Capabilities and deficiencies of terrestrial forest inventory systems in the assessment of forest degradation in the scope of REDD+

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I certify that the English of the cumulative dissertation "Capabilities and deficiencies of terrestrial forest inventory systems in the assessment of forest degradation in the scope of REDD+" written by Daniel Plugge from University of Hamburg (Institute for World Forestry) has been reviewed and is correct.

The dissertation was reviewed by Susan J. Ortloff (US citizen)

- currently working as a freelance translator and editor
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  - Prof. Dr. F.H. Schweingruber, *Trees and Wood in Dendrochronology*, Springer-Verlag
  - Prof. Dr. F. H. Schweingruber, *Tree Rings and the Environment*, Springer-Verlag, WSL
  - Dr. G. Kenk, New *Perspectives of Oak Silviculture in Germany*, FVA
  - Dr. E. E. Hildebrand, *The Heterogeneous Distribution of Mobil Ions in the Rhizosphere of Acid Forest Soils, Entry in the Journal of Environmental Science and Health*, FVA
  - Dr. G. Kattenborn, *Atmospheric Correction of Landsat/TM Data over Mountainous Terrain*, Entry in the Proceedings of the XVII ISPRS Congress

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Summary

Despite the well-known importance to human society and environment, the deforestation and degradation of forests continues at an alarming rate. The many efforts made in the past to reduce the loss and destruction of forests, and the ecosystem goods and services they provide, have had no significant impact on the negative development of forest areas. In the light of global climate change, the role of forests as the largest terrestrial carbon reservoir and their importance in the global carbon cycle has gained relevance. A new mechanism to reduce the deforestation and degradation of tropical forests called REDD (Reducing Emissions from Deforestation and Forest Degradation in developing countries) was introduced into the international climate negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) at the 11th Conference of the Parties (COP11) in Montreal in 2005. REDD aims to assign a monetary value to the carbon stored in forests and to reward developing countries for the reduction of their deforestation and forest degradation rates. Since the first submission, the debate on scientific, political and public levels has led to many valuable amendments and improvements to the initial proposal. These changes include the integration of the conservation of forest carbon stocks, the sustainable management of forests and the enhancement of forest carbon stocks, identified by the term REDD+. While the initial concept of REDD appears rather simple, its embodiment and implementation requires the careful harmonization of a multitude of topics. The following summary of this cumulative dissertation presents the major topics that need to be considered for a successful implementation of REDD+.

One of these topics is the establishment of a Measuring, Reporting and Verification (MRV) system for REDD+. The three articles that constitute this cumulative dissertation focus on the development, characteristics and specific features of a MRV system to assess changes in forest area and forest carbon stock and related emissions or removals.

The first part of the comprehensive summary presents the thematic context of the three articles. This thematic context consists of the major topics associated with the implementation of REDD+. It introduces the initial concept of REDD within the scope of global climate change negotiations and presents the main terms and definitions. Then, the ‘Framework of REDD+’ focuses on the ‘Drivers of Deforestation and Forest Degradation’, followed by short summaries on the implementation of REDD+ as a ‘Phased Approach’, the ‘Financial Aspects of REDD+’, the possibilities and implications of setting ‘Forest reference (emission) levels’ and the reasons for and scope of ‘Safeguards’. The framework includes a short explanation of the terms ‘Additionality, Permanence and Leakage’. After the framework is set, the summary presents the ‘Core issues of REDD+ for the thesis’. These are the issues of ‘Deforestation’, ‘Forest Degradation’, ‘Measuring, Reporting and Verification (MRV) for REDD+’ and the associated ‘Uncertainties’. These issues form the pillars on which the three articles of this cumulative dissertation are based.

The second part of the comprehensive summary integrates the three articles that constitute the cumulative dissertation into the thematic context. The first article focusses on the development and implementation of a combined inventory approach for REDD+. It demonstrates how reliable estimates of forest carbon stocks and its changes over time can be made with the introduced methodology. The second article analyses the influence of uncertainties and monitoring costs on the accountability of emission reductions. It shows, on the one hand, that uncertainties may outweigh successful efforts in the reduction of emission and, on the other hand, that the influence of uncertainties on the successful implementation of REDD+ is higher than the influence of the price paid per ton of carbon. The third article focuses on the influence on accountable emission reductions of uncertainties at two points in time and different area sizes for forest degradation. It shows that rules for the propagation of

uncertainties from one period to another are needed and that the size of forest degradation areas has a major impact on the accountability of successful emission reductions. Each article is presented with a short summary of the applied methods and gained results. Each summary is followed by a discussion of the respective article in the thematic context, showing the implications and recommendations of the findings for the issues presented in the first part.

On the basis of the results of the articles and their discussion in the thematic context, specific conclusions on the capabilities and the deficiencies of terrestrial forest inventory systems in the assessment of forest degradation in the scope of REDD+ are drawn. The first part of the conclusions shows that terrestrial forest inventory techniques are capable of and indispensable for assessing and estimating forest degradation. These techniques are readily available for the implementation of a transparent, consistent, robust, comparable and controllable MRV system. The second part shows that there are deficiencies in the applicability of these techniques such as high costs or difficulties in assessing remote areas and that terrestrial forest inventories alone cannot provide the required level of completeness for a credible MRV system. The comprehensive summary is completed by a general conclusion on ways to overcome the remaining deficiencies.

The complete versions of the three articles that, together with the comprehensive summary, constitute this cumulative dissertation and a short explanation of the personal contribution of the author to the articles are attached in the Annex.

