's accuracy of 93.7 % for the class 'Forest'. The change detection revealed a deforestation rate of 2.6 % across the entire study site and 6.4 % outside forest reserves, leaving only 12 % of the land outside reserves with a mixture of old growth and secondary forests. Forest reserves cover around one third of the analysed region. There, the forest cover remained stable although degradation is reported to be common. This indicates that forest degradation could not be detected with the data and methodology that was used. The carbon content of the land cover classes was inferred from carbon values of similar land cover types in Ghana. During the period of 21 years the conservative estimate of the gross carbon emissions is 26.8 million tC (1.3 million tC per year) over a landscape of 700,000 ha. If deforestation can be stopped immediately about 7.8 million tC or 28.6 tCO_2 could be avoided outside reserves from being emitted over the next decade. Since degradation is a common process in- and outside forest reserves it is likely, that over the long term the potential of reducing emissions from degradation is greater than that of reducing emissions from deforestation. Within a smaller site (around 88,000 ha) the trend in land cover changes was found to be similar. Therefore, pilot projects at the small scale are relevant for informing the development of strategies at a large scale. For the implementation of REDD strategies it is recommended that activities should start as early as possible in order to save the last remaining forests outside reserves and forest reserves should be included in a national strategy. However, the equitable participation of local communities in the development of strategies for REDD is required for developing locally accepted strategies that take into account the rights of forest dependent people.

Zusammenfassung

Wälder sind Ökosysteme mit hoher Bedeutung für die Speicherung von Kohlenstoff und die weltweite Entwaldung verursacht circa 18 % der globalen anthropogenen Treibhausgasemissionen. Daher werden Strategien für die Reduzierung von Emissionen durch Entwaldung und Degradation [Reducing Emissions from Deforestation and Degradation (REDD)] innerhalb der Klimarahmenkonvention der Vereinten Nationen (UNFCCC) erörtert, um eine Voranschreiten des Klimawandels zu vermeiden. Um die Umsetzung von Strategien für REDD auf nationaler und lokaler Ebene zu testen wurden zahlreiche Pilotprojekte in Ghana und anderen tropischen Ländern initiiert. Diese Arbeit untersucht das Potential für REDD in Südwest-Ghana indem die Emissionen durch Veränderungen der Wald- und Landbedeckung über einen Zeitraum von 21 Jahren mittels Daten von Landsat für 1986 und 2000 und ASTER für 2007 untersucht wurden. Die Satellitenbilder wurde nach dem FAO System für die Klassifizierung von Landbedeckung [FAO Land Cover Classification System (LCCS)] klassifiziert. Für die Klassifikation der ASTER-Szene wurden Geländedaten erhoben, wogegen für die Landsat-Szenen eine visuelle Datenerhebung innerhalb der Szenen nötig war. Die überwachte Klassifikation nach dem Verfahren der 'Maximum Likelihood' erreichte eine durchschnittliche Produzentengenauigkeit von 93.7 % für die Klasse 'Wald'. Die Veränderungserkennung zeigte, dass die Waldfläche im Untersuchungsgebiet jährlich um 2.6 % und außerhalb der Reservate um 6.4 % abnahm. Nur 12 % der Fläche außerhalb von Reservaten ist mit einer Mischung aus altbestehenden Wald und Sekundärwald bedeckt. Reservate bedecken circa ein Drittel des untersuchten Gebietes. Dort blieb die Waldbedeckung stabil obwohl Degradation innerhalb von Reservaten verbreitet ist. Dies zeigt, dass Degradation nicht mit den verwendeten Daten und Methodik erkannt werden konnte. Der Kohlenstoffgehalt der Landbedeckungsklassen wurde von Messdaten ähnlicher Landbedeckungen in Ghana abgeleitet. Während eines Zeitraumes von 21 Jahren entstanden nach einer konservativen Berechnung Kohlenstoffemissionen von brutto 26.8 Mio. tC (1.3 Mio. tC pro Jahr) innerhalb einer Fläche von 700.000 ha. Würde die Entwaldung sofort gestoppt, könnten außerhalb der Reservate Emissionen von circa 7.8 Mio. tC oder 28.6 tCO_2 innerhalb der nächsten Dekade vermieden werden. Da Degradation ein weit verbreiteter Prozess innerhalb und außerhalb der Reservate ist kann erwartet werden, dass über lange Sicht die Reduzierung von Emissionen durch Degradation ein größeres Potential hat als die Reduzierung von Emissionen durch Entwaldung. Innerhalb eines kleineren Untersuchungsgebietes (circa 88.000 ha) wurde ein gleicher Trend in der Veränderung der Landbedeckung festgestellt. Daher sind Pilotprojekte in einem kleineren Gebiet relevant für die Entwicklung von Strategien auf größerer Ebene. Für die Implementierung von Strategien für REDD ist es empfohlen, dass Aktivitäten so bald wie möglich starten, um die verbleibenden Wälder außerhalb der Reservate zu schützen und Reservate sollten in eine nationale Strategie einbezogen werden. Bei der Entwicklung von Strategien für REDD ist jedoch eine gleichberechtigte Partizipation der lokalen Gemeinden notwendig, damit lokal akzeptierte Strategien entwickelt werden, welche die Rechte der vom Wald abhängigen Menschen einbeziehen.

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The lists of figures and tables contain a short version of the headings that are used in the figures and tables in the text.

List of Abbreviations

AFOLU	Agriculture, Forestry and Other Land Uses
ALOS	Advanced Land Observing Satellite
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATCOR	Atmospheric Correction and Haze Reduction
AVHRR	Advanced Very High Resolution Radiometer
AVNIR	Advanced Visible and Near Infrared Radiometer
C	Carbon
CBD	Convention on Biological Diversity
CDM	Clean Development Mechanism
COP	Conference of the Parties
CREMA	Community Resource Management Area
FAO	Food and Agricultural Organization of the United Nations
FCPF	Forest Carbon Partnership Facility
GCP	Ground Control Point
GPS	Global Positioning System
GSBA	Globally Significant Biodiversity Area
IDL/ENVI	The Environment for Visualizing Images
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
IUCN	International Union for Conservation of Nature
LC	Land Cover
LCCS	Land Cover Classification System
LIDAR	Light Detection and Ranging
LLS	Livelihoods and Landscapes Strategy
MODIS	Moderate Resolution Imaging Spectrometer
MW	Mega Watt
NGO	Non Governmental Organisation
NIR	Near Infrared
NTFP	Non-Timber Forest Product
OECD	Organisation for Economic Co-operation and Development
PALSAR	Phased Array Type L-band Synthetic Aperture Radar
RADAR	Radio Detection and Ranging
RED	Reducing Emissions from Deforestation in developing countries
REDD	Reducing Emissions from Deforestation and Degradation
ROI	Region of Interest
SPOT	Satellite Pour l'Observation de la Terre
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

1.1 Forests and Climate Change

Forest ecosystems are of great importance for human well-being. They provide important goods, such as timber, fuel wood, medicinal products and food, and also services which are of cultural, aesthetic and recreational value (Alcamo, 2003 and Shvidenko et al., 2005). Many of these services are sustained by the biodiversity of natural forests and tropical forests alone are a haven for at least half of the earth's species (Shvidenko et al., 2005). Beyond these provisioning services forests also play a crucial role in regulating the water cycle and climate at regional to global scale (Bonan, 2008). The evapotranspiration of water by forests contributes to the generation of precipitation, which cools the regional climate and provides freshwater for drinking and food production. In the global carbon cycle forests are an important carbon sink. In the 1990s the uptake of carbon dioxide by forests from the atmosphere was equivalent to around 33 % of anthropogenic carbon emissions from fossil fuel and land use change (Denman et al., 2007). Recent findings indicate that in old growth forests across the tropics the carbon uptake and storage in the aboveground biomass is increasing and this effect is possibly due to increasing levels of CO_2 concentrations in the atmosphere (Lewis et al., 2009). However, the loss of carbon to the atmosphere due to deforestation is estimated to contribute about 18 % to the global anthropogenic greenhouse gas emissions (Gullison et al., 2007 and Stern, 2008). This is more than from the global transport sector and represents the largest single category of carbon emission within developing countries. The majority is caused by the conversion of tropical forests and about 17 % of the emissions from land use change occur in Africa (Canadell et al., 2009).

Current greenhouse gas emissions are within the upper range of the emission scenarios projected by the Intergovernmental Panel on Climate Change (IPCC) and recent findings indicate that a warming by 2 °C is likely to be inevitable (Richardson et al., 2009). Such a warming would have serious negative impacts on ecosystems, their functions and society at large (Smith et al., 2009). There is the risk that with continued climate change tropical forests could turn from a carbon sink into a carbon source (Fischlin et al., 2007). Consequently, emission reductions are urgently needed within all sectors and reducing the emissions from deforestation and degradation (REDD) has become an important part of the negotiations under the United Nations Framework Convention on Climate Change (UNFCCC).

Within the Kyoto Protocol there are no incentives for reducing the emissions from deforestation in tropical forest countries. Only the Clean Development Mechanism (CDM) includes activities for afforestation and reforestation for carbon sequestration. However, strategies and mechanisms for REDD could become part of a follow-up agreement of the Kyoto Protocol, which is ending in 2012. One of the major challenges is to tackle the multiple causes of forest loss. The direct drivers of deforestation are often the expansion of agriculture due to the increasing demand for food by a growing population and the harvest of timber (Geist & Lambin, 2002). However, there are also underlying drivers such as weak forest governance that is leading to illegal logging (Geist & Lambin, 2002) and subsidies for biofuels in developed countries that cause the expansion of oil palm plantations (Spracken et al., 2008). In order to address the drivers and to achieve REDD concerted effort at the international, national and local level is required. Currently, pilot activities for identifying and implementing mechanisms for REDD are undertaken in numerous tropical forest countries, in order to inform the development of REDD strategies at the national and international level. One of the central mechanism that is discussed for REDD is to provide payments for the avoided carbon emissions from reduced deforestation and degradation. The carbon finance would come from the carbon market or a forest carbon fund. However, putting a price on forest carbon alone is likely to be insufficient to effectively address the complexity of the drivers of deforestation. Improving forest governance and reducing perverse incentives such as subsidies for biofuels can be even more effective. Furthermore, the livelihood of local communities often depend on the use of forests and the land around and they would be directly effected by strategies for REDD.

In order to identify a country's potential for REDD, the past changes in forest cover and related emissions need to be quantified in order to assess possible future emissions under business as usual. The use of remote sensing is the most convenient method since satellites have been recording the earth's land cover over the past decades and the archived data allow the analysis of past changes in forest cover (Brown et al., 2008). There are a number of satellite systems that record high resolution images that are suitable for a detailed and continuous monitoring of the earth's land cover. However, there are also limitations in the monitoring of forests and consequently the success of REDD strategies with remote sensing. While it is possible to identify deforestation with satellite images the monitoring and quantification of emissions from forest degradation with remote sensing remains to be a challenge. Furthermore, the frequent cloud cover in tropical forest regions is problematic for the monitoring of the land cover with satellites with optical sensors. Other satellite sensors and technology such as RADAR can be used for analysing the land cover independent of cloud cover, but their operation at a global scale is still limited (Brown et al., 2008).

Over the past Ghana has experienced a high loss of natural forests at annual rates of 2 % (FAO, 2007). Therefore, Ghana is one of the first countries that is developing pilot strategies for REDD which are financed by the World Bank's Forest Carbon Partnership Facility (FCPF). The implementation of REDD-strategies involves a number of methodological and political issues such as the monitoring of deforestation and degradation, the determination of an emission baseline from past emissions, and the provision of incentives for reducing deforestation through the improvement of forest governance and payments for forest carbon. There is the hope that payments for forest carbon will provide a market-based incentive which can economically out-compete the logging of forests for timber extraction and agricultural expansion. Furthermore, these payments may provide additional income for forest stakeholders in particular local communities.

This study has the aim to identify the potential for reducing emissions from deforestation and degradation (REDD) in Western Ghana. It is the hypothesis that the study site experienced a historical deforestation rate that is similar to the national deforestation rate. This would offer the opportunity to reduce future emissions from deforestation and degradation thus offering a great potential for REDD within the region. By using remote sensing the historic trend of deforestation and forest degradation and the related carbon emissions are analysed, and the extent to which future emissions from the loss of forests can be reduced is identified. Many REDD pilot activities are implemented at the project level within smaller sites but REDD strategies will have to be upscaled to the national level in order to effectively address the drivers of deforestation and to avoid leakage. Therefore, the trends in deforestation are analysed for a large region of interest (ROI) and compared with a smaller region, the so-called LLS site, where pilot activities for REDD are tested. It is expected that strategies for REDD and in particular payments for forest carbon can be an economically attractive option for forest conservation in Ghana.

1.2 The Development of REDD

The Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC) is the first international agreement for reducing greenhouse gas emissions for mitigating climate change and came into force in 2005. The industrial countries that ratified the Kyoto Protocol, the so-called Annex 1 countries, have agreed on targets to reduce their greenhouse gas emissions below the emission levels of 1990. This agreement is an important step toward concerted action for mitigating dangerous climate change. Due to the greater historical contribution of the industrial countries to global climate change compared to developing countries the principle of common but differentiated responsibilities is applied under the UNFCCC. Therefore, developing countries and emerging economies such as India and China do not need to meet any reduction targets under the Kyoto Protocol. However, since their emissions are growing and significantly contribute to global anthropogenic greenhouse gas emissions, the Clean Development Mechanism (CDM) has been included. Through the CDM industrialized countries can invest in projects that help to reduce greenhouse gas emissions in developing countries. It includes the installation of more energy efficient technologies but also reforestation and afforestation projects for carbon sequestration (UNFCCC, 2003).

One of the major shortcomings of the Kyoto Protocol is that there are no incentives for reducing the emissions deforestation, which are contributing about 18 % to the global anthropogenic greenhouse gas emissions (Gullison et al., 2007 and Stern, 2008). There have been proposals to include avoided deforestation projects under the CDM, but the Marrakesh accords exclude such kind of projects. The reason were concerns about (i) leakage, (ii) non-permanence, (iii) uncertainties in estimating avoided deforestation, and (iv) that it might reduce efforts by industrialized countries to reduce emissions from the use of fossil fuels (Schlamadinger et al., 2005). (i) Leakage describes the problem that projects for avoiding deforestation may cause a shift of the drivers for deforestation into other regions or countries and thereby only shift the process of deforestation and the emissions from one place to another. In order to avoid leakage within a country it is generally agreed that approaches for REDD should be implemented at the national level in contrast to the project-based approaches under the CDM. (ii) Non-permanence addresses the risk that a forest that has been assigned for avoided deforestation might be deforested in future due to natural or anthropogenic disturbances. In particular natural and anthropogenic forest fires are a threat to long-term carbon sequestration in forests. (iii) Uncertainties in quantifying the avoided emissions due to REDD strategies can be significant since the errors that occur in the quantification of historic emissions and in the projection of future emissions under a business-as-usual scenario sum up in the final estimate. (iv) There is also the concern that large amounts of cheap carbon credits from the reductions of emission from deforestation flood the international carbon market and undermine strategies for reducing emissions from the use of fossil fuels. As stated in the Stern Review on the economics of climate change (Stern, 2008): *"Curbing deforestation is a highly cost-effective way of reducing greenhouse gas emissions and has the potential to offer significant reductions fairly quickly."* Therefore, REDD could encourage industrialized countries to rather offset their emissions instead of reducing the consumption of fossil fuels and hamper investments in the development of green technologies.

Nevertheless, due to the significance of deforestation for global greenhouse gas emissions, Papua New Guinea and Costa Rica requested that "Reducing Emissions from Deforestation (RED) in developing countries and approaches to stimulate action" should be considered as a mechanism under a post-Kyoto agreement (UNFCCC, 2005). This was also supported by several other Parties under the UNFCCC. Therefore, this item was taken up on the agenda of the negotiations on climate change mitigation at the eleventh session of the conference of the Parties (COP) to the UNFCCC in Montreal in 2005 (UNFCCC, 2005). The negotiations continued over the following sessions leading to the decision in the Bali Road Map at COP 13 in Bali in 2007, that methods and options for reducing emissions from deforestation in developing countries should be explored (UNFCCC, 2007). This includes the support and development of institutional capacities, the transfer of technology for the monitoring and reporting of emissions from deforestation and forest degradation, and the demonstration of pilot activities. There is hope that an agreement can be reached at the UNFCCC COP 15 in Copenhagen in December 2009 and that REDD will become part of a post-Kyoto mechanism. Within the UNFCCC reducing emissions from deforestation in developing countries (RED) is the official term, but in order to stress the importance of forest degradation for reducing emissions from deforestation and degradation (REDD) is widely used.

In order to achieve a reduction in the loss of forests the strategies for REDD need to address the specific causes of deforestation and degradation. However, the drivers of deforestation and degradation are diverse and complex and have their origin at the international, national and local level. Often the expansion of agriculture is the direct driver for deforestation (Geist & Lambin, 2002) and the increase in prices for agricultural products is an important indirect driver (Angelsen & Kaimowitz, 1999). Therefore, the cost of avoiding deforestation will largely be determined by the income from other land uses such as cash crop production. The payments for REDD can only compete with other land uses if the income from carbon payments is higher than the income from alternative land uses. Therefore, the variability in the price of commodities such as food crops and biofuels will directly compete with REDD-payments.

Over the past commodity prices have experienced sharp increases and can out-compete payments for REDD. This is in particular true for the production of palm oil. In Malaysia the annual income from palm oil plantation is between US$ 3835 and US$ 9630 per ha compared to the lower income from carbon payments between US$ 614 and US$ 994 per ha (Butler et al., 2009). The increasing demand for biofuels is seen as a major cause for the currently high deforestation rates (OECD/FAO, 2007). Therefore, the trend in industrialised countries to subsidise the use of biofuels that are imported from tropical forest countries is counterproductive to the goal of protecting forests for climate change mitigation (Spracken et al., 2008). However, in areas where the land use is less lucrative, such as shifting cultivation in Cameroon, carbon payments of US$ 2.85 per tCO_2 could already provide an economic incentive for farmers to protect the forest (Bellassen & Gitz, 2008). In carbon rich peatland forests emissions could be avoided at costs as low as 0.1 US$ per tCO_2 (Spracken et al., 2008).