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Part I. Thematic context

1 Introduction

1.1 Relevance of the world's forests

The world's forests spread over 4 billion hectares, thereby covering 31% of the earth's total land area (FAO 2010). They provide a multitude of goods and services to human society. Even in today's highly civilized and engineered world, 1.6 billion people still depend directly or indirectly on forests for their daily living. Most of the forest dependent people belong to the poorest of the poor, living with less than 1 US$ per day. 90% of these are directly dependent on forest goods and services for their livelihoods (World Bank 2001). Forests provide wood and non-wood goods as well as income by selling these products. Furthermore, forests are seen as a reserve for times of economic depression and as a source of arable land whenever the demand for food rises or the productivity of the available agricultural land diminishes. The dependence on goods and services from forests often extends beyond the capacity of the ecosystem to provide them. Increasing population growth jeopardizes the previous sustainable cycles of using, abandoning and after regeneration reusing forest land. Thus, more and more forests are overused, degraded or deforested. This decline continues at an alarming rate especially in the tropics. The United Nations Food and Agricultural Organization (FAO) estimated that 13 million hectares of forest have been converted into non-forest areas per year in the last decade. The effects of this trend are not only limited to local populations that directly depend on the forests, but also have a global dimension. Forest ecosystems fulfill a very important role in the regulation of the global climate and in the carbon cycle. FAO states that 289 gigatons of carbon are stored in the biomass of the world's forests (FAO 2010) and it is widely accepted that forests are responsible for a major proportion of the land-based carbon uptake (Pan et al. 2011). At the same time, the ongoing deforestation and forest degradation processes are estimated to contribute 12 – 20% to the anthropogenic carbon emissions. Deforestation and forest degradation do not only affect the global carbon cycle, but also the function of forests as a shelter for biodiversity. Tropical forest ecosystems are believed to support an estimated half of terrestrial biodiversity (Myers et al. 2000). One hectare of tropical forest may contain more than 280 tree species (Oliviera and Mori 1999). Furthermore, a substantial proportion of pharmaceuticals originate from tropical forests, and a large amount is expected to be still undetected (Mendelsohn and Balick 1995). On regional and local levels, forests regulate water systems, soil properties and air quality. Regarding the undoubted importance of especially tropical forests for human well-being and the human environment it is not surprising that there have been numerous efforts on public, institutional and political levels to slow down or prevent deforestation activities, like the boycott of tropical timber in the eighties, the creation of certification systems like FSC[1] and PEFC[2] or the Clean Development Mechanism. The management of tropical forests has been tested and promoted since the beginning of colonialism (FAO 2003). Even though none of these initiatives has had a breakthrough impact so far, all raised awareness in different groups of society for the problems arising from the loss and destruction of tropical forests. Through the emergence of the globalized world, which connects people from all continents in real time (Edmunds and Turner 2005), the existence and importance of global challenges, that can only be treated on a worldwide scale are perceived by an ever growing audience (Leichenko and O'Brien 2008).

[1] FSC stands for Forest Stewardship Council
[2] PEFC stands for Programme for the Endorsement of Forest Certification

1.2 Climate change, mitigation, and political arena

One of the most pressing global challenges at present is climate change, also termed global change. The latter signifies that small changes in the climate system can have a multitude of impacts on a global scale. However, these impacts are perceived in different ways on a local scale. For example, it is widely accepted that more extreme weather patterns such as hurricanes, severe and longer droughts, and longer heat periods will occur (IPCC 2007). It is also expected that climate change may lead to increasing precipitation and a rise of the sea water level in Northern Europe, thus increasing the risk of coastal erosions and floods (Alcamo et al. 2007). Especially small lagoon islands like Tuvalu are already facing the thread of being flooded (Mimura et al. 2007). While it is always difficult, or near impossible, to infer climate change from current weather phenomena, the augmenting intensity of extreme weather events and rising sea levels are apparent within the last decade.

Climate change is by no means a new topic. In 1988 the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) to assess all relevant information on the risk of human induced climate change. It supports the United Nations Framework Convention on Climate Change (UNFCCC) which was adopted at the Rio Summit in 1992 and entered into force in 1994. The UNFCCC provides the legal basis and overall policy framework for addressing the climate change issue on a worldwide basis (Le Treut et al. 2007). It is supported by the Subsidiary Body for Scientific and Technical Advice (SBSTA) that provides information and advice and responds to scientific, technological and methodological questions of the UNFCCC (UNFCCC 1992). Under the UNFCCC the Kyoto Protocol was developed and finally adopted in 1997. Its approval did not come until 2005 after being ratified by a sufficient number of countries, including notably Russia. It has not been ratified by several emission intensive countries such as the USA and China even though any ratifying country is free to withdraw from the Kyoto Protocol without being fined, as exemplified by Canada in 2011. When ratified, the Kyoto Protocol sets binding targets for industrialized countries to reduce greenhouse gas (GHG) emissions by adaptation or mitigation activities. It contains a set of eight policies and measures to achieve the reduction targets, such as the enhancement of energy efficiency, the promotion of sustainable forest management practices and afforestation and reforestation, or sustainable forms of agriculture. From these policies and measures the countries can choose the most appropriate according to their national circumstances. Furthermore, the Kyoto Protocol offers three mechanisms for meeting national reduction targets. These are (i) “emissions trading” also known as the carbon market, (ii) the “clean development mechanism” (CDM) and (iii) “joint implementation” (UNFCCC 1998). Despite all efforts undertaken by the ratifying countries to reduce the release of GHGs into the atmosphere, the World Meteorological Organization reported an overall increase in the release of all important GHGs for the last reporting period (WMO 2011). As the first commitment period of the Kyoto Protocol ends in 2012 UNFCCC has taken intensive actions to establish a “post-Kyoto Protocol” during several Conferences of the Parties (COP). Until COP15 no consensus on a prolongation of the Kyoto Protocol could be achieved. For this reason, the Kyoto Protocol was extended at the last COP (COP17) in Durban towards a voluntary second commitment period running either until the end of 2017 or the end of 2020. The aim is set at an aggregate reduction of GHG emissions from the industrialized countries of at least 25 – 40 % below 1990 levels by 2020 (UNFCCC 2011a). This emission reduction is needed to achieve the target of limiting global warming to not more than 2 degrees Celsius (EU 2008).

Global warming is threatening many already endangered ecosystems and species. This is due to the loss of natural refuge and the anticipated short time in which ecosystems or species will need to adapt to a changing climate. Even if their genetic resources would allow for it, forest ecosystems are especially incapable of reacting quickly to a fast changing climate. Taking into account the high relevance of forests in the global carbon cycle and for human well-being, a further decrease of the world's forests due to climate change and the related release of additional GHGs into the atmosphere would further fuel the vicious circle of climate change and natural processes enforcing climate change.