Currently, most of the carbon credits from the forest sector are traded on the voluntary carbon market outside the Kyoto Protocol, where the carbon price is significantly lower than on the compliance market (e.g. the EU carbon market). Within a compliance market there is a higher demand for carbon credits and therefore, a higher price than within the voluntary market. Therefore, it is expected that carbon payments for REDD will be higher if it is part of a compliance market within a post-Kyoto agreement under the UNFCCC. Furthermore, Payments for Ecosystem Services (PES), that also take into account other services such as the control of floods and erosion, the provisioning of freshwater and the conservation of biodiversity could help to increase the financial reward from forest conservation.

Not only agriculture but also logging for the production of timber is an important factor contributing to deforestation. In particular illegal logging due to poor forest governance and a lack in the enforcement of forest laws causes the overexploitation and destruction of forests. In Ghana, for example, there are laws for sustainable forest management but many of the forest reserves are heavily degraded due to overexploitation (Hawthorne & Abu-Juam, 1995). Therefore, improving forest governance, enforcing forest laws and building institutional capacities for sustainable forest management are crucial components of strategies for REDD.

Since REDD is likely to be based on a national approach the government will be a key stakeholder in the implementation of REDD strategies and also in the sharing of possible benefits. However, there are concerns that REDD can have negative consequences for forest dependent people and biodiversity. It is debated to what extent the local land users and indigenous people will actually be compensated for not practicing slash and burn agriculture. The forest dependent and indigenous people fear that they will lose access to the forest and the forest resources on which their livelihood depend. Thereby, REDD could marginalise indigenous and forest dependent people, threaten their livelihood, increase poverty and even create a potential for conflicts over the use of forests. Therefore, the rights of indigenous and forest dependent people over the use of forest resources, their equitable participation and the equitable sharing of benefits need to be taken into account in the development of REDD strategies.

There is also the risk that REDD could only take into account the value of carbon and neglect the biodiversity value of natural forests. Thereby, REDD could create a perverse incentive for expanding plantations of monocultural crops that may are of value for carbon sequestration but which could replace natural ecosystems with a high biodiversity value. Therefore, it is discussed within the negotiations that REDD should be based on sustainable forest management, but it is not defined to what extend this takes into account the social and ecological integrity of REDD. Agreements under other UN conventions, such as the UN Declaration on the Rights of Indigenous Peoples and those under the Convention on Biological Diversity (CBD) contain important regulations that are relevant for the equitable and sustainable management of forests and the conservation of biodiversity. However, there has not been any agreement yet to what extent these agreements will be included in REDD. Nevertheless, sustainability standards, reforms in forest governance and the improvement of the institutional capacities will be necessary in order to prevent possible negative consequences. If REDD is implemented in a sustainable and equitable manner it could help to generate additional income for forest dependent people, help to reduce poverty and promote the conservation of forests and biodiversity.

In response to the negotiations of a REDD strategy under the UNFCCC, countries and organisations are undertaking pilot activities in order to identify possible strategies for REDD and to inform the negotiation process. In accordance with the specific circumstances in each country and region appropriate incentives and mechanisms need to be developed and implemented. Besides building institutional capacities, the development of robust monitoring and verification systems for the accounting of emissions from deforestation and forest degradation is required. Thereby techniques such as remote sensing using aerial and satellite data for the monitoring of forests at the large scale but also on-the-ground measurements for the monitoring of gradual carbon loss from forest degradation need to be made operational at national and continental scale. Especially the monitoring of degradation is challenging since remote sensing alone can be insufficient to detect changes in the density and height of forest cover.

1.3 The Monitoring of REDD

The monitoring of forests is crucial in order to identify the historical and present changes in the extent of forest cover, its quality and carbon content, and to quantify related carbon dioxide emissions. This information is important for measuring the successfulness of REDD strategies and to determine possible carbon credits and payments. There has not been an agreement yet on how to exactly measure the emission reductions from REDD mechanisms. One possibility is to compare the emissions from deforestation and degradation of a historical reference period with the emissions from deforestation and degradation within a following period. This could be done by determining a reference forest cover area, called benchmark forest area map, at a certain historical point in time as reference level and monitor the actual changes over a certain following period. Another more complicated approach is to model a business-as-usual scenario for the emissions from deforestation and degradation based on the trend in emissions of a historical reference period, and to compare the business-as-usual scenario with the actual monitored emissions from deforestation and degradation. The changes in land cover and the related carbon emissions will be reported as gross changes for the entire country in order to account for the emissions from deforestation and degradation at the national level (Brown et al., 2008).

In order to achieve consistency and credibility in the monitoring of REDD at a global scale there needs to be an agreement on a general methodological approach. A standardised definition of deforestation and degradation is important for ensuring the comparability of land cover classifications between regions and countries from which land cover changes and resulting emissions are derived. A consistent approach requires to determine changes in emission trends by comparing a reference period with the actual development of emissions from forest cover changes. Thereby, uncertainties that are inherent in the several steps of quantifying emissions need to be taken into account, in order to provide a measure for the reliability of the emission estimates.

In general, deforestation describes the permanent or long-term conversion of a forested land cover to a non-forested land cover. Non-forested land can still include trees but the forest cover is below a certain threshold and the definition of the threshold can vary between countries (Brown et al., 2008). A decline in the forest cover, forest quality, or biomass and carbon content above the defined threshold of non-forested land can be defined as forest degradation. However, there is no standardised definition for forest degradation (Brown et al., 2008). Inconsistencies in the definition can cause discrepancies in quantifying deforestation and forest degradation and consequently in quantifying carbon emissions.

A thematic classification of the land cover in situ, within land cover maps and in remote sensing images allows to detect changes and modification in the land cover and its carbon content over time. The FAO Land Cover Classification System (LCCS) was developed in order to provide an objective classification of the land cover that can be applied at a global scale (Jansen & Di Gregorio, 2002 and Di Gregorio & Jansen, 2005). It is based on measurable parameters such as the percentage of vegetation cover and vegetation height which allow an objective description of the land cover. It is independent of names for land cover classes since names can be an insufficient class descriptor which is often not based on consistent criteria (Di Gregorio & Jansen, 1998). For example the class name 'Forest' in Europe can be applied for a very different forest ecosystem with different tree height and cover than the class 'Forest' in the tropics, whereas in regions with similar vegetation types the differences in language and culture can lead to different names for the same vegetation type. The FAO LCCS follows a hierarchical system that has eight major land cover characteristics at its highest level differentiating the land cover in (semi-) natural vegetation and cultivated areas, terrestrial and aquatic vegetation, artificial and bare areas, and in natural and artificial waterbodies, snow and ice. The parameters are the classifiers that are tailored to these categories and thereby provide a specific description for each class which also allows back tracking of the originally recorded parameters. The land cover parameters can be sampled in the field, in remote sensing images or by translating other land cover classifications. For ensuring consistency in recording of the land cover parameters the sampling is guided by the hierarchical LCCS protocol. However, the variability of the biomass content within a defined land cover class is often high causing uncertainties in the estimation of carbon emissions. Furthermore, there are uncertainties involved in the several steps from the visual sampling of the ground truth parameters for the land cover classification to the processing of the classification.

For the monitoring of deforestation and forest degradation different methods can be used. Remote sensing using satellite and aerial images allow the quantification of forest cover and deforestation over large areas from local to global scale (Goetz et al., 2009). Landsat satellites have been operating since 1972 with a global coverage making the Landsat archive the most comprehensive remote sensing data source for the global land cover (Jensen, 2007). Therefore, Landsat is the primary data source for analysing historic forest cover changes and since Landsat images are free of charge, it is also cost efficient.

For the purpose of REDD the resolution of Landsat images of 30 x 30 m is sufficient for monitoring deforestation but it is useful only to a limited extent for monitoring forest degradation (Brown et al., 2008). Asner et al. (2005) combined Landsat with MODIS data and together with a great amount of ground truth data the extent of selective logging in a large area within the Amazon could be quantified. The estimates showed that forest degradation caused by selective logging can considerably contribute to the carbon loss from forests (Asner et al., 2005). Since 2003 the Scan Line Corrector (SLC) in the Enhanced Thematic Mapper Plus (ETM+) of Landsat 7 has failed causing a partial lack of data in each Landsat image. Therefore, alternative sensors will have to be used for the future monitoring of the forest cover. For a more detailed analysis of deforestation and degradation satellite data with higher resolution, such as SPOT (2.5 to 20 m), ASTER (15 to 90 m), AVNIR (10 m), IKONOS (1 to 4 m), and QuickBird ($< 1\,m$), would be a better option compared to Landsat. However, the products of these systems are more costly and limited in their global coverage. While SPOT and ASTER can be used for mapping deforestation and quantifying changes in forest cover over larger areas, the products of IKONOS and QuickBird have a very limited coverage, are very expensive and are therefore only useful for validating the mapping of deforestation. With AVNIR the degraded state of forests can be detected up to two years after the impact of selective logging (Hirschmugl et al., 2009). Thereafter, the regenerated vegetation makes a differentiation more difficult, while the forest has by no means recovered and remains a degraded forest compared to the state before the logging. Therefore, the assessment of forest quality, its state of degradation and the related carbon content still requires extensive information from ground surveys and sampling. This can considerably increase the need for resources for the monitoring of REDD, depending on the detail to which forest degradation will have to be monitored.

The aforementioned satellite products have in common that they are passive optical systems which record the part of the incoming electromagnetic radiation from the sun which is reflected from the earth surface and the atmosphere back into space. The biophysical characteristics of the land cover determine the degree to which the incoming radiation is absorbed, reflected back into space and measured by the sensors in the satellite (Jensen, 2007). For example, the wavelengths and the depth to which electromagnetic radiation is absorbed by vegetation is different from the absorption of bare ground and thereby, these two land-cover types can be easily distinguished by multispectral remote sensing. Also, different vegetation types e. g. grassland and forests, and different states of the same vegetation type, e.g. forest under water stress and forest without stress can be distinguished. However, the more similar the reflected spectra of different vegetation types are the more difficult it is to distinguish these by remote sensing. This is in particular the case for identifying different stages of forest degradation, since the differences within the reflected spectra are often too small.

While multispectral remote sensing systems allow a wide range of applications in earth observation it also has considerable drawbacks concerning the monitoring of the land cover. The reflected and recorded spectra can be negatively influenced by atmospheric particles and clouds, which can cause disturbances to the reflected spectral signal from the earth surface (Jensen, 2007). In moist tropical regions the common and frequent cloud cover can limit the use of multispectral remote sensing sensors for the monitoring of the land cover. In particular over the vast areas of tropical forests around the equator, such as the Amazon and the Congo basin, cloud free remote sensing data can often only be recorded during short cloud free periods of the dry season. Another limitation of multispectral remote sensing data is that the reflectance provides little information on the characteristics of the land cover below the canopy such as tree height and the structure of the under story. This limits in particular the monitoring of forest degradation and related carbon content.

There is hope that the shortcomings of the passive remote sensing systems can be resolved by the use of active remote sensing systems, which send electromagnetic energy, such as short-wavelength laser light in the case of LIDAR or microwaves (RADAR) in the case of ALOS, to the earth surface and record the reflected signal (Jensen, 2007 and Kellndorfer et al., 2007). The advantage is that the microwaves of the active systems can penetrate the cloud cover and allow the monitoring of the vegetation cover independent of cloud conditions. To a certain extend the microwaves also provide information on the characteristics of the vegetation structure below the forest cover. However, this technology is still under development (e.g. Hirschmugl et al., 2009) and its use on a national or global scale is still limited. Therefore, the passive multispectral sensors will remain to be the first choice for the monitoring of REDD within the near future, since they are already operating at a global scale and provide a data base for the historical forest cover. Nevertheless, optical and passive remote sensing systems can complement each other and combining both systems in the analysis of land cover and carbon stocks can help to reduce the uncertainties that are involved when only one system is used.

The quantification of emission reduction through REDD strategies needs to be reliable and comparable at the global level. The IPCC guidelines for reporting emissions from Agriculture, Forestry and Other Land Uses (AFOLU, Aalde et al.) provide standards that could be applied for the monitoring of REDD. The IPCC guidelines require emission estimates to be transparent and consistent in the methodology and data, complete and comparable to other estimates, and accurate (Grassi et al., 2008). However, each step in estimating forest cover changes and related emissions involve a number of uncertainties: incomplete historical information on the forest cover and its carbon content during the reference period; errors in the land cover classification; errors in the estimation of historical and actual land cover changes; uncertainties in quantifying the emission reductions by the difference between the historical emissions, the predicted business-as-usual scenario and the actual monitored emissions. This can in particular be challenging for the quantification of emissions from forest degradation for which detailed on-the-ground monitoring data of the carbon content is required. In order to reduce uncertainties in the estimates of the avoided emissions by REDD, it is suggested to use the principles of conservativeness as it already exists within the IPCC guidelines (Grassi et al., 2008). In particular it is important to avoid an overestimation of emission reductions which would only create "hot air" but no real emission reductions. This can be achieved by using the lowest estimates within the range of the carbon content of forests in the reference period, and by comparing these with the highest estimates for the forest carbon content in the monitoring period (Mollicone et al., 2007). Carbon pools with high uncertainties, such as soils, may need to be excluded from emission accounting (Mollicone et al., 2007 and Brown et al., 2008).

For estimating the loss of carbon from deforestation Ramankutty et al. (2007) point out that besides the accuracy of estimates for biomass and the spatial resolution of the satellite data also land-cover dynamics that follow deforestation, which include the clearing of secondary vegetation, the decay of slash and forest products and the carbon flux of regrowing forest, are of importance for the carbon balance. Thereby, it is crucial to differentiate between the amount of carbon that is immediately released from biomass burning and the carbon in pools of slowly decaying biomass. It is suggested that the historical land-cover changes need to be taken into account over a period of at least 20 years.

The IPCC guidelines for reporting emissions from AFOLU provide different levels of detail for the reporting of emissions, the so-called Tiers (Aalde et al., 2006). According to the technical capacity and resources of each country to monitor REDD, different reporting levels could be chosen in order to allow a broad participation of countries with different capacities. Tier 1 is the simplest method with average national estimates for forest carbon content and the assumption that the entire forest carbon is emitted when deforestation occurs. Tier 2 includes regional specific and up-to date estimates of the forest carbon content. Tier 3 requires more detailed carbon measurements on the ground, which need to be repeatedly monitored in permanent plots. Also the fade of carbon is differentiated in different carbon pools such as direct losses to the atmosphere and storage in deadwood and soil. It is likely that Tier 1 and Tier 2 approaches will be more applicable for the national accounting in tropical forest countries because the need for data and capacity is significantly higher for Tier 3 than for Tier 1 and 2.

Goetz et al. (2009) suggest that the ambiguities and uncertainties involved in generating thematic maps of the land cover can be avoided by directly mapping the carbon stocks of the land cover. Such a carbon stock approach is directly linked with the dynamics in the biomass and is independent of land cover classifications. A direct remote sensing approach without the assignment of classes also provides a higher resolution of the map with a greater detail for monitoring the carbon dynamics of the land cover. Although it requires detailed data on the carbon content of the different land cover types the accuracy that could be achieved would allow the reporting of emissions according to Tier 2 or even Tier 3 under the IPCC guidelines (Aalde et al., 2006).

Independent of the methodology that is used, consistency in land cover classification and in the estimation of the carbon balance across space and time is required for the development of reliable monitoring systems for REDD. Accuracy and credibility is in particular important when it comes to the monetary compensation for avoided carbon emissions from reduced deforestation.

1.4 The Forest of West Africa

1.4.1 Climate

The coast line of West Africa is under the influence of the intertropical convergence zone (ITCZ). During the boreal summer, when the ITCZ is positioned north, cool and moist maritime, southwestern monsoon winds from the Atlantic and Gulf of Guinea bring high rainfalls across the coastal and inland regions. Consequently the western region of Upper Guinea with the more north-west directed coastline receives the highest precipitation with more than $3500\,mm\,a^{-1}$. When the ITCZ is moving southwards during the second half of the year, northeastern winds from the Sahara, also known as Harmattan, bring dry air and cause the decline in precipitation. The dry season is most pronounced from December to March. The monthly temperature varies between 24 to 28 °C (Poorter et al., 2004).

Past climate variability caused changing precipitation patterns in the Upper Guinean region and thereby shifts in the distribution of forests. The last major shifts occurred since the last cold period with major glaciation of the polar region about 18,000 years ago. At that time the Upper Guinean rainforest was reduced to some forest refuges in Liberia and southern Ghana (Hamilton, 1976 and Maley, 1996). Thereafter, the forests expanded with increasing warming temperatures and reached their maximum range, which was much larger than the present range, about 6000 years ago. At that time the Dahomey gap did not exist and the Upper and Lower Guinean forests where connected. Humans modify the landscapes of the Upper Guinean forest zone for a long time. Already back in the 16^{th} century the first Europeans that travelled Western Africa reported a large population and extensive farming activities (Poorter et al., 2004). However, since the beginning of the 20^{th} century forest loss has increased due to unsustainable farming practices, logging and rising population densities. In particular, the past five decades have seen a dramatic loss of forests linked to the harvest of timber for domestic use and export as well as to the production of cash crops, mainly cocoa, for export (Chatelaine et al., 2004).

Climate models indicate that the regional climate in Africa is strongly influenced by land cover characteristics (Paeth et al., 2009). Land cover changes, in particular deforestation, can cause greater changes in the regional climate in Africa than global climate change caused by greenhouse gas emission (Paeth et al., 2009). The degradation and loss of forest cover is changing the land surface properties (e.g. albedo) causing the increase in surface temperature and the weakening of the regional water cycle due to decreasing evapotranspiration. Both effects are projected to enhance the heat stress and to extend dry spells over most of tropical Africa if deforestation and forest degradation continues (Paeth et al., 2009). This stresses the importance of forest conservation and sustainable forest management for mitigating climate change not only at the global but also at the regional scale. It also indicates that healthy forest ecosystems are important buffers for reducing the impact of unavoidable global climate change and for helping forest dependent people to adapt to climate change. Global climate models with a more coarse resolution than the regional climate model identify the West African Monsoon as one of the critical tipping points in the earth system that can shift within a short time if global warming increases by 3 to 5 °C (Lenton et al., 2008). This shift is expected to increase precipitation over West Africa leading to an expansion of the vegetation zones northwards with the potential of greening the Sahara. This would be one of the few positive examples of the impact of global climate change. However, besides the parameters that govern the global climate, such as sea surface temperature and circulation patterns, the influence of regional factors, such as the vegetation cover, need further investigation in order to develop more reliable projections at the regional scale (Paeth et al., 2009).