1.3 REDD+

The rising knowledge about the impact of climate change and the continuous search for answers for the related challenges has opened the floor for discussion on a new initiative to reduce and halt deforestation and forest degradation initially called REDD (Reducing Emissions from Deforestation in Developing countries). In 2005, the Coalition for Rainforest Nations (CfRN), led by the governments of Papua New Guinea and Costa Rica, issued the idea of financially accounting for the carbon that is stored in the tropical forests to the Conference of the Parties at the 11th session of UNFCCC. In their submission CfRN considered that so far developing countries were not actively contributing to mitigation and adaptation activities and that the reduction of deforestation rates was not an eligible action for emission reductions under the Kyoto Protocol (UNFCCC 2005). The momentum was the realization by tropical developing countries that their broad extent of forests is equivalent to a wealth of global importance, which the global society historically considered a common good, despite the fact that it had to be administrated on a national level. Preserving forests against the pressures driven by the needs of the rural poor and the financial and political power of large agricultural or livestock companies is a futile task as long as the forest itself has no economic value. Thus, CfRN proposed to the international community to assign a value to the carbon stored in forests and to reward countries for efforts towards reducing their rates of deforestation and thereby diminishing the release of carbon into the atmosphere. This idea was termed REDD. It was extended shortly afterwards by the inclusion of the topic of forest degradation, since direct human induced degradation can be seen as a precursor for deforestation. REDD was taken into consideration by a broad majority of the parties. From 2005 onwards the idea of REDD and its implementation have been discussed broadly in the political and scientific arenas. It offered a new and aspiring topic that kept hundreds of policy makers, scientists and experts busy. Especially the results of the Stern Review on the Economics of Climate Change (Stern 2007), showing that the reduction of tropical deforestation would be the most cost effective way of tackling climate change, together with the fact that about one fifth of the anthropogenic release of GHGs is due to tropical deforestation, fuelled the action towards this topic. REDD gained awareness not only in the scientific and political communities, but also in the broader public, particularly by those who would be most affected by its implementation: the indigenous people and the forest dwellers of the tropical forest nations. With the support of many NGOs that work for and with these people, several platforms for critical surveillance currently exist and have an impact on the development of the ideas and the implementation of REDD. Scientists and governments have made important steps towards the practicability and the aims of REDD. In 2008, the European Commission proposed to "halt global forest cover loss by 2030 at the latest and to reduce gross tropical deforestation by at least 50 % by 2020" (EC 2008). Constant modifications have finally led to the recent status of REDD, now termed REDD+. In the complete wording REDD+ stands for "Reducing emissions from deforestation and forest degradation in developing countries, and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries". However, this entails by far not the entire dimension of REDD+. While REDD+ originates from a simple idea, i.e. giving a financial value to the carbon stored in forests, the implementation of this idea requires a highly complex and multi-targeted approach.

1.4 Structure of the comprehensive summary

The comprehensive summary gives an overview of important topics regarding the successful implementation of REDD+. The emphasis of this overview is to provide insights into the scientific, social, political and financial framework of REDD+. To facilitate the understanding of the framework it is preceeded by a short introduction on main terms and definitions relating to REDD+. The main issues of deforestation, forest degradation and MRV (Measuring, Reporting and Verification) and aligned uncertainties will be discussed after the framework is set. The framework and the main issues form the thematic context of the three articles that constitute this thesis. The articles are briefly summarized and discussed in the context of the framework in the second part of this comprehensive summary. These articles are:

1. Plugge, D., Baldauf, T., Rakoto Ratsimba, H., Rajoelison, G., Köhl, M. 2010. Combined biomass inventory in the scope of REDD (Reducing Emissions from Deforestation and Forest Degradation). Madagascar Conservation and Development 5, 23–34.
2. Plugge, D., Baldauf, T., Köhl, M. 2012. The global climate change mitigation strategy REDD: monitoring costs and uncertainties jeopardize economic benefits. Climatic Change. Published with Open Access.
3. Plugge, D., Köhl, M. 2012. Estimating carbon emissions from forest degradation: implications of uncertainties and area sizes for a REDD+ MRV system. Canadian Journal of Forest Research 42, 1996–2010.

1.5 Definitions

1.5.1 Forest[1] and Forest Land

As REDD+ focuses on forests and forest land, defining these terms is decisive for a proper implementation. IPCC (2006) adopted FAO's definition of forests which reads:

"Forest is a minimum area of land of 0.05 – 1.0 hectares with tree crown cover (or equivalent stocking level) of more than 10 – 30 per cent with trees with the potential to reach a minimum height of 2 – 5 metres at maturity in situ. A forest may consist either of closed forest formations where trees of various storeys and undergrowth cover a high portion of the ground or open forest. Young natural stands and all plantations which have yet to reach a crown density of 10 – 30 per cent or tree height of 2 – 5 metres are included under forest, as are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest."

Forest Land is defined as:

"… all land with woody vegetation consistent with thresholds used to define Forest Land in the national greenhouse gas inventory. It also includes systems with a vegetation structure that currently fall below, but in situ could potentially reach the threshold values used by a country to define the Forest Land category."

[1] In the context of the Kyoto Protocol, as stipulated by the Marrakesh Accords, cf. paragraph 1 of the Annex to draft decision -/CMP.1 (Land Use, Land-use Change and Forestry) contained in document FCCC/CP/2001/13/Add.1, p.58

1.5.2 Deforestation

Deforestation is the first ‘D’ in REDD+ and has always been part of the initial concept. It is defined by IPCC (2006) as:

“The direct human-induced conversion of forested land to non-forested land.”

Deforestation thus entails a land cover change from forest land into any other land category according to the forest definition given above.

1.5.3 Forest Degradation

Forest Degradation is the second ‘D’ in REDD+ and was added to the initial concept. A binding definition for forest degradation has not yet been adopted, but it undoubtedly can only happen in the land use category ‘Forest Land Remaining Forest Land’. Thus, in contrast to deforestation, no land cover change occurs. Two of the most common proposals for defining forest degradation are:

“The reduction of the capacity of a forest to provide goods and services.” (FAO 2002)

“A direct human-induced long-term loss (persisting for X years or more) of at least Y% of forest carbon stocks [and forest values] since time T and not qualifying as deforestation or an elected activity under Article 3.4 of the Kyoto Protocol.” (IPCC 2003a)

While the first definition is rather generic, the second is more detailed and used in the context of REDD+ under UNFCCC. However, both definitions are criticized for the difficulties in measuring, reporting and verifying the used parameters (Penman 2008, Simula 2009).

1.5.4 Measuring, Reporting and Verification

Under UNFCCC there exists no finally adopted definition for Measuring, Reporting and Verification (MRV) for REDD+ activities. A decision on a definition is expected at the next COP18 in Doha (UNFCCC 2012a). UN-REDD[1] (2009) gives the following explanation for the elements of MRV in a Draft Discussion Paper:

“Measurement: Processes of data collection over time, providing basic datasets, including associated accuracy and precision, for the range of relevant variables. Possible data sources are field measurements, field observations, detection through remote sensing and interviews.

Reporting: The process of formal reporting of assessment results to the UNFCCC, according to predetermined formats and according to established standards, especially the IPCC Guidelines and GPG. It builds on the principles of transparency, consistency, comparability, completeness and accuracy.

[1] UN-REDD is the “United Nations Collaborative initiative on Reducing Emissions from Deforestation and forest Degradation in developing countries” initiated by the FAO, the United Nations Development Programme (UNDP) and the United Nations Environment Programme (UNEP) in September 2008.

Verification: The process of formal verification of reports, for example, the established approach to verify national communications and national inventory reports to the UNFCCC." (UN-REDD 2009)

While a binding definition on these topics is still pending, it is clear that an unambiguous and consistent MRV approach will be an indispensable component of REDD+.

2 Framework of REDD+

The following chapter outlines major topics for the implementation of REDD+. First, an overview on the main ‘Drivers of Deforestation and Forest Degradation’ is given. Thereafter brief summaries present the construction of REDD+ as a ‘Phased Approach’, the ‘Financial aspects of REDD+’, the possibilities and implications of setting ‘Forest reference (emission) levels’ and the reasons for and scope of ‘Safeguards’. The framework is completed by a brief explanation of the terms ‘Additionality, Permanence and Leakage’.

2.1 Drivers of Deforestation and Forest Degradation

Any approach that aims at reducing deforestation or degradation of forests has to tackle the drivers leading to these processes. Numerous studies have been undertaken on the identification of the different drivers, identifying two major types that have to be differentiated. These types of drivers have been given different names, e.g. “proximate” and “underlying” (Geist and Lambin 2002) or “immediate” and “underpinning” (Rosengren 2010) or “direct” and “indirect” (Broadhead and Izquierdo 2010). The distinction, however, is always the same. While the first are directly leading to deforestation and forest degradation, the latter are enabling and facilitating conditions for the first to happen. Broadhead and Izquierdo (2010) developed an overview on these drivers introducing a further division into sub-categories regarding their link to the forestry sector which is adapted and displayed in Table 1. Other sub-categories are possible and presented e.g. in Geist and Lambin (2002) or Lanly (2003).

Table 1: Direct and indirect drivers of deforestation and forest degradation (Source: Broadhead and Izquierdo 2010)

	Within the forest sector	Outside the forest sector
Direct	• High impact and illegal logging.	• Agricultural expansion; • Low agricultural yields; • Expansion of settlements; • Infrastructure development; • Fire; • Timber demand; • Fuelwood demand.

Indirect	• Low institutional capacity and weak policy implementation; • Weak forest sector governance o Weak enforcement and control; o Low levels of stakeholder participation and involvement; o Corruption, clientelism and nepotism; o Lack of transparency and accountability; o Lack of assessment of social and environmental impacts. • Lack of demarcation of forest areas; • Low awareness of forestland management rights and responsibilities • Lack of sustainable or alternative supply of wood and energy; • Lack of incentives promoting sustainable management of forests; • Low efficiency of wood use; • Inadequate information and statistics on forest resources and products.	• Population increase; • Rising incomes and demands for resources; • Increasing accessibility of forest areas; • Low agricultural yields; • Migration into forest areas; • Military activity; • Large scale agri-industrial development; • Lack of information on national land use and land use plans; • Governance o Overlapping/unclear jurisdictions; o Weak land tenure – tenure is weakest in forests and other areas outside residential or farming zones; o Weak enforcement of the law; o Lack of a fair and transparent conflict resolution mechanism; o Chronic incidence of high-level interministerial and interagency disputes. • Social norms (claiming land through utilisation); • Low awareness of environmental roles of forests.

While the list in Table 1 is already rather comprehensive, it is far from being complete. This is due to the fact that country specific circumstances influence the occurrence and importance of different drivers. Direct drivers are subject to local and sub-national circumstances, while indirect drivers are more likely to be influenced on a national and regional level. This has a distinct influence on how these drivers can be assessed and tackled. Lanly (2003) describes the direct drivers as locally known and therefore subject to objective observation, while the influence of the triggering indirect drivers are subject to higher uncertainty, subjectivity and ideological posing. Direct drivers are thus easier to influence by incentives that are supposed to be provided through REDD+ benefits. Most of the publications name the need for agricultural land as the main direct driver of deforestation (Geist and Lambin 2002), while selective logging and fuel wood collection are seen as the major direct drivers for forest degradation (Lanly 2003). The need for agricultural land can be both, small scale and locally driven as well as broad scale and commodity market driven (e.g. worldwide demand for meat, biofuels and aliments). Thus, incentive mechanisms have to be designed in a way that will work across several scales ensuring that the distribution of possible REDD+ benefits will reach the local communities. Therefore, a strengthening of good governance is needed, i.e. minimizing the risks of depletion of benefits on high levels and without direct influence on the drivers of deforestation and forest degradation. Ensuring good governance is one example of tackling the underlying (indirect) drivers on a national scale. The recent discussion on the demand for agricultural land in tropical regions for the rising consumption of biofuels or meat in developed countries is an example of how policies and social aspects in countries that are not subject to the immediate effects of direct causes (i.e. forest loss) have an influence on the deforestation in tropical countries (Lapola et al. 2010). Tackling the underlying causes is thus issue to a much broader public and involves different levels of abstraction. A successful implementation of a REDD+ mechanism is only possible if these underlying causes are properly addressed.

2.2 Phased Approach

It is common sense that any REDD+ mechanism should be implemented in a 'Phased Approach' (UNFCCC 2011b). This entails three phases (readiness, policy reforms, result-based actions) to tackle the different national circumstances of the countries applying for REDD+ and guarantee a comparable basis for the financial reward of reduced emissions from deforestation and forest degradation.