1.4.2 Biogeography

The tropical forests of West Africa belong to the Upper Guinean forest and stretch along the coast from Togo in the East to Senegal in the West. The Upper Guinean forests are separated from the Lower Guinea and Congolian forests of Central Africa by the Dahomey gap which is a region with woodland savanna of the Sahel that reaches to the coasts of the Gulf of Guinea in Eastern Ghana, Togo and Benin (Poorter et al., 2004).

Due to its isolation from other forest regions the Upper Guinean forest harbours a large number of endemic animal and plant species (Hall & Swaine, 1981 and Brooks et al., 2001) which qualifies the region as one of the world's biodiversity hotspots (Meyers et al., 2000). The Upper Guinean forest contains about 2800 vascular plant species of which 650 species (23 %) are endemic and 400 species are considered to be rare (Jongkind, 2004). The largest tracts of continuous old growth forests are remaining in the region of Liberia and Western Côte d'Ivoire. The greatest threat to biodiversity is the degradation and fragmentation of habitats through deforestation, which has caused a dramatic decline in the original forest cover since the 19^{th} century. The biogeography of the forests in Ghana is described in more detail in the following section.

1.5 The Forest of Ghana

The moist and dry tropical forests of Ghana are situated in the south and west of the country within the so-called high forest zone. The central and northern areas are savanna and cover about two thirds of the country.

The west of Ghana receives higher rainfalls during the boreal summer ranging between 2000 and 2500 $mm\,a^{-1}$. The rainfall decreases along the coast toward the east with 900 $mm\,a^{-1}$ in Accra, the capital of Ghana. The reason is the north-eastern direction of the coastline toward Eastern Ghana causing it to be less exposed to the moist western monsoon winds. Additionally a cold up-welling ocean current before the eastern coast of Ghana causes lower surface air temperatures and reduces the convective uplift of air. Therefore, the air masses that reach the eastern part of Ghana decrease in their content of air moisture, causing the Dahomey gap, a dry savanna area between the moist forests in Ghana and Nigeria (Hayward & Ogantoyinbo, 1987 and Poorter et al., 2004).

There is a strong gradient in rainfall from the coast toward inland which determines the gradient in vegetation from wet rainforest in the southwest to dry savanna in the north (Poorter et al., 2004). The south-western areas with precipitation of more than 1750 $mm\,a^{-1}$ are the ecological range of wet evergreen forests with a canopy height of 30 m. The regions with a precipitation of 1500 to 1750 $mm\,a^{-1}$ are naturally covered by moist evergreen forests with a height of up to 40 m but with less species than the wet evergreen forests. Moist semi-deciduous forests occur in areas with 1250 to 1750 $mm\,a^{-1}$ rainfall and have the tallest tree height of up to 50 m. This forest type has less species than the former two forest types but has the highest density of commercial tree species. This is followed by the dry-semi deciduous forest which occurs between 1250 and 1500 $mm\,a^{-1}$ and has an open canopy with a height of 30 to 45 m. The forest savanna boundary generally coincides with the isohyet of 1200 $mm\,a^{-1}$. However, there are also some exceptions in southern and eastern marginal regions with an annual precipitation below 1250 $mm\,a^{-1}$, where forests with a thick under story and a canopy height below 30 to 15 *m* occur.

The earliest estimate of the forest cover in Ghana is for the year 1912 with a forest area of 5,830,000 *ha* (Chevalier, 1920). The most recent estimate gives a forest area of 5,517,000 *ha*, which includes forest plantations and is corresponding to 24.2 % of the area of Ghana (FAO, 2005 and FAO, 2007). According to these figures there would have been only a small decrease in forest cover during the 20^{th} century. However, there are also large variations in other estimates ranging from 1,710,000 *ha* of closed forest in 1980 FAO & UNEP (1981) to 9,608,000 *ha* of forest in 1990 (Odoom, 1999). The comparability of these figures is partly limited due to differences in the definition of "*closed*", "*original*" or "*primary*" forests and whether plantations are included as forests or not. Therefore, these estimates do not allow a qualitative assessment of the forest cover with regards to carbon content or biodiversity. "*Primary*" or old growth forests with a high carbon content and rich biodiversity could be replaced by plantations and agroforests with smaller carbon content and less biodiversity, but would still qualify as forest under the definition of the FAO. This is likely to be the case for the most recent estimate of the forest cover by the FAO. Although the FAO estimate is similar to the forest cover from 1912, it is very likely that today a great part of the forest cover is comprised of plantations. In 1980‘s the slash and burn practice caused 70 % of the deforestation (Agyarko, 2001) and 50 % of the timber harvest originated from off-reserve forests. This increased to 80 % in the 1990‘s (Kotey et al., 1998) and lead to an annual deforestation rate outside the reserves of up to 5 % (Ghana National Communication to the UNFCCC, 2000). The annual deforestation rate for the entire country is 2 % for the period 1990 to 2005 (FAO, 2007).The degradation and fragmentation of forests is difficult to measure and requires extensive field surveys. Therefore, it is usually not included in the statistics although these processes are of significance as shown for Ghana (Hawthorne & Abu-Juam, 1995) and Côte d'Ivoire (Chatelaine et al., 2004).

There are 216 state-managed forest reserves in the high forest zone of Ghana that comprise an area of 1.6 million *ha* of which 22 % is under permanent conservation and the remaining part is assigned for timber production (Agyarko, 2001). The forest reserves are divided into concessions of the size of 128 *ha* and within the areas of timber production logging takes place in 40 years rotation cycles (Samartex Timber and Plywood Company Ltd., pers. comm.). The selective logging is reported and monitored by the governmental Ghana Forest Service Devision. However, despite this strategy for a sustainable management of the forests many of the reserves are degraded due to overexploitation and agricultural expansion (Hawthorne & Abu-Juam, 1995 and Osafo, 2005).

2 Study Site

The study site is in the western region of Ghana at the border to Côte d'Ivoire (6°20'0"N and 2°10'0"W to 5°20'0"N and 2°50'0"W, Figure 1). It was selected due to its forest rich vegetation, which makes it in particular relevant for REDD. The site stretches along a south-north gradient in precipitation and vegetation: from 2000 to 2500 mm rainfall per year and wet evergreen forests in the south, to 1500 to 1750 mm rainfall per year and moist evergreen forests in the north (Poorter et al., 2004).

The region of interest (ROI) is situated within the Wasa Amenfi West District that covers an area of 34,646 km^2 with a population of 156,260 inhabitants (Wassa Amenfi West District Report 2005, unpublished). The annual population growth is 3.2 % for the period 1994 to 2000. During the 20^{th} century, and especially since the 1960s, farmers from the north and east of Ghana but also from Togo and Burkina Faso have migrated into the district mainly for growing cocoa. Consequently, the area under agricultural production increased on the expense of the natural forest (Akrofi, pers. comm.). Settlers are given land from the indigenous chiefs and half of the area, which the farmers cultivate within the first six years is returned to the chief. The other half is kept by the farmer for an often undefined period which can cause a lack of clarity in land tenure rights. The authority of the indigenous chiefs and their ownership of the land is widely accepted by the civil society and until today the chiefs have the power for designating land to farmers. Even though farmers can own land the natural resources on the land and in the ground remain in the ownership of the Ghanaian government. Due to the growing population the pressure on the remaining forested land outside and inside reserves is increasing.

Today, old growth forest outside the reserves is only found in smaller patches on steep hills and as sacred forests near communities. Outside the reserves agroforests of cocoa (*Theobroma cacao*) that are partly covered by shade trees are the dominating land use. Plantations of rubber (*Hevea brasiliensis*), teak (*Tectona grandis*), cola (*Cola ssp.*) and oil palm (*Elaeis guineensis*) are also found in the region but are less abundant. For local consumption cassava (*Manihot esculenta*), plantain (*Musa ssp.*), corn (*Zea mays*), rice (*Oryza ssp.*), pineapple (*Ananas comosus*) and avocado (*Persea americana*) are grown within the cocoa plantations and on newly cleared and cultivated land. Farmers also collect NTFPs such as the fruits of the native Allenblackia palm (*Allenblackia parviflora*) which are used for the production of palm oil. Within the agroforests there are also large shade trees and patches of secondary forests. These, however, are more frequent closer to the forest reserves and less abundant in the more intensely managed agroforest systems further away from forest reserves. Due to the decrease in forests outside the reserves logging companies also extract trees from farmlands causing damage to the crops. The compensation is often not adequate and therefore, farmers are encouraged to clear larger trees on their farm before planting crops. This trend is also promoted by new cocoa hybrids that need less shade and therefore the abundance of shade trees within the farmland is declining. In addition, the old growth forests and naturally grown trees are state owned

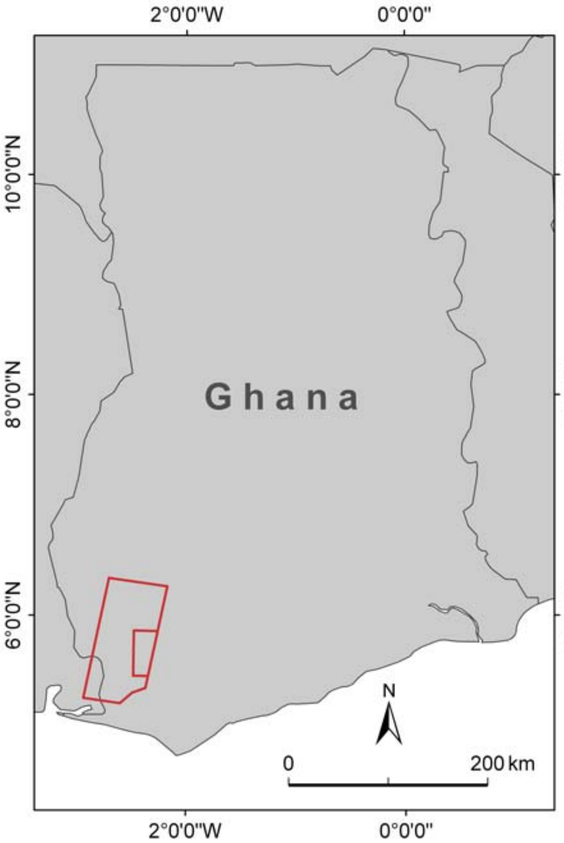


Figure 1: The study site in W-Ghana with the regions of interest (ROI): Land cover (LC) and LC changes were analyzed for the years 1986, 2000 and 2007 for both, the large ROI and the smaller LLS site, in order to test whether the LC changes within a smaller area are representative for a larger region.

resources and the farmers do not have the right to commercially exploit the timber on their land (Osafo, 2005). The lack of property rights over the natural forest discourages farmers from practicing sustainable forest management, since they cannot get income except by clearing the forest and planting cash crops and commercial tree species for the production of NTFPs and timber.

Within the study site the International Union for Conservation of Nature (IUCN) is implementing its Livelihoods and Landscapes Strategy (LLS) (Figure 1). The initiative is aiming at identifying the causes of rural poverty and the loss of forests and to develop strategies that reverse the trends in deforestation in order to improve the livelihoods of forest dependent people and maintain the region's biodiversity. Thereby, IUCN is investigating options for sustainable forest management and forest conservation, which are relevant for REDD. Strategies are explored that improve forest governance and promote the sustainable use of forest resources with the aim of improving people's livelihoods. This also includes the analysis of the socio-economic impact of carbon payments from REDD and whether these can provide an attractive alternative to deforestation and cash crop production (Sandker et al., submitted). Alternative land uses instead of monocultural cash crop production can be a promising option for reducing deforestation since Chatelaine et al. (2004) found that deforestation in Côte d'Ivoire is linked to the type of land use rather than to population density. In areas with traditional land use the forest cover remained stable over the past decades while most of the deforestation occurred in areas with agricultural expansion for cash crop production. The LLS initiative is supporting the already ongoing efforts by the communities to establish a Community Resource Management Area (CREMA) which has the aim to diversify the land use and protect the rich biodiversity of the area. This includes the plantation of a range of native tree species for the production of non-timber forest products (NTFPs) but also for the use of timber.

The southern part of the ROI includes the parts of the Ankasa Reserve which is close to the former refuge for biodiversity during the last ice age at Cape Three Point and represents an important area for the protection of biodiversity within the Upper Guinean rainforest (Wieringa & Poorter, 2004). Within the forest reserves of the LLS site Oates (2006) found nests of chimpanzees in the northern part of the Mamiri Forest Reserve, which is partly under protection as a Globally Significant Biodiversity Area (GSBA). Further populations are also in the Bura and Fure Headwater forest reserves. In 1995 the condition of the two reserves was described to be "*good*" or "*partly degraded*" (Hawthorne & Abu-Juam, 1995). The Mamiri Forest Reserve is described as "*degraded*" and poaching being a common practice (Oates, 2006). According to information provided by Samartex Timber and Plywood Company Ltd. (pers. comm.) some of the concessions in the reserves will be selectively logged over the next decade starting in 2011. Despite the great species potential of the region the sampling intensity has been low over the past, indicating that the flora and fauna of the region very likely harbours unknown species (Wieringa & Poorter, 2004). Many of the known endemic species are endangered or threatened due to deforestation. This includes the chimpanzees (*Pan troglodytes*) which are one of the more prominent threatened species of the forests in Western Ghana (IUCN, 2008).

Deforestation and degradation was analysed for the large region of interest (ROI) and the smaller LLS site, in order to identify, whether the processes and trends within the smaller pilot site are representative for the larger region. This information is important since many REDD pilot activities are taking place within smaller regions but activities for REDD will have to be upscaled to the national level in order to be effective.

3 Materials and Methods

3.1 Data

For analysing the potential of REDD in Western Ghana the historical rate of deforestation is estimated for the past 21 years using remote sensing data (Table 1). Landsat scenes for the years 1986 and 2000 were chosen since they were almost the only available cloud free images of the region with a resolution that is high enough for the analysis of deforestation. For the year 2007 ASTER scenes were acquired since they were the most recent, cloud-free satellite data that is available for the region. They also allow a more accurate analysis of the land cover due to the higher resolution of the image with a pixel size of $15\,m$ (Table 1). The mosaic of the two adjacent ASTER scenes from 2007 represents the large ROI and includes the LLS site within the smaller ROI (Figure 1). Both the ASTER and Landsat images were already orthorectified.

Table 1: Satellite data for analysing the land cover changes in Western Ghana.

Sensor	**Resolution**	**Acquisition date**
Landsat 5TM	$28.5\,m$	1986-01-18
Landsat 7ETM+	$28.5\,m$	2000-02-02
ASTER	$15\,m$	2007-01-13

The sensors in the satellite record the spectral reflectance of the sunlight from the earth surface at certain bands and the recorded satellite data in the form of satellite images is used for analysing the characteristics of the land cover. There is a direct relationship between the reflection within the near-infrared (NIR) and red region of the spectra and the characteristics of vegetation cover such as its greenness and biomass (Jensen, 2007). The NIR reflectance increases the more dense the vegetation cover is. Conversely the red band within the reflected spectra decreases the more green the vegetation cover is due to the use of red radiant flux for photosynthesis. The more photosynthetic active vegetation there is the less is the reflectance within the red band. Therefore, the bands of NIR and red reflectance within the satellite data provide valuable information on the characteristics of vegetation cover and allow distinguishing different vegetation types and states of degradation or senescence. The narrower the bands of the recorded reflectance are the more unique characteristics of the reflectance from the vegetation cover can be distinguished. Therefore, to a certain extent hyperspectral sensors can provide more detailed information as compared to sensors with a smaller number of broader bands. For the classification of the land cover the reflectance of both, the NIR and red regions, is used.

The Landsat TM was developed with a particular focus on recording the bands of the reflected spectra that are controlled by the characteristics of the vegetation such leaf pigmentation, leaf and canopy structure and moisture content (Jensen, 2007). Therefore, the Landsat TM with its seven recorded bands is a sensor that is in particular suitable for monitoring changes in vegetation cover. The 14 bands of the ASTER satellite are also covering most characteristics of the reflectance from vegetation. Only the blue band is not recorded loosing out on some of the spectral information on the pigmentation of leafs. Nevertheless, ASTER is a satellite which is also suitable for analysing vegetation cover. Cloud cover, haze and atmospheric particles can disturb the reflected spectra, which is recorded by the satellite. Therefore, cloud cover needs to be masked and the influence of haze and atmospheric particles needs to be reduced by applying an atmospheric correction. If the images are treated and classified separately and only the results of the land cover classification is used for further analysis, such as post-classification change detection, then an atmospheric correction is not necessary (Jensen, 2005). For this study the cloud cover was masked and atmospheric correction was done in order to allow further analysis beyond a classification-based change detection.

3.2 Land Cover Classification

The classification of the land cover is a means of transforming the spectral data of the satellite image into thematic information on the land cover types (Jensen, 2005). This is in particular relevant for analysing changes in land cover over time by comparing the extent of land cover types at different time steps. The classification was done as a supervised classification, meaning that the specific land cover types have been identified in the field and in the image before the classification of the entire satellite image. The samples of sites with the known land cover type, the so called training sites, are used to identify the spectral characteristic of each land cover type by calculating multivariate statistical parameters for each land cover type. This spectral information of the land cover is used to train the spectral data of the entire satellite image. Thereby, the spectral information of each pixel in the image is analysed and assigned to the spectra of the respective land cover type of which it is most likely to be a member using the Maximum Likelihood classification (Jensen, 2005). This way the entire satellite image is mapped for the land cover classes. For validating the result of the mapped land cover classes, the spectral information of validation sites that have been collected before the land cover classification, are used in order to identify the accuracy of the generated land cover classification.