The first phase, also called the 'readiness phase', focuses on the development of a national REDD+ strategy or action plan. This includes the setup or strengthening of national capacities and institutions as well as the development of a MRV system. This system should be capable of estimating changes in the emissions resulting from deforestation and forest degradation. Furthermore, reference (emission) levels (RL/REL) should be defined against which future emissions are set off (see chapter 2.4 for details). Throughout the whole phase the applying countries should be supported by external facilities such as the Forest Carbon Partnership Facility (FCPF), UN-REDD, or bilateral agreements. The aim of this phase is to develop a national strategy and to build up the necessary resources for a sound implementation of REDD+ (Meridian Institute 2009).

The second phase ('policy reforms') entails the implementation of the policies and measures that have been developed and described in the national REDD+ strategy in the first phase involving further capacity building, technology development and transfer and the implementation results-based demonstration activities (UNFCCC 2011b). It includes a guaranteed and performance based funding for the successful implementation of the policies and measures. Thus, all achievements of the first phase will be further developed and the implementation and operability of national capacities will be tested and enhanced. This phase allows for evaluating and adjusting the national policies and measures and controlling the effectiveness of the distribution of funds generated through REDD+.

The third phase ('result-based actions') will be completely performance based, assessing the quantified forest emissions and removals against the agreed RL/RELs. The financing of this third phase is foreseen as part of a global compliance market or a non-market compliance mechanism or a combination of both (see chapter 2.3 for details). Only the emission reductions or removals during phase three are accountable for achieving benefits. However, the continuation of policies and measures initiated in the second phase should be credited (Meridian Institute 2009).

It is likely that in most country cases there will be a smooth transition or a partially concurrent development of the first and the second phases. For example, the development of a MRV system is highly dependent on already existing capacities for the conduction of e.g. a national forest inventory. Whenever sufficient capacities exist, the development of a sound MRV system for REDD+ is likely to be acquired in less time and at less expenditure than would be the case if no or less capacities on the monitoring of a countries forest existed (Hardcastle and Baird 2008, UNFCCC 2009a).

For the transition to the third phase, special focus should be placed on the definition of the RL/REL. In their Options Assessment Report for REDD (Meridian Institute 2009) the authors argue that besides national historic deforestation as a near-term predictor of deforestation, additional variables, including forest cover and income level should also be considered. Furthermore, RL/REL should be compatible for a possible "future incorporation into a broader agriculture, forests, and other land uses (AFOLU) sectoral reporting framework." In general, the choice of the RL/REL determines the opportunities of gaining financial benefits from a REDD+ mechanism (see chapter 2.4 for further details).

2.3 Financial aspects

While REDD+ is seen as the quickest and least expensive measure to achieve large emission cuts (Stern 2007, Stoltenberg 2010), the setup and implementation of policies and measures for REDD+ in the first and second phase, as described above, is associated with considerable costs. Eliasch (2008) assigned the costs into two groups: "upfront capacity-building costs", due largely to the activities in the first and second phase, and "ongoing emission reduction costs" which cover the opportunity costs of not deforesting or degrading the forest, the ongoing monitoring costs and the expenditures for the adoption of forest emission reduction policies (forest protection costs). Lubowski (2008) added a third group, the "transaction costs" involved in connecting buyers and sellers of REDD+ credits. Eliasch estimates the costs of halving emission from forests by 2030 to be in the range of 17 – 33 billion US Dollars per year, while the net benefits are estimated to amount up to 2 to 3.7 trillion US Dollars (Eliasch 2008, Lubowski 2008, Tavoni et al. 2007), not including additional benefits from the preservation of other ecosystem services provided by forests. The World Bank has published a 'training manual' for project developers to calculate the costs associated with the implementation of REDD+ on a national level (World Bank 2011). It is intuitively clear that a country or a project will only implement REDD+ activities when the benefits of these activities outweigh all associated costs. Thus, a cost benefit analysis should be carried out prior to the project initiation (WWF 2012).

The Copenhagen Accord developed at COP15 in 2009 and confirmed at COP16 in Cancun in 2010 pledged funds to combat climate change through mitigation and adaptation of 10 billion US Dollars per year from 2010 to 2012, rising up to 100 billion US Dollars per year by 2020 (Nakhooda et al. 2011). An interim REDD+ Partnership was founded in 2010, consisting of 58 developed and developing countries to facilitate access for the developing countries to an interim financing of 4 billion US Dollars from 2010 to 2012. The platform is intended to foster a fast establishment or further development of REDD+ activities. The developing countries have to prove that they are implementing measures for the first or second phase of REDD+ (OCFC 2010). Table 2 gives an overview of the previewed allocation of the interim financing, showing the main activities of developing countries to implement REDD+.

Table 2: Allocation of interim financing for REDD+ activities (2010 to 2012) (Source: Intergovernmental taskforce 2010)

Category	Activity	US$ [millions]	%
1	Development of national REDD+ strategies and action plans, including consultation	104.2	5.3
2	Implementation of national REDD+ strategies and capacity building activities, including development of MRV systems and regulatory reforms	542.0	27.4
3	Demonstration activities	43.0	2.2
4	Performance-based payments for emissions reductions	552.0	27.9
5	Multiple categories	306.6	15.5
6	Other	427.8	21.7

Besides interim financing provided through intergovernmental agreements, there are other financing options for REDD+ activities. Climatefundsupdate.org lists a total of 26 funds related to combating climate change, of which 15 are directly linked to sponsoring REDD+ activities (climatefundsupdate.org 2012). However, this list is far from being complete, as many bilateral funding or financial support of donor agencies is intransparent or not assessable. The vast amount of financing options shows the complexity of financing REDD+ readiness activities. In this light, COP16 in Cancun decided to establish a Green Climate Fund (GCF) (UNFCCC 2011b). This decision was adopted at COP17 in Durban and enhanced by a report of the “Transitional Committee for the design of the Green Climate Fund”. The objective of the GCF is to “operate in a transparent and accountable manner guided by efficiency and effectiveness. The Fund will play a key role in channelling new, additional, adequate and predictable financial resources to developing countries and will catalyse climate finance, both public and private, and at the international and national levels” (UNFCCC 2011c). Thus, the GCF is intended to downsize the complexity of climate finance. Nakhooda et al. (2011) give an overview of the main financial resources and the possible setup of the GCF.