For the classification of the land cover in the ASTER scene from 2007, ground truth samples were collected in the study site in April and September 2008 and were used as training and validation data (Figure 2). The difference of one year between image acquisition and collection of the training data was taken into accounted by estimating the age of the recorded land cover in the field and excluding samples with recent land cover change processes, such as freshly deforested areas and fields that were newly planted. For old growth forest additional training data was visually sampled in forest reserves within the

ASTER image in order to increase the amount of validation data. Due to the limited accessibility of old growth forest a map of the logging concessions and the timing of selective logging within forest reserves was used for the visual sampling of training and validation data for old growth forests within the satellite image.

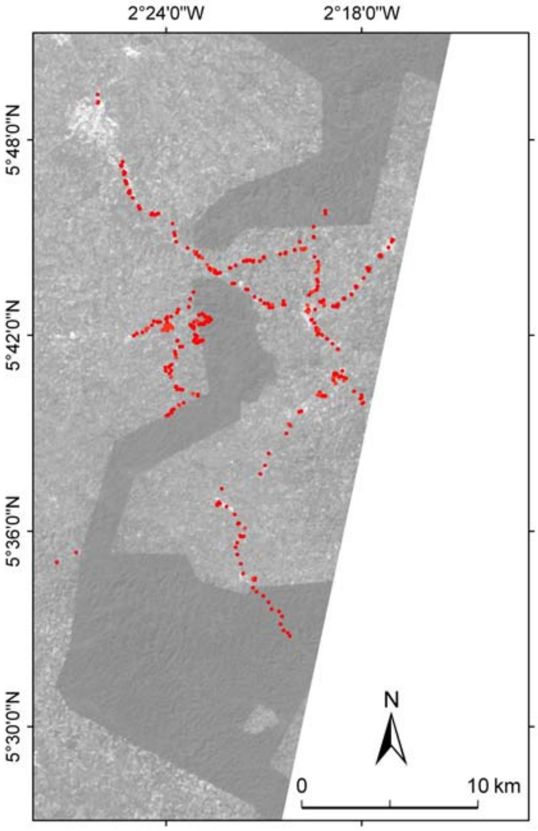


Figure 2: Ground-truth samples of the training and validation data that was used for the land cover classification of the ASTER scene from 2007. For the Landsat scenes and the large ROI additional training and validation data was visually sampled within the satellite images.

For the Landsat images only few of the training and validation data that was sampled in the field could be dated back in time and used for the image classification. The method of reconstructing the land cover through its age was only possible for old growth forests where the age of the trees confirmed the existence of the forest for more than the past two decades. Therefore, most of the training data for the Landsat scenes was visually sampled by the author in the satellite images of the year 2000 and 1986 after having gained experience in the identification of the land cover types in the field. Due to the field experience the different land cover characteristics could be identified in a reliable way within the image. This procedure is also suggested in cases where not sufficient ground truth data and land cover maps are available (Brown et al., 2008). However, this method also restricted the number of land cover classes that could be visually identified and that were used for the classification.

The land cover in the study site was recorded in the field following the guidelines of the FAO Land Cover Classification System (LCCS, Di Gregorio & Jansen, 2005) and using the LCCS field protocol (Appendix A). The dominating land cover types were identified by a visual assessment in the field, interviewing local experts and farmers and using topographic maps. Based on this information and with the help of a local guide the ground-truth samples were systematically collected at a minimum distance of 30 m from roads, small trails and off track with the goal of collecting samples for each dominating land cover type of the region. The distance between each sample point and the radius with homogeneous land cover around each sample point was at least 30 m in order to account for the resolution of the Landsat and ASTER image. Land cover information such as vegetation type (tree, shrub, and herb), the percentage of vegetation cover, the height of the different vegetation layers and slope aspects were recorded according to the instructions of the LCCS protocol. This also includes taking photographs of all four cardinal points north, east, south and west in order to be able to reproduce the classification if necessary and to increase the objectivity of the classification. The coordinates of the ground truth samples were recorded with a Global Positioning System (GPS) and a minimum accuracy of 6 m.

The classification of the land cover was done after the collection of the data in the field using the software LCCS 2.4.5 (Di Gregorio & Jansen, 2005). The LCCS software is guiding the user through the classification system and allows a consistent processing and classification of the recorded ground truth data. First the observed land cover is assigned to one of eight major land cover types (dichotomous phase). Thereafter, the user follows a hierarchical order of pre-defined land cover classifiers (modular-hierarchical phase) which are tailored to the previously selected land cover type. For each class a Boolean formula of the classifiers, a numerical code and a name is generated which is a unique description of the class. This guided and hierarchical process of land cover classification based on key land cover parameters is meant to provide objectivity and consistency in the land cover classification.

For the classification of the ASTER scene a 20 m buffer was created around each ground truth sample using the software ArcGIS®9 (© ESRI, 2005). From linear objects such as roads the data for classification and validation was selected manually since a 20 m radius would have included a mixed spectral signature from a variety of land cover types adjacent to the road. The shapes of the ground truth samples were overlaid the ASTER scene and the recorded spectral signature of each ground truth sample and class was used for the supervised classification of the ASTER image. For the classification of the Landsat images from 1986 and 2000 the visually sampled training and validation data was used.

The classification of the satellite images was performed with the remote sensing software IDL/ENVI. The training data was used for the supervised Maximum Likelihood classification and the validation data was used for the evaluation of the accuracy of the classification result. The ratio between the number of pixels for the training data and the validation data was chosen to be around 2:1. It was paid attention that the data is evenly distributed within the study site. The land cover classes were clustered further and thereby reduced in number until the overall accuracy of the image classification was above 80 %.

For separating areas inside and outside the forest reserves a digitized topographic map (Survey of Ghana, Edition 1999, scale 1:50000) was used for creating polygons of the forest reserves, which were used for masking the forest reserves. Clouds occurred in the ASTER scene from 2007 in the south-eastern corner of the mosaic, which was cut entirely from all three images. In the Landsat image of the year 2000 clouds occurred at the north-western edge of the larger subset. In order to exclude the cloud covered areas a cloud mask was created and applied to all three images.

3.3 Land Cover Change

The analysis of the land cover change in the ROI between 1986 and 2000 was done in the IDL/ENVI software with a post-classification comparison on a pixel-by-pixel basis using a change detection matrix. When performing a change detection it is in particular important that the images are acquired by a similar sensor, with similar spatial and spectral resolution and at similar environmental conditions. Any sources of error in the pre-processing need to be reduced as much as possible (Jensen, 2005). Variations in these requirements or errors, in particular those in the classification, will also be present in the result of the change detection.

Inconsistencies in the classification can arise due to the three different satellite sensors with which the images were acquired (Table 1). Seasonal effects on the phenology of vegetation with consequences for the land cover classification and change detection can be neglected since all three images were recorded within the same period of the year with a difference of less than three weeks (Table 1). Also the effect of the four hours difference in the time of the day when the images were acquired can have impact on the shade within the image and thereby on the image classification but is expected to be minor. Relief is likely to have only little impact on the land cover classification since the ROI is generally flat with few rolling to steep hills. Where cloud cover occurred it was masked in all three images and the influence of haze was reduced by atmospheric correction. With regards to the sampling of training and validation data for generating the land cover classification it was paid attention to achieve the highest accuracy as possible for each image. It was also made sure that the dimensions and spatial resolution of the ROIs of all three time steps match exactly. Prior the change detection the images were co-registered using Ground Control Points (GCP) that were visually sampled within the ASTER image using distinct features such as street crossings, buildings and the corners and edges of the ROI as reference. The ASTER image was resampled to the spatial resolution of the Landsat images with the nearest neighbour method (GCP error of 3.2). Differences in the spectral resolution, meaning differences in the bands of the sensors, can have a minor influence on the land cover classification.

3.4 Carbon Balance

In order to quantify carbon emissions from land cover changes data on the mean carbon content of the land cover in Western Ghana was used, which was collected within the CarboAfrica research project (www.carboafrica.net). The average carbon content of the vegetation cover in the high forest zone is reported by Henry et al. (unpublished) to be 223.8 $tC\,ha^{-1}$ for intact deciduous forests, 210.3 $tC\,ha^{-1}$ for intact broadleaf forests, 125 $tC\,ha^{-1}$ for degraded forests, 32.8 $tC\,ha^{-1}$ for cropland, 17.7 $tC\,ha^{-1}$ for shrubland and 0 $tC\,ha^{-1}$ for urban and bare ground and 90.3 $tC\,ha^{-1}$ for cocoa agroforest Tutu (pers. comm.). The carbon content of intact forests is similar to the 213 $tC\,ha^{-1}$ reported in the Ghana National Communication to the UNFCCC (2000) and the figures for the carbon content for cocoa agroforest and cropland are also within the range of the 20 to 100 $tC\,ha^{-1}$ used for quantifying the carbon content of the land cover in off-reserve areas by Osafo (2005). The land cover classes used for the classification of the satellite images are comprised of different land cover types with differing carbon content. Therefore, the carbon content for the land cover classes as used in the image classification was derived from average estimates of the original data given above. The uncertainty of the carbon estimates was assumed to be 10 %.

The change in the carbon balance is determined from the change in the area of the respective land cover classes as derived from the change detection based on the LCCS classification. The carbon emissions were estimated by multiplying the area of the class changes by the difference in the average carbon content between the respective classes. Thereby, also regrowth is taken into account and gross as well as net changes are reported. For example in the case where old growth forest has been cleared after the image of 1986 was recorded, the major part of the forest carbon was lost in the first place. Where the forest has been replaced by cocoa agroforest or secondary forest until 2000 and 2007, carbon was sequestered through regrowth. When determining the difference in carbon content between forest and agroforests this regrowth is taken into account. For estimating the potential of REDD the area of the remaining forest cover is multiplied by the carbon emissions that would result from the complete loss of the forest. Where appropriate the carbon emissions where converted into emissions of carbon dioxide (CO_2) by multiplying one unit of C emission by the factor of 3.667.

Since the data for the carbon content is up-to-date and specific for the analysed region the estimation of the carbon emissions follow Tier 2 in the IPCC AFOLU guidelines (Aalde et al., 2006). It is assumed that the carbon content of the natural forests is similar throughout the study site and does not vary due to natural differences in forest ecology. However, a stratification of the carbon content of the natural forest would be necessary if the analysis covered a larger area with the different ecological zones of Ghana ranging from high carbon content in the moist forests to lower values in the dry forests (Brown et al., 2008). The carbon flux from the decay of biomass and changes in below-ground carbon pools were not included.

3.5 Accuracy

When interpreting the results and their implication for the potential of REDD in Western Ghana the different sources of errors have to be taken into consideration. These include the differences in the characteristics of the satellite and land cover data and the errors that are involved in the various steps of processing and classifying the images.

The extensive field experience and knowledge gained by the author helped to reduce the errors that are involved in the sampling of the training and validation data for the land cover classification. The classification of the ASTER scene from 2007 was verified by using the validation data collected in the field. Thereby, thematic errors can occur in the interpretation and recording of land cover parameters such as the density and height of the vegetation cover. Since these parameters were not measured but estimated by sight a certain bias and variability in these parameters can be a possible source for errors. For determining the accuracy of the classification of the Landsat scenes from 1986 and 2000 both the validation and training data was visually collected within the Landsat satellite images. The errors due to the variability in sampling in the land cover validation and training data can be reduced by reducing the number of land cover classes that are used for the classification. Thereby, the likelihood that the validation and training data is correctly assigned to the corresponding land cover class increases. For the land cover classification the overall accuracy, the user's and producer's accuracy together with the commission and omission errors were recorded.

For estimating the overall uncertainty in the carbon emissions the square root of the sum of the uncertainties in the carbon content (U_1) and the overall uncertainty in the land cover classification of 1986 (U_2) and 2007 (U_3) was determined according to the formula suggested by Brown et al. (2008):

$$U_{total} = \sqrt{U_1^2 + U_2^2 ... + U_n^2} \qquad \text{Equation 1}$$

$U_{total} = total\ uncertainty$
$U_i = uncertainty\ of\ each\ component$

According to the conservativeness principle (Mollicone et al., 2007 and Grassi et al., 2008) the total uncertainty U_{total} was subtracted from the total estimated carbon emission in order to report the lower range of emissions with the highest accuracy. As reported in Grassi et al. (2008) errors up to 20 % are common in determining forest cover changes with remote sensing.

4 Results

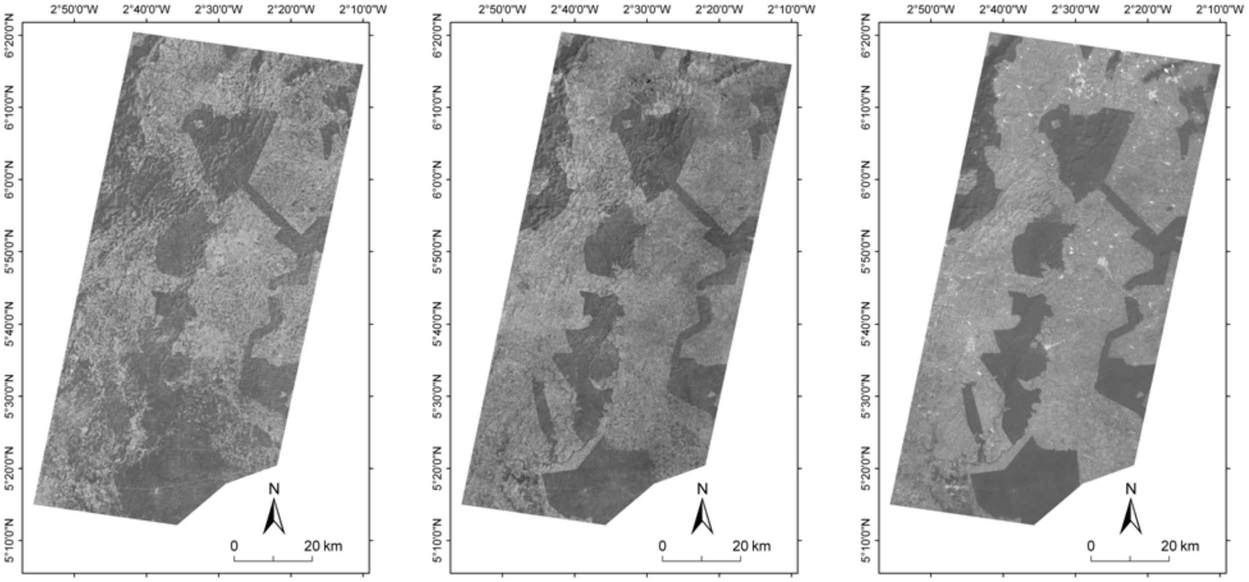
4.1 Land Cover Classification

After excluding the cloud covered areas from all three images the analysed area of the large region of interest (ROI) comprises about 700,000 ha (Figure 8) of which 30 % are forest reserves. The smaller LLS site has an area of around 88,000 ha of which 32 % are forest reserves (Table 9). There is an insignificant deviation in the size of the analysed area between the Landsat and the ASTER scenes of about 0.03 %, which is due to the higher resolution of the ASTER scene, where the pixels fill closer to the edge of the analysed area than in the Landsat scenes, causing an "*edge effect*".

During the collection of ground-truth data in the field 489 samples of the land cover were recorded in the LLS site and classified according to the LCCS (Figure 2). After the classification of the LCCS around 107 land cover types of different characteristics were identified. These were clustered into classes according to the type of land cover, vegetation, percentage of tree cover and tree height following the definitions and the hierarchical order of the LCCS.

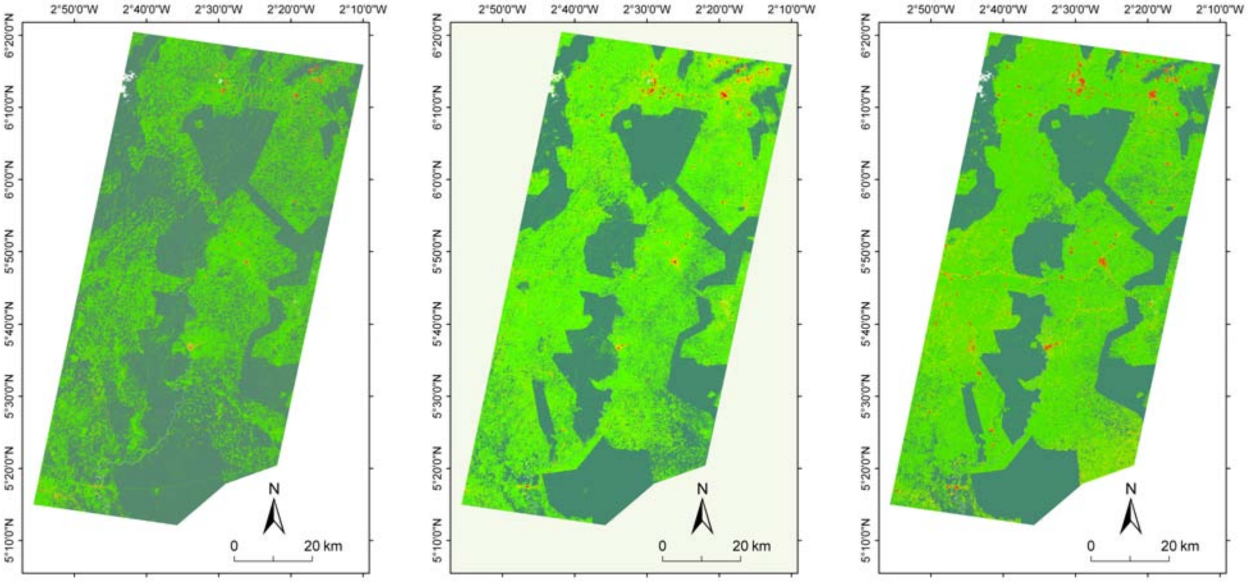
The dominating land cover types within the LLS site, were all the samples were collected, can be described as (i) old growth forests within reserves and patches of forest outside reserves with a tree cover of 65 to 100 % and a tree height above 25 m; (ii) secondary forest and plantations of oil palm, teak and rubber with a tree cover of 65 to 100 % and a tree height of 10 to 25 m; (iii) agroforests with shade trees with a tree cover of 65 to 100 % and a minimum tree height of 3 m of the agroforest trees and 10 m of the shade trees; (iv) agroforests without shade trees, a cover of 10 to 100 % and a tree height below 10 m; (v) shrubland with a vegetation cover of 10 to 100 % and a height of maximum 6 m; (vi) urban areas and settlements; (vii) bare ground without vegetation cover comprised of agricultural fields, gravel and tarred roads and bare soil around settlements.