Beside fund based mechanisms, there are discussions about integrating REDD+ trading units into the international carbon trading scheme. So far this scheme only allows for trading carbon credits from afforestation and reforestation projects, excluding REDD+. The integration of REDD+ credits into the official carbon market is an issue of much debate as it is foreseen that integrating REDD+ credits may lead to the risk of flooding the market with credits. This would lower the costs for carbon credits and negatively affect the incentive to develop or employ new clean energy technologies (Lubowski 2008). Nevertheless, it is contingent on the policy how REDD+ credits can and will be integrated into the market, thus offering the opportunity to lower the negative effects. A further opportunity would be to install voluntary carbon markets that are independent of the official trade of GHG emission credits. It is proposed to include the market based trade with REDD+ credits in the last phase of REDD+ implementation and to facilitate the first two phases with fund based and bilateral financing options (Meridian Institute 2009, Olander et al. 2009).

2.4 Forest reference (emission) levels

To achieve benefits from issuing REDD+ credits a countries’ emission reductions need to be verified. For this purpose UNFCCC (2011b) requests developing country parties that want to participate in REDD+ to establish a national forest reference emission level (REL) and/or forest reference level (RL). These are to be expressed in tons of carbon dioxide equivalent per year and serve as benchmarks for assessing each country’s performance in implementing REDD+ activities according to their national circumstances and respective capabilities. The national circumstances may incorporate the Gross Domestic Product (GDP) per capita of a country; the respective capabilities may entail the data availability for a country, which, in the case of insufficient data, may lead to subnational REL/RL. Although the difference between REL and RL is not always clear, it can be subsumed that REL applies to those activities that result in emissions (source), i.e. deforestation and forest degradation (REDD), while RL include these two activities as well as all the ‘plus-actions’ of REDD+ (conservation of forest carbon stocks, enhancement of forest carbon stocks and sustainable management of forests), which may result in emissions or removals (sink) (Conrad 2009). In the following the term RL is used as it includes the emissions accounted for by REL.

The development of RL is among the most critical elements of a REDD+ mechanism (Angelsen 2008a). By establishing a specific RL a country determines the ability to gain benefits from REDD+. UNFCCC (2011b) agreed to allow developing countries to apply a step-wise approach for the construction of RL enabling Parties to improve the RL by incorporating better data, improved methodologies and, where appropriate, additional pools, and also allowing for using interim subnational RL. During the Expert Meeting on “Forest reference emission levels and forest reference levels for implementation of REDD-plus activities” in Bonn in 2011 it was advised that it should not be obligatory to include the plus-actions into RL (UNFCCC 2011d). Thus, a country may deploy a combination of REL and RL or opt to start with REL whenever it decides not to integrate the plus-actions into the REDD approach from the beginning. Furthermore, it was proposed that deforestation should be included in RL, while the requirement to include forest degradation was discussed due to its high complexity for creating RL. In their submission to the SBSTA the USA stated that: "Deforestation is highly complex - drivers vary significantly by region and are subject to a range of unpredictable variables. Degradation is even more complex. Therefore it is extremely difficult to accurately predict long-term future deforestation and degradation rates" (USA 2011).

Two main approaches for the establishment of RLs are discussed. One is based on historical deforestation rates and the other on projected or expected deforestation rates (i.e. models of deforestation). There is a broad agreement on the usage of historical data for the establishment of RL. The RL should be implemented for one period and then updated with newly available data for the next (UNFCCC 2009b). Predictions created with historic data are mainly based on satellite data that is able to detect land cover changes in a consistent manner from 1990 onwards (Mollicone 2011). However, not all countries have the same quality or amount of ground based data to verify the findings of the satellite imagery analyses. This may lead to substantial problems due to false classifications of land cover changes, i.e. a land cover change is detected via remote sensing (RS) where no land cover change occurred or vice versa. In general, the extrapolation of historical trends to predict future deforestation rates (forest degradation is hardly detectable with available historic remote sensing data and techniques) and the aligned emissions has the risk of over- or underestimating current and future deforestation. The basis for this risk is subsumed in the "forest transition theory" (FT, see Figure 1) (Mather 1992). It categorizes countries along a forest area development curve that starts with high forest cover and low deforestation rates (HFLD), then deforestation accelerates (HFHD) and the forest cover diminishes towards a low forest cover (LFHD). At a certain point the deforestation can no longer proceed on its high rate and lowers, too (LFLD). From this state onwards the forest cover either stabilizes or starts increasing (LFND).

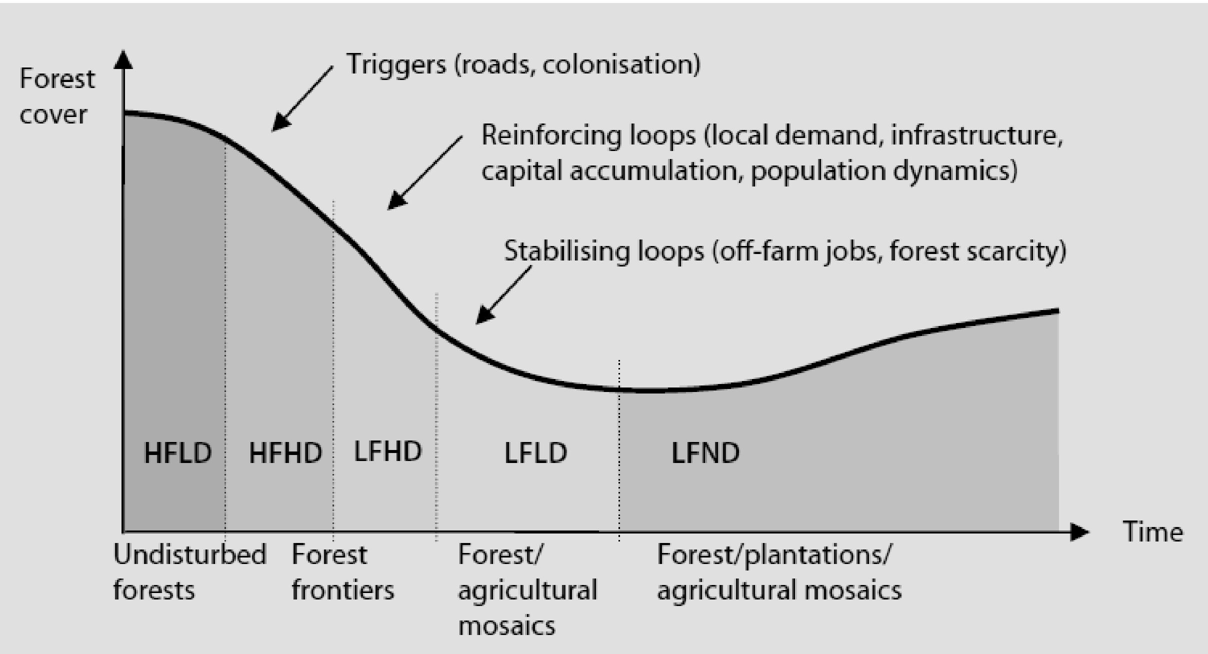

Figure 1: Different stages in the forest transition (Source: Angelsen et al. 2009)