The visual sampling of the land cover within the Landsat images from 1986 and 2000 allowed distinguishing only four major land cover classes: (i) old growth forests; (ii) vegetated areas other than old growth forest which are dominated by agroforests, secondary forests and shrubland; (iii) urban areas and settlements and (iv) bare ground including roads. In accordance with the terminology and classification parameters of the LCCS these four classes were given the names (i) Forest; (ii) Woodland and Shrubland; (iii) Urban and (iv) Bare ground. The visually sampled data was used for the classification of the Landsat scenes. The data that was sampled in the field was clustered into these four classes and used for the classification of the ASTER scene from 2007.



(a) 1986 **(b)** 2000 **(c)** 2007

Figure 3: Landsat (1986 and 2000) and ASTER (2007) scenes of the large ROI.



(a) 1986 **(b)** 2000 **(c)** 2007

Figure 4: Land cover classification of the large ROI: Forest (dark green), Wood-& Shrubland (light green), Bare ground (orange), Urban (red).

Table 2: Confusion matrix for classification of large ROI, Landsat 1986. (Overall accuracy = 91.2%; kappa coefficient (K) = 0.8440)

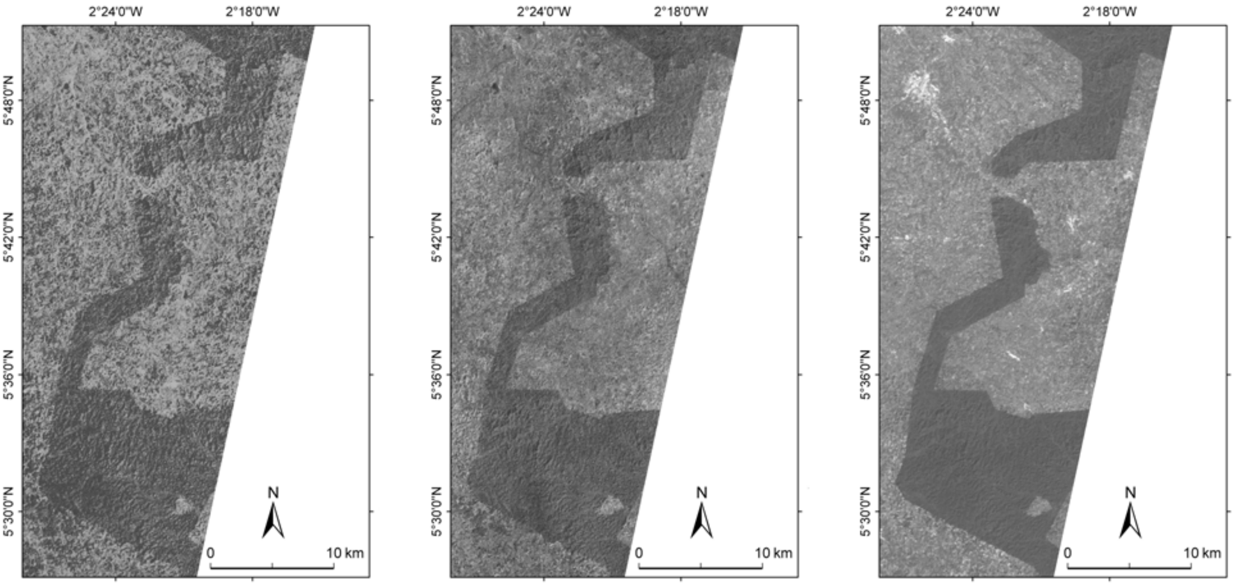
	Ground truth data (Pixels)				
LC Classes	Forest	Wood- & Shrubl.	Urban	Bare ground	Row total
Forest	738	54	0	4	796
Wood- & Shrubland	54	427	0	5	486
Urban	0	0	54	0	54
Bare ground	0	4	4	75	83
Column total	792	485	58	84	1419
User's accuracy (%)	93	88	100	90	
Commission error (%)	7	12	0	10	
Producer's accuracy (%)	93	88	93	89	
Omission error (%)	7	12	7	11	

Table 3: Confusion matrix for classification of large ROI, Landsat 2000. (Overall accuracy = 83.7%; kappa coefficient (K) = 0.7781)

	Ground truth data (Pixels)				
LC Classes	Forest	Wood- & Shrubl.	Urban	Bare ground	Row total
Forest	666	48	0	9	723
Wood- & Shrubland	50	412	2	34	498
Urban	0	0	277	86	363
Bare ground	0	18	80	342	440
Column total	716	478	359	471	2024
User's accuracy (%)	92	82	76	78	
Commission error (%)	8	17	24	22	
Producer's accuracy (%)	93	86	77	72	
Omission error (%)	7	14	23	28	

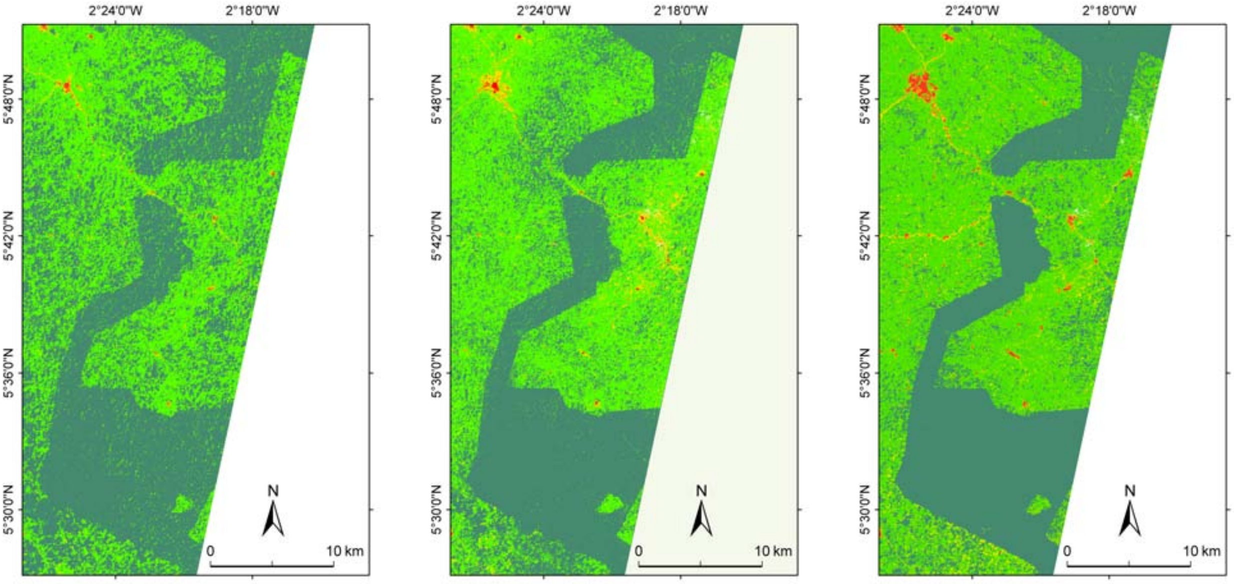
Table 4: Confusion matrix for classification of large ROI, ASTER 2007. (Overall accuracy = 87.2%; kappa coefficient (K) = 0.8069)

	Ground truth data (Pixels)				
LC Classes	Forest	Wood- & Shrubl.	Urban	Bare ground	Row total
Forest	888	40	0	0	928
Wood- & Shrubland	40	947	1	24	1012
Urban	0	1	129	85	215
Bare ground	0	41	8	220	269
Column total	928	1029	138	329	2424
User's accuracy (%)	96	94	60	82	
Commission error (%)	4	6	40	18	
Producer's accuracy (%)	96	85	93	66	
Omission error (%)	4	15	7	34	



(a) 1986 **(b)** 2000 **(c)** 2007

Figure 5: Landsat (1986, 2000) and ASTER (2007) scenes of the LLS site.



(a) 1986 **(b)** 2000 **(c)** 2007

Figure 6: Land cover classification of the LLS site: Forest (dark green), Wood-& Shrubland (light green), Bare ground (orange), Urban (red).

Table 5: Confusion matrix for classification of LLS site, Landsat 1986. (Overall accuracy = 86.5%; kappa coefficient (K) = 0.7763)

	Ground truth data (Pixels)				
LC Classes	Forest	Wood- & Shrubl.	Urban	Bare ground	Row total
Forest	490	127	0	4	621
Wood- & Shrubland	2	302	0	5	309
Urban	0	0	54	0	54
Bare ground	0	2	4	75	81
Column total	492	431	58	84	1065
User's accuracy (%)	79	98	100	93	
Commission error (%)	21	3	0	7	
Producer's accuracy (%)	99	70	93	89	
Omission error (%)	0	30	7	11	

Table 6: Confusion matrix for classification of LLS site, Landsat 2000. (Overall accuracy = 89.2%; kappa coefficient (K) = 0.8101)

	Ground truth data (Pixels)				
LC Classes	Forest	Wood- & Shrubl.	Urban	Bare ground	Row total
Forest	455	102	0	0	557
Wood- & Shrubland	34	672	0	0	706
Urban	0	0	70	5	75
Bare ground	0	8	2	45	55
Column total	489	782	72	50	1393
User's accuracy (%)	82	95	93	82	
Commission error (%)	18	5	7	18	
Producer's accuracy (%)	93	86	97	90	
Omission error (%)	7	14	3	10	

Table 7: Confusion matrix for classification of LLS site, ASTER 2007. (Overall accuracy = 88.4%; kappa coefficient (K) = 0.8148.)

	Ground truth data (Pixels)				
LC Classes	Forest	Wood- & Shrubl.	Urban	Bare ground	Row total
Forest	241	59	0	0	300
Wood- & Shrubland	34	673	0	1	708
Urban	0	0	130	7	137
Bare ground	0	11	8	136	155
Column total	275	743	138	144	1300
User's accuracy (%)	80	95	95	88	
Commission error (%)	20	5	5	12	
Producer's accuracy (%)	88	88	94	84	
Omission error (%)	12	12	6	16	

The overall accuracy of the land cover classification of the large ROI and the LLS site ranges between 83.7 % and 91.2 % with an average of 87.7 % (Table 2 to 7; Figure 3 to 6).

The omission error describes the part of the land cover that was wrongly classified and is missing in the land cover class to which it should belong in the final image classification. For 'Forest' the omission error is between 0 % and 12 % and has an average of 6.2 % (Table 2 to 7). For the other classes the average omission error is 8.8 % for 'Urban', 16.2 % for 'Woodland and Shrubland', and 18.3 % for 'Bare ground'. The omission error determines the producer's accuracy which is a measure for the accuracy of the classification of the image data by the analyst. The class 'Forest' has the highest producer's accuracy between 93 % to 99 % and an average of 93.7 %. The producer's accuracy of all land cover classes ranges between 66 % and 99 % with an average of 87.6 % (Table 2 to 7). The greater confusion occurs in the class 'Woodland and Shrubland' with a producer's accuracy between 70 % and 88 % and an average of 83.8 %. The class 'Urban' has a producer's accuracy between 77 % and 97 % and an average of 91.2 %, and the class 'Bare ground' has a producer's accuracy between 66 % and 90 % with an average of 81.7 %.

The opposite of the omission error is the commission error which describes the part of the land cover that was wrongly classified and added to a land cover class in the final classification, although it belongs to a different class. For 'Forest' it ranges between 4 % and 21 % with an average of 13 %. For the other classes the average commission error is 8.0 % for 'Woodland and Shrubland', 12.7 % for 'Urban' and 14.5 % for 'Bare ground' (Table 2 to 7). The commission error for 'Forest' is high for the smaller LLS region (average 19.7 %) while it is lower for the large ROI (average 6.3 %). The commission error determines the user's accuracy which is a measure for how well the classification is matching the land cover in the field. The user's accuracy is highest for 'Woodland and Shrubland' with an average of 92 % while it is on average 87.3 % for 'Urban', 87 % for 'Forest', and 85.5 % for 'Bare ground'.

4.2 Land Cover Change

The changes that were found in the land cover include no change, the modification of the land cover such as the degradation of forest to secondary forests and agroforests with shade tress, and the full transformation through the replacement of forest and agroforests by bare ground or urban areas.

Between 1986 and 2007, the greatest change with regards to the change in area occurred in the forest cover (Figure 7). In the large ROI the forest area decreased by 42 %, corresponding to an annual deforestation rate of 2.6 % (Table 8). Outside the reserves the forest cover decreased by 76 % corresponding to an annual deforestation rate of 6.4 %, while the forest cover within reserves remained stable with almost no change (Table 8). Most of the forest was transformed into 'Wood- and Shrubland' and in 2007 only 12 % of the area outside the reserves remained covered with forest. Although the classes 'Urban' and 'Bare

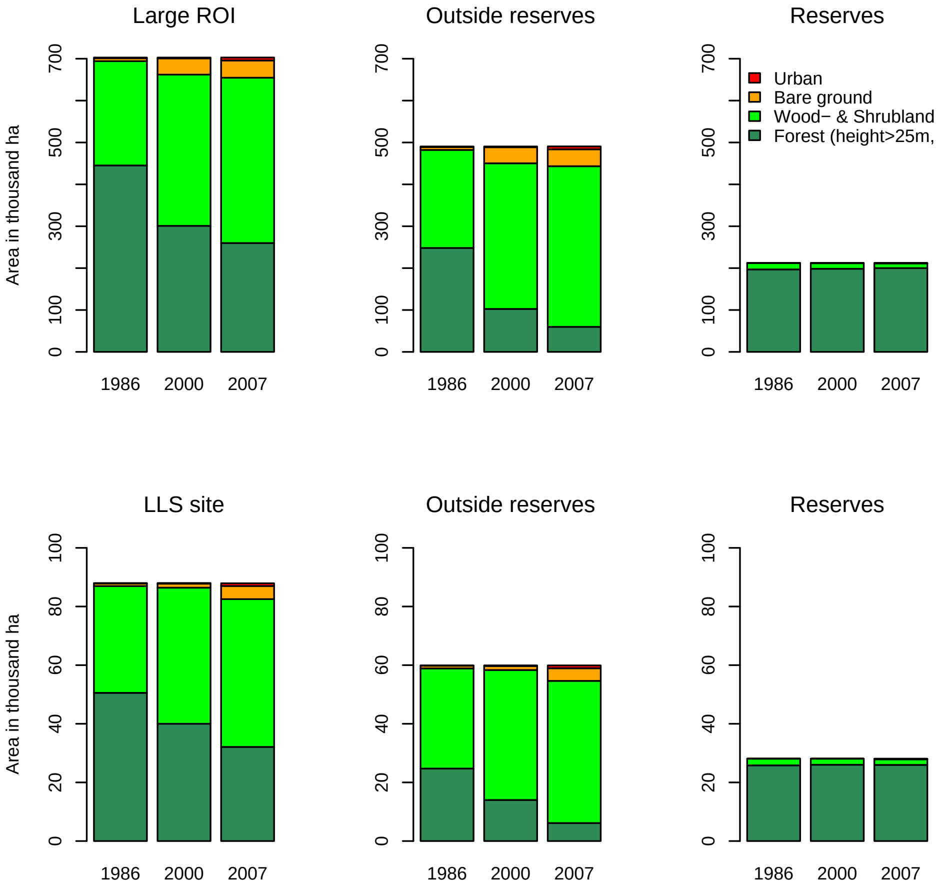


Figure 7: Land cover of the large ROI, in the LLS site and separated into the areas outside and inside reserves for the years 1986, 2000 and 2007.

ground' cover only an area between 1 % and 6 %, these classes experienced an increase by 320 % and 491 % respectively (Table 8).

The trends in land cover change within the smaller LLS site are similar to the trends within the large ROI (Figure 7, Table 8 and Table 9). In the LLS site the forest cover decreased by 39 % corresponding to an annual deforestation rate of 2.3 % (Table 9). While the forest cover within the reserves remained stable the forest outside the reserves decreased by 77 %, corresponding to an annual deforestation rate of 6.5 %. In 2007 only 10 % of the area outside the reserves remained covered with forest. The classes 'Urban' and 'Bare ground' cover only about 1 % and 5 % respectively but experienced an increase by 747 % and 316 % over the peiod of 21 years (Table 9).

Table 8: Land cover (LC) of the large ROI with the producer's accuracy of the LC classification for Landsat scenes (1986, 2000) and ASTER scene (2007) with LC change for 1986-2007. * Deviation in total area due to edge effects caused by the difference in resolution of the Landsat scenes (resolution 28.5 x 28.5 meter) and the ASTER scene (resolution 15 x 15 meter).