FT only depicts broad trends and is focusing more on forest area development then on carbon stocks. However, it can be deduced that during the HFLD phase, historic trends tend to underestimate future emissions, while in the LFHD phase it tends to overestimate emissions (Angelsen 2008a, Meridian Institute 2009).

The modeling approaches are able to include country-specific factors in the prediction of deforestation rates. These factors could be population density and growth, forest area, economic growth, commodity prices, governance variables, energy security, extension of biofuel production and the incorporation of a "development adjustment factor" (DAF) (Angelsen 2008a, UNFCCC 2009b). The mentioned factors are far from being complete, thus already giving an impression on the complexity that these models may reach. This is identified as one of the major weaknesses of deforestation models. The necessary data to fill complex models are hardly available and the results of these models are rather case and parameter specific than generic. Where input parameters are based on low quality data or estimates, the results tend to be inaccurate (UNFCCC 2009b).

Setting up RL should follow the general principles of reporting as elaborated by the IPCC (see chapter 1.5.4) and the principle of equity of the UNFCCC. Hence, no country should be favored by the finally agreed option of setting a RL. While the Meridian Institute (2011a) identified general steps applicable for all countries for the preparation of RLs as introduced above, there are several other approaches discussed. These range from the introduction of a global baseline (Mollicone et al. 2007), dividends for maintaining carbon stocks (Cattaneo 2008, Cattaneo 2010) to separate systems not based on carbon stock changes (Meridian Institute 2011b). These approaches are especially important to those countries with low deforestation and forest degradation rates and further described in the second article of this thesis (Plugge et al. 2012).

The RLs described above all serve as benchmarks for rewarding developing countries for reduced emissions from deforestation and forest degradation as compared to a "business as usual scenario" or a prediction based on models. In both cases the developed RL is the level against which future emissions are compared. On this basis the idea of a crediting baseline or financial incentive benchmark is discussed (Angelsen 2012). This baseline is set to an emission level lower than the RL. Setting of emissions against a crediting baseline is argued with the requirement of 'Additionality' of REDD+ measures (see chapter 2.6), i.e. the emission reductions must be additional to those achieved by any other GHG mitigation policy. Furthermore, the setting of a crediting baseline would allow for the control of the amount of carbon credits issued through REDD+ on the carbon market. However, a crediting baseline would demand efforts from developing countries that would not be rewarded. Depending on the strictness of this baseline, and regarding the influence of uncertainties on the accountability of emission reductions, as discussed in the second and third article of this thesis and in Köhl et al. (2009) and Plugge et al. (2011), the additional and unrewarded effort for developing countries might hinder broad participation in REDD+.

2.5 Safeguards

The aspects presented above already show the high complexity of successfully implementing REDD+. Beside the already mentioned stakeholders (e.g. policy makers, scientists, negotiators, NGOs, indigenous people), there are many other stakeholders (e.g. local forest management entities, other international conventions, economists) and aligned topics (e.g. ecosystem services, biodiversity, food security, tenure rights) that are affected by a possible REDD+ mechanism. It is good practice for negotiations under the UNFCCC to involve all relevant stakeholders and topics and to open the floor for their views and positions. The arguments and concerns about possible risks of the evolving REDD+ mechanism have been brought into the discussions during several COPs. Two major groups of risks emerging from REDD+ can be differentiated: environmental risks and social and political risks. Table 3 summarizes some of the main risks in these two groups and their cause in the REDD+ context.

Table 3: Some of the main risks in the REDD+ context (adapted from: Miles and Dickson 2010, Moss and Nussbaum 2011)

Risk Group	Risk	Main cause in REDD+ context
Environmental (after Miles and Dickson 2010)	Displacement of land-use change to non-forest or low carbon ecosystems	reduced deforestation and forest degradation
	Continued extractive pressures	reduced deforestation and forest degradation, sustainable management of forests
	Low tree diversity or introduction of non-native or non-local species	enhancement forest carbon stocks
	Afforestation of valuable non-forest ecosystems or natural forest	enhancement of forest carbon stocks
Social and political (after Moss and Nussbaum 2011)	Loss of traditional territories, rights to lands and resources	conservation of forests
	Displacement or relocation of indigenous peoples and forest dependent communities	conservation of forests
	Loss of or reduced access to forest products important for local livelihoods	reduced deforestation and forest degradation, conservation of forests
	Loss of traditional and rural livelihoods and ecological knowledge	sustainable management of forests, conservation of forests
	Social exclusion and elite capture in the distribution of benefits from REDD+	facilitated through weak governance
	Creation of contradictory or competing national policy frameworks	facilitated through weak governance

The discussions on the risks mentioned in Table 3 and further, often country and case-specific risks have led to the inclusion of 'Safeguards' into the official UNFCCC documents during COP16 in Cancun (UNFCCC 2011b). These safeguards are policies and measures that identify, analyze and ultimately manage risks and opportunities of REDD+ (Murphy 2011). However, until now they are more a set of non-binding principles than a set of rules (Jagger et al. 2012). The safeguards as included in Decision 1/CP16 Appendix I are listed in the following (UNFCCC 2011b):

1. "That actions complement or are consistent with the objectives of national forest programmes and relevant international conventions and agreements;
2. Transparent and effective national forest governance structures, taking into account national legislation and sovereignty;
3. Respect for knowledge and rights of indigenous people and members of local communities, by taking into account relevant international obligations, national circumstances and laws, and noting that the United Nations General Assembly has adopted the UN Declaration on the Rights of Indigenous Peoples;
4. The full and effective participation of relevant stakeholders, in particular indigenous people and local communities, in the actions referred to in paragraphs 70 and 72 of this decision;