Year	**1986**			**2000**			**2007**			**LC change 1986-2007**		
Land cover (LC) classes	Area (*ha*)	Fraction (%)	Accuracy (%)	Area (*ha*)	Fraction (%)	Accuracy (%)	Area (*ha*)	Fraction (%)	Accuracy (%)	Area (*ha*)	Fraction (%)	Rate (% $year^{-1}$)
Overall accuracy			91.2			83.7			87.2			
Large ROI												
Forest	445149	63.4	93.2	300972	42.8	93.0	259730	37.0	95.7	-185419	-42	-2.6
Woodland/Shrubland	248985	35.4	88.0	361017	51.4	86.2	394460	56.2	85.5	145475	58	
Urban	1688	0.2	93.1	1941	0.3	77.2	7080	1.0	93.5	5392	320	
Bare ground	6965	1.0	89.3	38857	5.5	72.2	41189	5.9	66.3	34224	491	
Total	702786	100		702786	100		702459	100		-328*	0*	
Absolute change in total area (%)											53	
Area outside reserves												
Forest	248182	50.6	93.2	102530	20.9	93.0	59834	12.2	95.7	-188348	-76	-6.4
Woodland/Shrubland	233930	47.7	88.0	347741	70.9	86.2	383158	78.1	85.5	149228	64	
Urban	1558	0.3	93.1	1861	0.4	77.2	6883	1.4	93.5	5325	342	
Bare ground	6803	1.4	89.3	38341	7.8	72.2	40441	8.2	66.3	33638	494	
Total	490473	100		490473	100		490316	100		-157*	0*	
Absolute change in total area (%)											54	
Area inside reserves												
Forest	196967	92.8	93.2	198442	93.5	93.0	199896	94.2	95.7	2929	1	0.1
Woodland/Shrubland	15056	7.1	88.0	13276	6.3	86.2	11303	5.3	85.5	-3753	-25	
Urban	129	0.1	93.1	79	0.0	77.2	196	0.1	93.5	67	52	
Bare ground	162	0.1	89.3	516	0.2	72.2	748	0.4	66.3	586	362	
Total	212313	100		212313	100		212143	100		-171*	0*	
Absolute change in total area (%)											1	

Table 9: Land cover (LC) of the LLS site with the producer's accuracy of the LC classification for Landsat scenes (1986, 2000) and ASTER scene (2007) with LC change for 1986-2007. * Deviation in total area due to edge effects caused by the difference in resolution of the Landsat scenes (resolution 28.5 x 28.5 meter) and the ASTER scene (resolution 15 x 15 meter).

Year	**1986**			**2000**			**2007**			**LC Change 1986-2007**		
Land cover (LC) classes	Area (*ha*)	Fraction (%)	Accuracy (%)	Area (*ha*)	Fraction (%)	Accuracy (%)	Area (*ha*)	Fraction (%)	Accuracy (%)	Area (*ha*)	Fraction (%)	Rate (%$year^{-1}$)
Overall Accuracy			86.5			89.2			88.4			
LLS site												
Forest	52868	60.1	99.6	40007	45.5	93.1	32072	36.5	87.6	-20796	-39	-2.3
Woodland/Shrubland	33938	38.6	70.1	46405	52.7	85.9	50366	57.3	88.4	16427	48	
Urban	116	0.1	93.1	219	0.3	97.2	986	1.1	94.2	869	747	
Bare ground	1079	1.2	89.3	1370	1.6	90.0	4494	5.1	84.5	3414	316	
Total	88002	100		88002	100		87917	100		-85*	0*	
Absolute change in total area (%)											47	
Area outside reserves												
Forest	26966	45.0	99.6	13988	23.3	93.1	6130	10.2	87.6	-20836	-77	-6.5
Woodland/Shrubland	31757	53.0	70.1	44342	74.0	85.9	48449	80.9	88.4	16692	53	
Urban	116	0.2	93.1	218	0.4	97.2	980	1.6	94.2	864	746	
Bare ground	1071	1.8	89.3	1362	2.3	90.0	4300	7.2	84.5	3229	301	
Total	59910	100		59910	100		59859	100		-51*	0*	
Absolute change in total area (%)											47	
Area inside reserves												
Forest	25902	92.2	99.6	26020	92.6	93.1	25942	92.5	87.6	39	0.1	0.0
Woodland/Shrubland	2180	7.8	70.1	2063	7.3	85.9	1916	6.8	88.4	-264	-12	
Urban	1	0.0	93.1	0	0.0	97.2	6	0.0	94.2	5	929	
Bare ground	8	0.0	89.3	9	0.0	90.0	194	0.7	84.5	186	2360	
Total	28091	100		28091	100		28058	100		-33*	0*	
Absolute change in total area (%)											<1	

4.3 Emissions from Land Cover Change

For the four classes the average carbon content was estimated using the data of the CarboAfrica project, which was provided by Henry et al. (unpublished). For the class 'Forest' the average of the carbon content of deciduous forest (223.8 $tC\,ha^{-1}$) and broadleaf forest (210.3 $tC\,ha^{-1}$) was used, giving 217.1 $tC\,ha^{-1}$. For the class 'Woodland and Shrubland' the average of degraded forest (125 $tC\,ha^{-1}$), cocoa agroforest (90.3 $tC\,ha^{-1}$) and shrubland (17.7 $tC\,ha^{-1}$) was used, with each component being weighted according to its approximate contribution to the class of 10 %, 80 % and 10 % respectively, giving 86.5 $tC\,ha^{-1}$. For the classes 'Urban' and 'Bare ground' the above ground carbon content is 0 $tC\,ha^{-1}$.

Within the period of 1986 to 2007 the land cover change in the large ROI lead to gross carbon emissions of 26.8 million tC. This is a conservative estimate after subtracting an overall uncertainty U_{total} of 16.5 % (Table 10). The conversion of forest to other land cover types is contributing 93 % to the gross carbon emissions. After accounting for regrowth the change from forest to woodland causes 78 % of the emissions and the conservative net carbon emissions are estimated to be 23.4 million tC. For the same period the conservative estimate for the gross emissions within the LLS site is 2.9 million tC after subtracting an overall uncertainty U_{total} of 20.5 % (Table 11). Also here deforestation is contributing 93 % to the gross carbon emissions. After accounting for regrowth the change from forest to woodland causes 80 % of the emissions and the conservative net carbon emissions are 2.4 million tC. This corresponds to annual gross carbon emissions of around 1.1 million tC for the large ROI and 0.1 tC for the LLS site. The average estimate for the annual gross carbon emissions per hectare are 1.8 $tC\,ha^{-1}\,a^{-1}$ for the larger ROI and 1.6 $tC\,ha^{-1}\,a^{-1}$ for the LLS site and the annual net carbon emission per hectare are 1.6 $tC\,ha^{-1}\,a^{-1}$ and 1.3 $tC\,ha^{-1}\,a^{-1}$ respectively.

The potential of reducing emissions from deforestation corresponds to the amount of carbon that is stored in the remaining forest cover and that can be saved from being lost by reducing or stopping deforestation. Within the large ROI the remaining forest cover outside the reserves is 12 % or around 60.000 ha. If current deforestation rates continue the forest outside reserves is likely to be lost within the next decade (Table 10) which would result in emissions of 7.8 million tC. Within the smaller LLS site about 10 % of the area outside reserves or around 6000 ha is covered with forests and their loss would result in emissions of around 800.000 tC within the next decade if current deforestation rates continue (Table 11). While the change detection with four land cover classes allowed quantifying deforestation it was not possible to detect and quantify forest degradation.

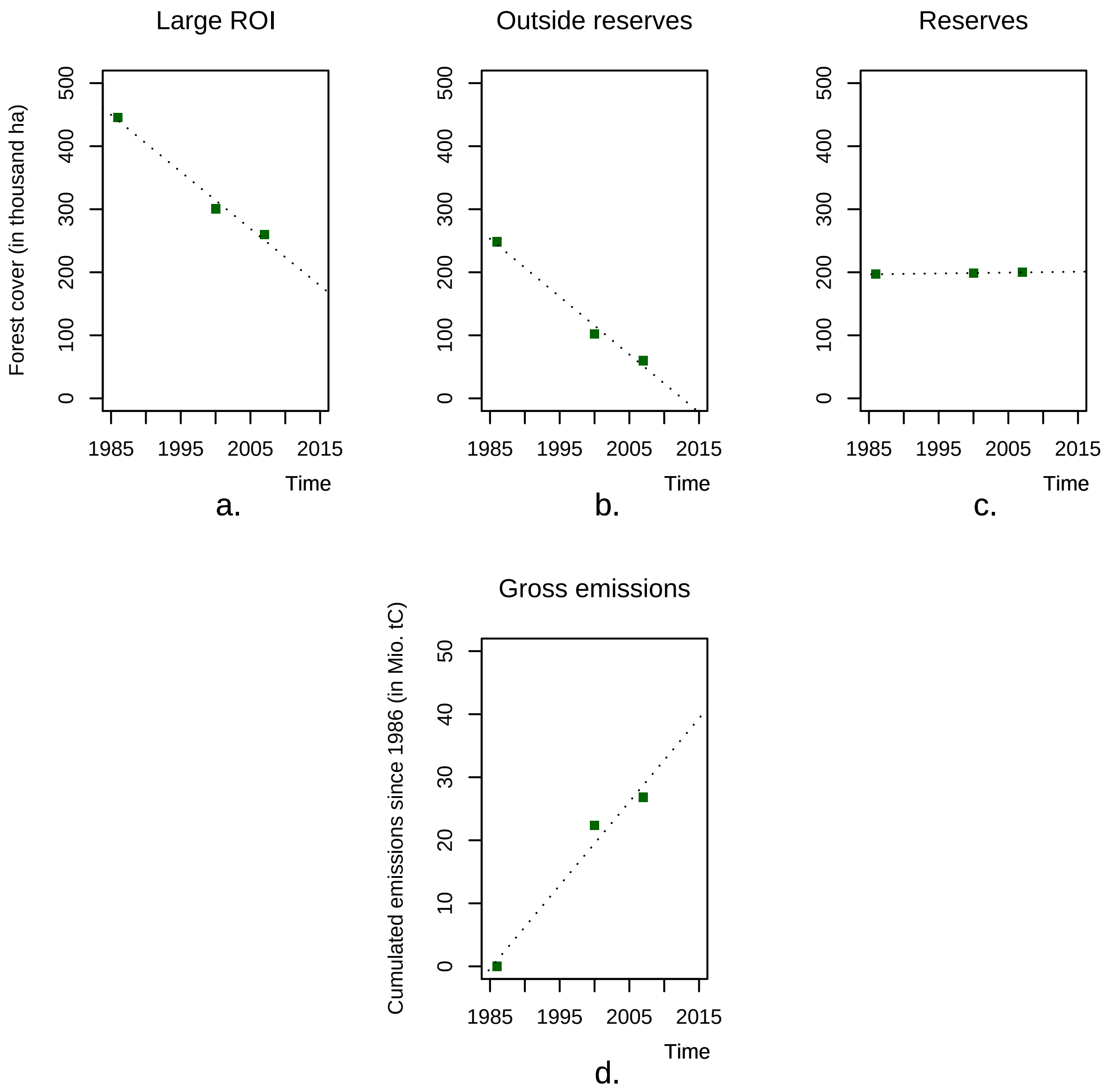


Figure 8: Forest cover change in the large ROI (a), outside reserves (b), inside reserves (c), and cumulated gross carbon emissions from land cover change (d).

Table 10: Carbon (C) emissions from land cover (LC) change in the large ROI for 1986-2007.

Large ROI	**LC change 1986-2007**		**Carbon emissions**			
	LC classes	Area (ha)	Per ha ($tCha^{-1}$)	Annual ($tCyear^{-1}$)	Total (tC)	Percent (%)
	Carbon source					
	Forest to Woodland/Shrubland	196636	130.6	1222886	25680616	93
	Forest to Urban	1382	217.1	14287	300024	1
	Forest to Bare ground	18431	217.1	190541	4001354	14
	Woodland to Urban	3462	86.5	14259	299432	1
	Woodland to Bare ground	21249	86.5	87524	1838006	7
Gross Emissions				1529497	**32119433**	116
Conservative estimate (-16.5 % uncertainty)				1277130	**26819726**	
	Carbon sink					
	Woodland/Shrubland to Forest	30997	-130.6	-192773	-4048240	-15
	Urban to Forest	66	-217.1	-678	-14248	0
	Urban to Woodland/Shrubland	387	-86.5	-1595	-33486	0
	Bare ground to Forest	394	-217.1	-4073	-85542	0
	Bare ground to Woodland/Shrubland	4147	-86.5	-17082	-358732	-1
Net Emissions				1334450	**28023458**	100
Conservative estimate (-16.5 % uncertainty)				1114266	**23399588**	

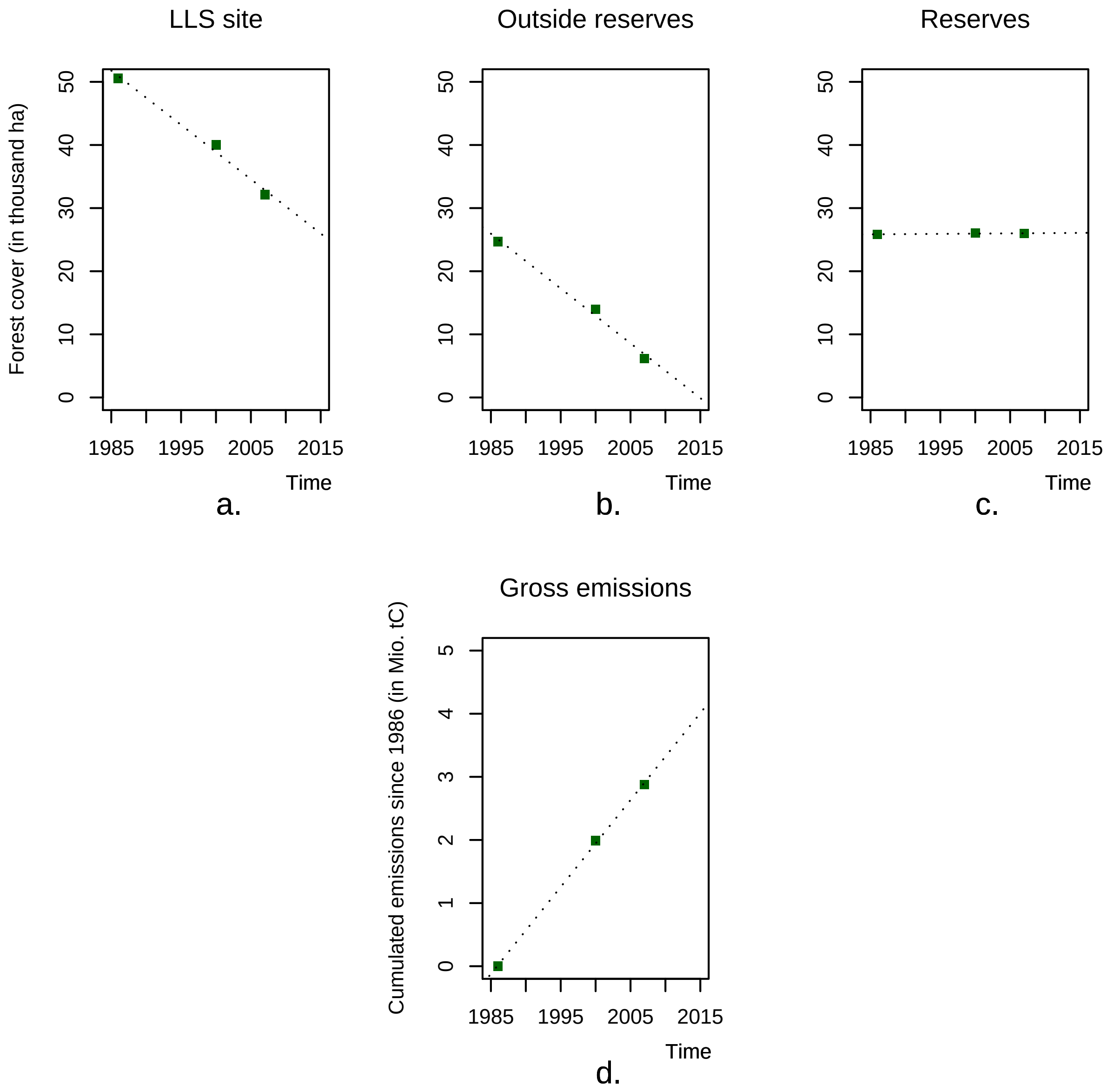


Figure 9: Forest cover change in the LLS site (a), outside reserves (b), inside reserves (c), and cumulated gross carbon emissions from land cover change (d).

Table 11: Carbon (C) emissions from land cover (LC) change in the LLS site for 1986-2007.

LLS site	**LC change 1986-2007**		**Carbon emissions**			
	LC classes	Area (*ha*)	Per ha ($tCha^{-1}$)	Annual ($tCyear^{-1}$)	Total (tC)	Percent (%)
	Carbon source					
	Forest to Woodland/Shrubland	22421	130.6	139439	2928228	95
	Forest to Urban	173	217.1	1786	37507	1
	Forest to Bare ground	1808	217.1	18689	392479	13
	Woodland to Urban	514	86.5	2116	44432	1
	Woodland to Bare ground	2476	86.5	10201	214215	7
Gross Emissions				172231	**3616861**	117
Conservative estimate (-20.5 % uncertainty)				136924	**2875404**	
	Carbon sink					
	Woodland/Shrubland to Forest	3621	-130.6	-22516	-472840	-15
	Urban to Forest	1	-217.1	-8	-159	0
	Urban to Woodland/Shrubland	18	-86.5	-74	-1553	0
	Bare ground to Forest	30	-217.1	-308	-6472	0
	Bare ground to Woodland/Shrubland	640	-86.5	-2637	-55379	-2
Net Emissions				146689	**3080459**	100
Conservative estimate (-20.5 % uncertainty)				116617	**2448965**	

5 Discussion

5.1 Overview

Within the United Nations Framework Convention on Climate Change (UNFCCC) it is explored how mechanisms for reducing emissions from deforestation and forest degradation (REDD) can be included in a post-Kyoto agreement for reducing global greenhouse gas emissions (UNFCCC, 2007). Ghana is one of the first countries that have started early actions for REDD and this study has been initiated in order to inform the development of national and local strategies. It is the aim to analyse the potential of REDD in Western Ghana where pilot activities for REDD are currently developed.

For an area of 700,000 ha the potential of REDD was investigated using satellite data for the analysis of the historical changes in the forest cover from 1986 to 2007. It was assumed that due to the high national deforestation rate of 2 % (FAO, 2007) there will be a great potential for REDD within the region. The results confirm a high historical deforestation rate of 2.3 % within the study site. However, after an era of rapid deforestation during the past decades only 12 % of the area outside forest reserves remains covered with old growth and secondary forest (Figure 7). If current deforestation rates continue the forest outside reserves will be lost completely within the next decade (Figure 8 and 9). Under a business as usual scenario the amount of carbon that can be expected to be emitted due to a complete conversion of forests to agroforests outside the reserves is 7.8 million tC or 28.6 tCO_2. This is the maximum potential of reducing emissions from deforestation outside forest reserves, if deforestation can be stopped immediately. If it can not be stopped forest degradation is likely to become the main source of carbon emissions once the forest outside reserves is lost.

Within forest reserves deforestation could not be detected indicating that the protection and sustainable use of the reserves is preventing the loss of forest inside reserves. However, forest degradation due to the overexploitation of timber is reported to be common and having negative consequences for biodiversity (Hawthorne & Abu-Juam, 1995). There is the risk that the complete loss of forests outside reserves is likely to increase the pressure on forest resources within reserves leading to forest degradation or even deforestation. It can be expected that this is likely to increase the carbon emissions from forest reserves in future if there will be no measures for improving forest conservation. Including forest reserves in a national strategy for REDD could help to prevent this scenario and would also increase the potential for REDD within the region since reserves comprise about 30 % of the area and store significant amounts of carbon. However, it is not sure whether forest reserves will be part of REDD strategies under the UNFCCC since the protection and sustainable use of forests within reserves is already regulated under the current national law.

The causes of deforestation and forest degradation are different for the areas outside and inside the reserves. Outside the reserves the increase in urban areas and bare ground together with the annual population growth of 3.2 % (Wassa Amenfi West District Report 2005, unpublished) indicate that there has been a significant increase in population and expansion of settlements since 1986. The related demand for food and cash crop production is very likely to be the driver for the rapid loss of forests. Although deforestation and degradation could not be detected within forest reserves the overexploitation of timber is reported to be an important driver for the degradation of forests within reserves (Hawthorne & Abu-Juam, 1995).

In the following sections the results and the use of remote sensing are discussed in more detail.

5.2 Satellite Data

The availability and quality of historical remote sensing data is a key requirement for the reconstruction of historical emissions from forest loss. Since the study site is situated within a moist tropical forest region, frequent cloud cover has a negative impact on the availability of satellite images. Landsat scenes from 1986 and 2000 and ASTER scenes from 2007 were used for reconstructing the historical changes in the forest cover. There were only few additional cloud free images available that would have allowed the analysis of more time steps, indicating that cloud cover can be a serious obstacle for the monitoring of REDD. This can be in particular the case were REDD strategies would be based on historical emission baselines that are fixed to a certain period of e.g. 5 or 10 years as it is discussed in some proposals for REDD strategies. It is important to note that only for the study site cloud free ASTER images were available, while the ASTER images of the area around the site had a thick cloud cover and would not have been suitable for this analysis. The ASTER satellite is not recording the global land cover by default and data is acquired only on demand for specific regions. Therefore, alternative satellite data with a global coverage such as SPOT may need to be considered where ASTER scenes are not available.

5.3 Land Cover Classification

The historic land cover changes and related carbon emissions were analysed based on a thematic land cover classification of satellite images which is in accordance with the methods that are currently developed for the monitoring of REDD (Brown et al., 2008). However, one has to be aware that each step in the identification, recording, classification and mapping of the land cover involves uncertainties that affect the accuracy of the classification and the result of the change detection. The sampling of the ground truth data in the field for the classification of the ASTER scene from 2007 helped to gain knowledge on the characteristics of the land cover. This expertise was also important for the visual sampling of the land cover classes within the Landsat satellite images from 1986 and 2000 for which historic land cover maps were missing.

In order to achieve a reliable estimate for the emissions from land cover change it is necessary to reach a high accuracy for the land cover classification in the first place. While more than 100 different land cover characteristics were distinguished in the field following the FAO Land Cover Classification System (LCCS, Di Gregorio & Jansen, 2005), this detail could not be reproduced in the classification of the land cover in the satellite images. Therefore, the collected samples were clustered into major land cover classes of similar land cover characteristics and carbon content. The number of land cover classes that were differentiated with the Maximum Likelihood classification depends on the amount of available training data for each class, the spectral characteristics of the different land cover types, and the resolution and quality of the satellite data. The more similar the spectral signal of two classes the greater can be their confusion within the classification. This makes it in particular difficult to differentiate between vegetation cover that differs only little in its spectral characteristics, which is the case, for example, for the stages of forest degradation between old growth and secondary forest. Therefore, there is a trade-off between the number of land cover classes and the overall accuracy of the classification since the class confusion within similar vegetation classes can increase the more similar classes there are. Increasing the number of ground truth samples for each vegetation type can help to increase the accuracy of the classification and to distinguish different vegetation types. However, there is also a limit in the remote sensing data which is determined by the resolution and spectral bands that are recorded by the satellite sensor.

The higher resolution of the ASTER scene allows the separation of the classes 'Woodland', which is dominated by agroforests with shade trees, from the class 'Shrubland', which is dominated by agricultural areas and degraded grass- and shrubland. Also small scale disturbances such as logging roads could be identified within the forest reserves. However, this detail in classes could not be reached in the classification of the Landsat scenes where only four major land cover classes were visually distinguished with high certainty. This is due to the more coarse resolution of the Landsat scenes but also due to the lack of ground truth data for the historic land cover. Nevertheless, the class 'Forest', which is mainly comprised of old growth forests, can visually be distinguished from other classes since its spectral signature is distinct to that from other vegetation types. This can be observed in the original satellite data in Figure 3 and 5 where the forest within reserves can easily be identified by bare eye. Due to this distinct spectral characteristic the class 'Forest' has a low average omission error of 6.2 % and achieved the highest accuracy of all classes with an average producer's accuracy of 93.7 % (Table 2 to 7). This indicates that deforestation and the therein resulting emissions can be quantified with a high accuracy.

While the coarse classification with four land cover classes does allow the analysis of the transformation of old growth forest to agroforests and non-vegetated areas, it is not sufficient for analysing and quantifying forest degradation. The class 'Woodland and Shrubland' includes agroforests, secondary forests and shrubland at different stages of degradation and regrowth. These differences could not be distinguished into further classes since the average producer's accuracy is with 83.8 % close to the limit of a minimum producer's accuracy of 80 % (Table 2 to 7). The reason for the lower accuracy of the class 'Woodland

and Shrubland' compared to 'Forest' is the greater heterogeneity of land cover types within the 'Woodland and Shrubland' class, ranging from agricultural areas with low vegetation cover to agroforests with large shade trees and secondary forests. Confusion occurs where the spectral signature of the class 'Woodland and Shrubland' is close to the spectral signature of the neighbouring land cover classes 'Bare ground' and 'Forest' causing a high omission error of 16.2 %. For example sparsely vegetated agricultural areas can be confused with 'Bare ground', and areas with a dense tree cover such as agroforests and secondary forests can be confused with 'Forest'. This makes it difficult to analyse forest degradation with a thematic classification. The class 'Forest' contains different types of forest which differ in tree height, ranging between 25 m to more than 40 m, and in tree cover, ranging between 65 % and 100 %. Forest types that are at the lower end of these parameters are in their spectral characteristics similar to agroforests and secondary forests and therefore can be confused with the class 'Woodland and Shrubland'.

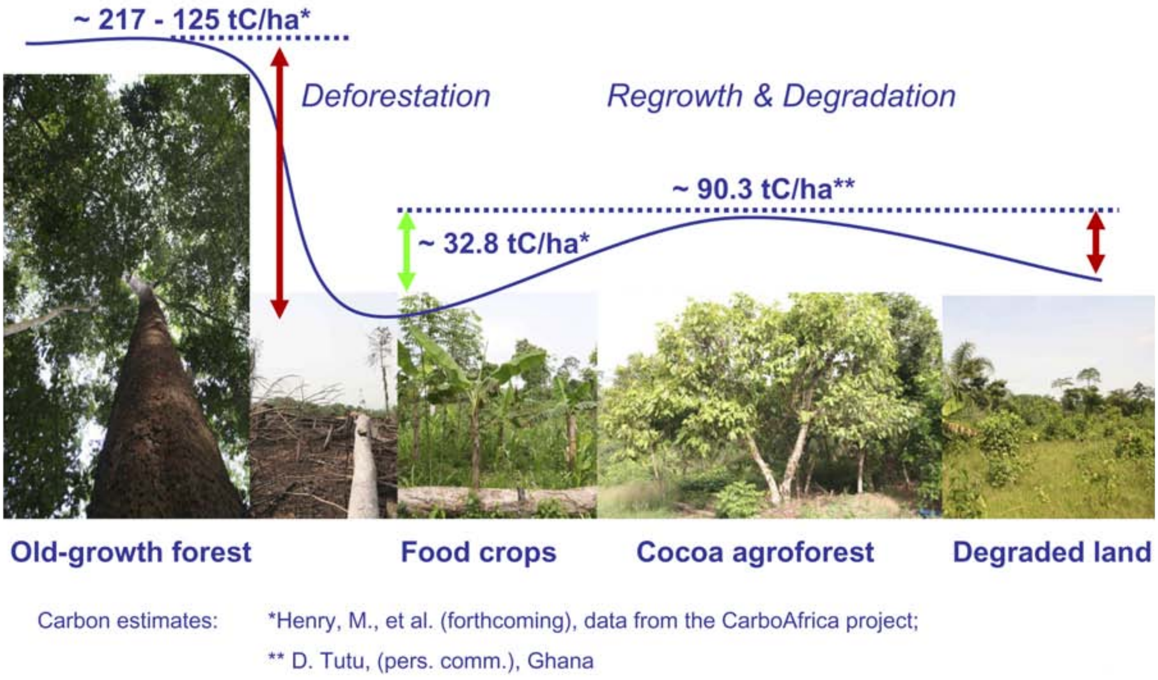


Figure 10: Dynamics in land cover and carbon content: the conversion of old-growth forest to agroforests with intermediate food crops is the main driver of deforestation and degradation. Over the long term the monoculture cocoa agroforests degrade and turn into unfertile land.

Monitoring forest degradation can be difficult due to restrictions in the quality and quantity of the available ground truth data, limitations in the multispectral satellite data and the use of a thematic land cover classification with discrete classes. With regards to the carbon content forest degradation is occurring along a gradient in vegetation cover and biomass (Figure 10). While deforestation is often related with the entire loss of the above ground biomass within a short time due to burning, forest degradation can occur due to the overuse of forest resources over a longer period. Also the depletion of the nutrients in the soils can cause the degradation of agroforests over time.

Parameters such as tree density, tree height and the percentage of the canopy cover can indicate the degree of forest degradation. Therefore, a classification that is based on continuous parameters, such as the percentage of tree cover, could allow to map and quantify forest degradation (Gessner et al., 2008). However, a single parameter, such as tree cover, can not provide sufficient information for quantifying the degree of forest degradation and the related carbon content. For example a dense agroforest with shade trees can have a closed crown cover of more than 65 % and reach a percentage in tree cover equally dense to that of an old growth forest. However, both forest types are different in their average tree height and carbon content. Therefore, further parameters such as tree height, carbon content or the structure of the stem and crown system need to be included in order to better account for forest degradation. The approach suggested by Goetz et al. (2009) of directly mapping the carbon content and avoiding the thematic mapping of land cover classes can help to reduce uncertainties in particular in the interpretation of vegetation classes. Also RADAR satellite systems such as LIDAR and ALOS are tested for analysing tree height, density and carbon content of forests (Jensen, 2007 and Kellndorfer et al., 2007). However, RADAR systems are still under development and not operational at the national and continental scale. There is also no historical data from RADAR satellites which limits their use for the analysis of historical changes in forest cover. This is why RADAR data was not considered for this study.

The other non-vegetated classes 'Urban' and 'Bare ground' achieved an average producer's accuracy of 91.2 % and 81.7 % respectively. As for the class 'Wood- and Shrubland' the class 'Bare ground' includes different land cover types reaching from roads, to open areas around settlements and to bare fields with little or no vegetation. This is likely to cause a greater confusion with the areas of little vegetation cover within the class 'Woodland- and Shrubland' and areas of bare ground within the class 'Urban'. This source of confusion is also likely to be the reason for the lower producer's accuracy of the class 'Bare ground' compared with 'Urban'. The class 'Urban' is more easily distinguished from the other classes since it includes artificial built-up areas that are distinct in their spectra from the other land cover classes and can explain the higher accuracy of the class 'Urban'. Since the carbon content of the land cover classes 'Urban' and 'Bare ground' is insignificant low the confusion between these two classes has no impact on the estimates for the carbon emissions from land cover change.

5.4 Land Cover Change

The trends in land cover changes that were found in the large ROI are very similar to the trends within the smaller LLS-site (Figure 7, 8 and 9). From 1986 to 2007 the forest cover experienced the greatest loss. While in 1986 forests within the large ROI still covered 63 % of the area it was only 37 % in 2007 (Figure 7 and Table 8). The loss of 42 % of the forest area is corresponding to an annual deforestation rate of 2.6 %. This rate is higher than the 2.0 % national deforestation rate presented by the FAO (2007). Within the LLS site the annual deforestation rate is with 2.3 % not as high as in the large ROI but still higher than the national deforestation rate (Table 9). Almost all land cover changes occurred outside of the forest reserves. The annual deforestation rate outside reserves is with 6.4 % in the large ROI and 6.5 % in the LLS-site higher than the rate of 5 % that is reported for the national level in the Ghana National Communication to the UNFCCC (2000). This indicates that the analysed region has experienced a rapid loss in forest cover that is above the national average. 79 % of the forest in the large ROI was converted into 'Wood- and Shrubland' and the remaining part into 'Bare ground' indicating that most of the forest was converted into agroforests for the production of cocoa (Table 8). In 2007 only 12 % of the area in the large ROI that is outside the reserves remained covered with forest (Figure 7 and Table 8) and if deforestation continues at current rates it is likely that the old growth forest outside the reserves will be lost completely within the next decade (Figure 8). A similar scenario can be expected for the LLS site where only 10 % of the area outside reserves is remaining covered with forest. When assuming a linear trend in deforestation the complete loss of forests can occur already by 2015 (Figure 8b. and 9b.). By then deforestation will have reached the boarders of the reserves in most places and it is likely that this will increase the pressure on the forest resources within reserves. If there are no measures for slowing deforestation it can be expected that forest reserves will be threatened by heavy degradation as has been observed in more northern reserves (Hawthorne & Abu-Juam, 1995).

Over the period of 21 years the increase in the classes 'Urban' and 'Bare ground' in the large ROI by 320 % and 491 % respectively is likely due to two factors. The first is the real change in land cover caused by the increase in urbanisation and land use, which is driven by population growth and intensification of the agricultural production. The second can be attributed to the higher resolution of the ASTER scene from 2007. It allows a more detailed classification of the land cover and the detection of smaller areas with settlements and bare ground than it is possible with the Landsat scenes. However, due to the high growth in population with an annual rate of 3.2 % (Wassa Amenfi West District Report 2005, unpublished) it can be assumed that the main reason for the significant increase in the classes 'Urban' and 'Bare ground' is the increase in urbanisation and land use intensification due to population growth. Also in the LLS-site the area of the classes 'Urban' and 'Bare ground' experienced a significant increase and is very likely caused by the growth in population. The associated increase in the demand for land in order to grow food and cash crops can explain the conversion of forest to agroforests and agricultural land, which has lead to the dramatic decline in the forest cover over the past two decades.

This is also reported to be the main reason for the loss of forest in the neighbouring region in Cote d'Ivoire and other tropical regions (e.g. Geist & Lambin and Chatelaine et al., 2004). Thereby, the land use is often following a similar pattern (Figure 10). After the clearing and burning of old growth forests food crops such as plantain and cassava are planted together with cash crops such as cocoa. Within the first three to four years the food crops provide continuous income. Thereafter, the cocoa trees are growing bigger and form an agroforest which is replacing the food crops. At an age of seven years the cocoa agroforests start to bear fruits which usually last up to an age of 25 to 30 years. Thereafter, the old cocoa agroforest is replaced with new cocoa trees or is left fallow. After two to three cycles of cocoa agroforests the nutrients in the soil are usually depleted and the land becomes unsuitable for agriculture or even for the regrowth of forest.

But not only is the need for agricultural production driving the loss of forest. Also the lack of clarity in land and tree tenure causes farmers to remove most of the forest and shade trees before planting new agroforests. Since all old growth forest and trees are state-owned and farmers cannot make any profit from practicing sustainable forest management, there is no incentive for the farmers to maintain the forest on their land. Often large shade trees within agroforests are cut by the farmers when the agroforests are planted in order to prevent their removal by logging companies at a later stage when the logging is causing damages to the crops. However, there has been a positive development that farmers are allowed to own the trees that they have planted themselves. This is creating an incentive to plant trees for timber and NTFPs and farmers are already starting to invest in tree plantations.

As the trends in land cover change within the LLS-site are very similar to those found in the large ROI (Figure 7, 8 and 9), the causes of deforestation are likely to be very similar at the small and large scale. This is an important finding as it shows that the analysis of strategies for REDD within pilot sites, such as the LLS-site, are of relevance for identifying ways for the implementation of REDD strategies within the larger region and even at the national level.

5.5 Forest Reserves

About one third of the region are forest reserves and there the forest cover remains constant throughout the past two decades (Figure 7, 8c. and 9c. and Table 8). The changes in land cover that occurred within the forest reserves correspond to only 1 % of all changes in the entire area. This indicates that the forest cover in most of the reserves is intact and that deforestation is not occurring. However, several studies indicate that due to overexploitation the forests within the reserves are at different stages of degradation and it is reported that some of the reserves are in "*poor conditions*" (Hawthorne & Abu-Juam, 1995 and Oates, 2006). This is not only leading to the loss of carbon but also creates a serious threat to biodiversity (Oates, 2006). However, the different stages of forest degradation and the impact of selective logging could not be detected with remote sensing. Therefore, ground monitoring will be necessary to assess the current state of the reserve and quantify possible carbon losses from degradation.

There is one forest reserve north of the Tano Anwia Reserve in the central part of the large ROI that was still intact in 1986 but was deforested completely by the year 2000 (Figure 4 and 6). In Hawthorne & Abu-Juam (1995) the condition of the reserve was categorised as "*very poor*" and in the topographic maps of the Survey of Ghana (Edition 1999) it was not included anymore. It is not clear whether there have been any changes in the legal status of this reserve. Since it was not indicated as forest reserve in the topographic map from 1999 it was included into the statistics for the area outside reserves. However, when assuming that it used to be a forest reserve in 1986 and including it into the statistics of forest reserves then deforestation would of course become an issue also within forest reserves.

5.6 Emissions from Land Cover Change

The analysed period from 1986 to 2007 is long enough to not only analyse gross changes in the forest cover and related carbon emissions but also to account for regrowth and carbon sequestration that is taking place when forest is cleared and replaced with agroforests and secondary forest (Ramankutty et al., 2007). Large carbon emissions occur when old growth forests are cleared within a very short time whereas the sequestration of carbon due to regrowth by e.g. cocoa agroforests is taking place over a period of up to 25 years (Figure 10). Since REDD is focusing on reducing the emissions from the loss of forests the gross carbon emissions are of significance (Table 10 and 11). Within the design of REDD strategies also incentives for reforestation and sustainable forest management are discussed, which would also take into account carbon sequestration. Therefore, carbon sequestration due to regrowth is also reported and included in the net carbon emissions (Table 10 and 11). Since the average carbon content of the land cover types were used that are specific for the region (Henry, unpublished), the reported carbon emissions are in accordance with the criteria under Tier 2 within the IPCC guidelines for Agriculture, Forestry and Other Land Uses (AFOLU; Aalde et al., 2006).

In both the large ROI and the smaller LLS site deforestation is responsible for 93 % of the gross carbon emissions showing the significance of deforestation for greenhouse gas emissions in Western Ghana. From 1986 to 2007 the total gross carbon emissions within the large ROI are estimated to be 26.8 million tC (Table 10, Figure 8). This includes already the subtraction of an uncertainty of 16.5 % in order to provide a conservative estimate as suggested by Grassi et al. (2008) and Brown et al. (2008). Also in the estimated gross carbon emissions of 2.9 million tC within the LLS-site an uncertainty of 20.5 % was subtracted (Table 11). The determined uncertainties are in the upper range of the 5 to 20 % uncertainty, that usually occur when estimating forest cover changes with remote sensing (Grassi et al., 2008). These uncertainties could be reduced by improving the land cover classification. In particular more and better ground truth samples for the class

'Bare ground' in the large ROI could increase the accuracy of the class. Furthermore, the uncertainties of the different classes could be weighted according to their contribution to the total area while in the current estimate the uncertainties of all classes have an equal weight. Since most emissions occur from the changes in the class 'Forest', which has with an average producer's accuracy of 93.7 % the highest accuracy of all classes, the conservative estimate is likely to not overestimate real emissions and to provide a reliable estimate.

The annual gross carbon emissions from the large ROI with an area of around 700.000 ha amount to 1.3 million tC (Table 10), which is equivalent to 4.7 million tCO_2. This is similar to the emissions of a modern 670 MW coal fired power plant with annual carbon dioxide emissions of 4.8 million tCO_2 which is currently under construction in Eastern Germany[1]. Outside the reserves most of the forest has already been lost but the potential for reducing emissions from deforestation is still significant. If it can be prevented that the remaining forest outside the reserves is converted into agroforests, the emission of about 7.8 million tC or 28.6 tCO_2 can potentially be avoided. This corresponds to the emissions of a coal fired power plant as described above over a period of six years. This indicates the magnitude that REDD can have in avoiding emissions if it is implemented at a large scale. The LLS-site is about ten times smaller than the large ROI and also the carbon emissions and the emissions that can be avoided by reducing deforestation are about ten times smaller (Figure 9). Therefore, the potential for REDD within the LLS site is proportionally similar to that within the large ROI. However, the window of opportunity for REDD is closing quickly since the forests outside reserves will be lost completely within the next decade if deforestation continues at current rates (Figure 8b. and 9b.).

Determining the potential for REDD within forest reserves is more difficult since it is not clear yet whether forest reserves will be included in a national strategy for REDD or not. There exist already national laws and regulations for sustainable forest management and biodiversity conservation within forest reserves, which aim at preventing deforestation and forest degradation. There is also a monitoring system that controls the selective logging within reserves. In theory forest reserves should already be protected from deforestation and forest degradation. However, in reality forest reserves are experiencing forest degradation and in some cases even deforestation due to overexploitation of timber and a weak enforcement of the existing forest laws (Hawthorne & Abu-Juam, 1995). It is difficult to predict and quantify the rate of forest degradation or deforestation within reserves in order to estimate the potential for REDD in the future. As observed in the study site the forest within some reserves has completely vanished and was converted into agroforests within a short time while other forest reserves are degrading more slowly. The drivers for forest degradation and deforestation within forest reserves are mainly legal and illegal logging. Therefore, they differ from those outside reserves and require a more detailed analysis. One approach to quantify the potential of REDD within reserves could be to analyse the amount of timber that is harvested, taking into account the emissions that are caused by the damage due to selective logging. It can be expected that without increasing the efforts

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[1] Source: BUND, http://www.bund.net/index.php?id=2390, retrieved from the web on 2009-08-03

for forest conservation and sustainable forest management, it is likely that forests within reserves will degrade further causing not only the loss of carbon but also having negative impacts on biodiversity (e.g. Hawthorne & Abu-Juam, 1995 and Oates, 2006).

The results confirm that land cover changes and in particular deforestation is a significant source for greenhouse gas emissions within Western Ghana. Even after accounting for regrowth deforestation is still contributing 78 % to the emissions. Therefore, Western Ghana qualifies in particular for activities for REDD. However, the potential of REDD in Western Ghana depends on several factors: i) it needs to be differentiated between the potential of reducing deforestation and the potential of reducing degradation and ii) the potential of REDD for the areas outside and inside reserves needs to be assessed separately.

Since future REDD strategies will require a thorough quantification of the carbon emissions from deforestation and degradation at the national level, solutions for monitoring forest degradation are needed. Asner et al. (2005) have shown that the detection of forest degradation shortly after selective logging is possible using Landsat images and a great amount of ground truth data. This indicates that the timing of the forest monitoring with remote sensing is also of importance. With RADAR satellite data degradation can be detected up to two years after the logging occurred Hirschmugl et al. (2009). Thereafter, the regrowth of secondary vegetation is creating a dense cover, which is difficult to be distinguished from old growth forest using remote sensing although the forest is still in a degraded state since the regeneration to old growth forest takes more than 40 years. It might be worth testing a combination of approaches using multispectral satellite data as suggested by Goetz et al. (2009) and RADAR systems (e.g. Hirschmugl et al., 2009) for developing a monitoring systems that can detect forest degradation. Thereby the forest reserves of Ghana could provide a test ground. The forest within the reserves is selectively logged in 40-year rotation cycles within assigned concessions. Therefore, the places where selective logging is taking place and the intensity of impact from logging are well known. This would allow testing the monitoring of forest degradation by combining the information on forest degradation in reserves with satellite data.

5.7 Outlook on Possible Strategies for REDD

Western Ghana is experiencing a shift from an era where deforestation has been the main source for carbon emissions to a new era in which the emissions from the degradation of secondary forests and agroforests outside reserves and of forests within reserves will be the dominating source for greenhouse gas emissions.

In order to tap into the maximum potential of REDD in Western Ghana it is recommended that (i) activities for REDD should start as early as possible in order to save the last remaining forests outside reserves and (ii) that forest reserves should be included in national REDD strategies in order to avoid further degradation.

Like in Cameroon, where carbon payments can provide a positive incentive for cocoa farmers to protect forests (Bellassen & Gitz, 2008), carbon payments could also be an option in Ghana for the protection of forests within the cocoa agroforests outside the reserves. However, recent investigations indicate that in Ghana the income from payments for REDD are not significantly higher than the income from cocoa production and therefore, the financial incentive by carbon payments might not be high enough Sandker et al. (submitted). Furthermore, the expansion of highly lucrative cash crops, such as the production of palm oil, can out-competed payments for REDD (Butler et al., 2009). Therefore, strategies for REDD should not only build on carbon payments alone but also consider the multiple benefits that intact forest ecosystems provide for the livelihoods of forest dependent people and include incentives for sustainable forest management and good forest governance.

The multiple goods and services of forest ecosystems are of greater value for the livelihoods of local forest dependent people than the value of carbon alone. Besides the relevance of forests for mitigating climate change at a global scale, they also play an important role in maintaining the regional climate in particular the regional water cycle and precipitation (Bonan, 2008 and Paeth et al., 2009). Thereby, intact forest ecosystems can help to reduce the impact of global climate change on the local level and increase the capacity of local people to adapt to climate change. An intact water cycle and regular precipitation is crucial for sustaining agriculture and food production. Consequently, strategies for REDD need to consider more holistic approaches for forest conservation and sustainable forest management that go beyond the value of carbon. It is important to allow an equitable participation of the communities and forest stakeholders in the development of such strategies in order to make sure that the causes of deforestation and forest degradation are addressed and that possible benefits will be shared equitably. Incentives for reducing deforestation and forest degradation that are not based on carbon payments can include the clarification and protection of the land and tree tenure of forest dependent people in order to promote sustainable forest management and a diversification of the use of agroforests.

The inclusion of forest reserves in a national strategy for REDD could significantly increase the potential of REDD in Western Ghana, since forest reserves account for around 30 % of the total area and store significant amounts of carbon. The expected income from carbon payments for REDD could increase the capacities for forest conservation and help to enforce the existing laws and regulations for the sustainable management and protection of forest reserves. They could also support activities for sustainable forest management and development in communities next to the reserves and help to reduce the risk of encroachments and illegal logging. But instead of locking people out of the forests, the communities should still be able to benefit from forest reserves by being allowed to collect NTFPs within reserves. Since Western Ghana is within one of the world's biodiversity hotspots (Meyers et al., 2000) the strengthening of the protection of forest reserves through strategies for REDD would be an important benefit for biodiversity conservation.

Besides the possible benefits from REDD, the current development of financing forests through the carbon market should not lead to a situation where sustainable forest management and forest conservation becomes depend on the income from carbon finance alone.

Beyond the value of forests for climate regulation and the market value of forest products there is also an intrinsic value of forest ecosystems and biodiversity, which is relevant for local people and humankind at large (Alcamo, 2003). This intrinsic value is comprised of, for example, the cultural value of forests or the value of forest species, which cannot be expressed in monetary terms. The intrinsic value justifies the conservation of forests independent from the market and use value of goods and services that forests provide. Carbon finances can support efforts for forest conservation and reward sustainable forest management, but should not become the only underlying motivation and mechanism for forest conservation. There is the risk that markets and prices for forest carbon and commodities can change, leading to perverse incentives that could undermine the conservation of forest ecosystems and biodiversity. If carbon prices are too low to provide sufficient monetary incentives for forest conservation, other land uses such as the production of cash crops and biofuels are likely to out-compete strategies for REDD (e.g. OECD/FAO, 2007; Spracken et al., 2008 and Butler et al., 2009). Therefore, good forest governance that provides for the sustainable use and protection of forest ecosystems should be the core of any national strategy for REDD.

6 Conclusion

Currently Western Ghana is experiencing a shift from an era where deforestation has been the main source for carbon emissions to a new era where the emissions from the degradation of forests and agroforests will be the dominating source of greenhouse gas emissions. From 1986 to 2007 the loss of forests occurred almost entirely outside of forest reserves. At the same time urban areas and areas of bare ground increased, indicating that population growth and increasing demand for food and cash crop production are the main driver for deforestation. Most of the forest was converted to agroforests, mainly for the production of cocoa. Assuming that deforestation will continue at present rates it is likely that the forests outside reserves will be lost completely within the next decade and that forest reserves will be threatened by degradation. Therefore, the window of opportunity for REDD in Western Ghana is closing quickly.

If there will be strategies for REDD that help to protect the remaining forest outside reserves, emissions of about $7.8\,\text{million}\,tC$ or $28.6\,tCO_2$ can potentially be avoided. This is equivalent to the emissions of a $670\,MW$ coal fired power plant over a period of six years. Furthermore, if forest degradation will be monitored it is likely that the potential for REDD, in particular within forest reserves will be even greater. Therefore, it is recommended that activities for REDD should start as early as possible in order to save the last remaining forests outside reserves. Furthermore, since forest reserves cover about one third of the analysed region they should be included in a national strategy for REDD. In order for REDD strategies to effectively address the drivers of deforestation local communities should be involved in the planning and design of REDD strategies. Through an equitable participation and benefit sharing it is more likely that strategies for REDD will be accepted at the local level and successfully implemented. Thereby, REDD could promote sustainable forest management and the enforcement of good forest governance.

In order to include also forest degradation in strategies for REDD the monitoring of forest degradation using remote sensing technology will have to be developed further and intensive ground truth measurements will be required. While it was possible to measure deforestation with Landsat and ASTER satellite data it was not possible to detect forest degradation. This is mainly due to the lack of sufficient ground truth data and the limits of differentiating the stages of forest degradation with multispectral satellite data. Therefore, more ground truth data is needed and different approaches such as the direct mapping of the carbon content of the vegetation or a combination of multispectral and RADAR data need to be tested.

Besides the potential for REDD the forests of Western Ghana are also of great importance for maintaining the regional water cycle and contribute to the generation of precipitation that is needed for agricultural production. The forests are also part of one of the world's biodiversity hotspots and harbour a great number of endemic and threatened species. Therefore, strategies for REDD that aim at forest conservation would also support national strategies for climate change adaptation and biodiversity conservation.

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Appendix

A: Field protocol of the FAO Land Cover Classification System (LCCS)

ANNEX 1: FIELD VERIFICATION FORM *Africover Project*

A. GENERAL INFORMATION

RELEVEE Nº
AREA NAME
LOCATION
OBSERVER
DATE
TIME
RELEVEE SIZE (in m² or ha)

FIELD SAMPLE COORDINATES

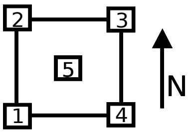
N or S	East

ACCESSIBILITY
- ☐ Very Good
- ☐ Good
- ☐ Medium
- ☐ Bad

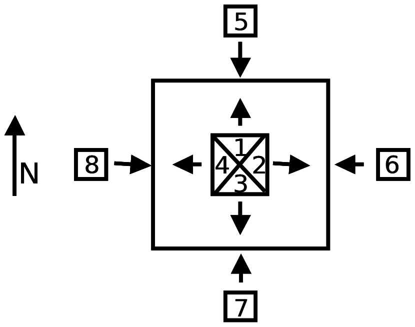
COORDINATES

N or S	East	LAT/LONG	UTM	GPS	Topo Map
		☐	☐	☐	☐
		☐	☐	☐	☐
		☐	☐	☐	☐

On the spot	Observing the spot from a distance
Indicate Relative Position of Coordinates	Distance from viewpoint to observed point ____ (m) The bearing of the observed point ____ (º)



FIELD PHOTOGRAPHS



Relative Position of photograph

Film Roll Nº	

Photo Shot Nº	Position

GENERAL LANDFORM

Slope
- ☐ Flat to Gently Sloping Terrain (0 - 7 %)
- ☐ Gently Sloping to Moderately Sloping (8 - 3 %)
- ☐ Sloping to Moderately Steep, Undulating to Rolling terrain (14 - 20 %)
- ☐ Steep to Very steep, Rolling to Hilly Terrain (21 - 55 %)
- ☐ Extremely Steep Terrain, Steeply Dissected Hilly and Mountainous Terrain (56 - 140 %)

B. GENERAL LAND COVER INFORMATION

LAND COVER

- General Land Cover Type Relevee Site

A.	☐	Vegetated	☐	Non-Vegetated
B.	☐	Terrestrial	☐	Aquatic or Regularly Flooded Land (Including WADY Areas)

- Specific Land Cover Type

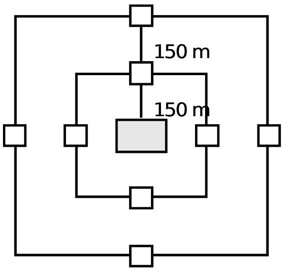
	Single Major Land Cover Aspect	Two Mixed Major Land Cover Aspects	
		Most Important	Second
Cultivated	☐	☐	☐
Natural / Semi-Natural	☐	☐	☐
Built Up	☐	☐	☐
Bare	☐	☐	☐
Artificial Water Body	☐	☐	☐
Inland Water	☐	☐	☐

AREA LANDCOVER HOMOGENITY (Applicable if on spot)

Land Cover Homogeneous for more than 300 m around the sample area :

☐ Yes

☐ No



LAND COVER SEASONAL ASPECTS

	Natural / Semi-Natural Vegetation				Cultivated Fields			
	dry	green	flowering	fruits	ploughed	initial stage	full mat. stage	harvested
TREES	☐	☐	☐	☐	☐	☐	☐	☐
SHRUBS	☐	☐	☐	☐	☐	☐	☐	☐
HERBS	☐	☐	☐	☐	☐	☐	☐	☐

C. SPECIFIC LAND COVER INFORMATION

NATURAL AND SEMI-NATURAL VEGETATION

				Leaf Type			Leaf Phenology	
	Level	Cover	Height	Broad	Needle	Aphyllous	Evergreen	Deciduous
WOODY				☐	☐	☐	☐	☐
Trees	1			☐	☐	☐	☐	☐
	2			☐	☐	☐	☐	☐
	3			☐	☐	☐	☐	☐
Shrubs	1			☐	☐	☐	☐	☐
	2			☐	☐	☐	☐	☐
HERBACEOUS								
Graminoids								
Forbs								

Cover Estimation of vegetation Visual ☐ Instrumental ☐ Other ☐

Eidesstattliche Erklärung

Ich versichere hiermit, dass ich meine Masterarbeit

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selbstständig und ohne fremde Hilfe angefertigt habe. Von mir wurden keine anderen als die angegebenen Hilfsmittel benutzt. Ich habe alle von anderen Autoren wörtlich Übernommenen Stellen wie auch die sich an die Gedankengänge anderer Autoren eng anlehnenden Ausführungen meiner Arbeit besonders gekennzeichnet und verwendete veröffentlichte wie unveröffentlichte Quellen zitiert. Diese Arbeit hat in gleicher oder ähnlicher Form noch keiner anderen Prüfungsbehörde vorgelegen.

Johannes Förster Bayreuth, den 31.08.2009