5. That actions are consistent with the conservation of natural forests and biological diversity, ensuring that actions referred to in paragraph 70 of this decision are not used for the conversion of natural forests, but are instead used to incentivize the protection and conservation of natural forests and their ecosystem services, and to enhance other social benefits;
6. Actions to address the risk of reversals;
7. Actions to reduce the displacement of emissions." (UNFCCC 2011b)

These safeguards should be promoted and supported by the parties that undertake actions towards REDD+. However, as it is reflected in the safeguards the national sovereignty regarding social and environmental policies has to be respected. Thus, it is apparent that the implementation and even more the monitoring of the safeguards poses some challenges to developing countries. While the monitoring definitions and standards are yet to be clarified by an expert group to the UNFCCC, the implementation has to take place on various levels (international, national, local) and in a horizontal manner (i.e. harmonized with other international safeguard policies). This, however, involves significant transaction costs that have to be compensated by the benefits of adhering to these safeguards (Jagger et al. 2012).

To cope with the complex implementation and monitoring of the safeguards, several international governmental and non-governmental organizations have developed standards according to which the implementation is facilitated and efforts can be measured. These organizations offer support to the developing countries in different ways. Moss and Nussbaum (2011) give an extensive overview on the three main initiatives, which are: (i) the Forest Carbon Partnership Facility - Strategic Environmental and Social Assessment (FCPF – SESA) with its Environmental and Social Management Framework (ESMF); (ii) the REDD+ Social and Environmental Standards (SES) initiative facilitated by the Climate, Community and Biodiversity Alliance (CCBA) and CARE International; and (iii) UN-REDDs "Social and Environmental Principles Framework".

Greenpeace has issued a consultation document comparing the different initiatives in the field of REDD+ safeguards. They conclude that while the above named three initiatives are already fulfilling major parts for implementing safeguards in a sound and feasible manner, all of them have their deficits (Greenpeace 2012). In general, all three initiatives aim at managing the risks associated with REDD+ and reverse them into "multiple benefits", or "co-benefits". The safeguards themselves can be seen as "do no harm" principles. When appropriately applied, REDD+ and its safeguards have the potential to achieve significant co-benefits, including alleviating poverty, improving governance, conserving biodiversity and providing other environmental services (Angelsen 2008b).

2.6 Additionality, Permanence and Leakage

The presented framework of REDD+ is completed by brief descriptions of three important issues that have already been introduced in the previous chapters. 'Additionality' was mentioned in chapter 2.4, while 'Permanence' is referred to in the sixths and 'Leakage' in the sevenths safeguard. Together they form a major pillar for the implementation and success of REDD+.

Additionality refers to the necessity that any emission reduction that is assigned to a REDD+ activity would not occur without this activity. Otherwise it cannot be rewarded under REDD+, as this would impose the danger of a double-accounting of emission reductions. Additionality is assessed against a reference level as described above.

Permanence describes the need that efforts made towards the reduction of deforestation and forest degradation are not temporarily but sustained over a long period. Ensuring permanence should avoid that actions to reduce emissions are reversed shortly after they have been turned into benefits.

Leakage describes the process of relocating deforestation and forest degradation into another area that is not part of a local REDD+ project. By avoiding leakage the integrity of a national REDD+ process is assured. However, leakage may occur across national boundaries and thus needs to be addressed on international level.

All three topics necessitate the implementation of meaningful incentives and alternative incomes for local people. Only if forest dependent communities have access to means and resources that allow for the sustention of their livelihoods under the impacts of REDD+ activities they will be able and willing to adhere to policies and measures that are intended to protect the forest.

3 Core issues of REDD+ for the thesis

The above set framework deals with major issues that are necessary for a comprehensive and successful implementation of REDD+. Despite their high significance for REDD+, the issues of deforestation, forest degradation, MRV and aligned uncertainties have yet to be described. They form the core issues for the three articles constituting this thesis. The following section introduces these issues.

3.1 Deforestation

As stated in the definitions chapter, deforestation is the "direct human-induced conversion of forest land into any user land category" (IPCC 2006). Apart from a few exceptions, like a clear-cut of forest land that is left to regenerate, or other forest management operations or specific national forest laws, deforestation is a process that can be easily identified. At one point in time a given area has been forested, at a future point in time there is no more forest. Because forests are easily defined deforestation is deemed easy to be measured and quantified. Nevertheless, the definition used by the IPCC includes various ranges for thresholds. From these ranges a prudent selection for the national forest definition has to be made. Especially the threshold for the crown cover (between 10% and 30%) has a major impact on the area that may qualify for carbon accounting projects (Simons 2012, Zomer et al. 2007).

The development of remote sensing technologies since the 1970s has made it possible to monitor the development of vast forest areas (Lanly 2003). A national or global monitoring of deforestation is only feasible by deploying remotely sensed data (DeFries et al. 2006). Today deforestation can be surveyed on a daily basis e.g. by Brazils Real-Time Deforestation Detection System (DETER) (INPE 2012). This system and other advanced remote sensing technologies are, however, limited either in terms of their spatial or their temporal resolution. Spatial resolution has two meanings in this context. One is the spatial resolution in terms of the area that can be monitored (i.e. the strip-width of the acquired images), the other is the resolution of the images itself (i.e. the area that is covered by a single pixel). The temporal resolution is the time needed by a satellite hosting a remote sensing sensor to pass an area of interest twice. To minimize the temporal resolution some observation systems deploy two or more satellites that fly on synchronized orbits.

Global monitoring of deforestation on an annual basis is feasible with optical sensors of medium spatial resolution. Referring to the pixel size this resolution is 250-1000 meters while the size of the deforestation would need to be above 10-20 hectares. Costs for images from these sensors are generally low, or they come for free. However, on a national scale high resolution images (resolution of 10-60 m) are needed to account for smaller deforestation patterns, thus increasing the costs (DeFries et al. 2006). The utility of widely used optical sensors is limited especially in tropical areas with frequent cloud covers. New types of active sensors (e.g. the RADAR based satellite TerraSAR-X) are working to solve this problem and allow for the detection of deforestation and biomass change even in areas that are covered by clouds (GOFC-GOLD 2011). These sensors, however, are more costly and less tested for the scope of deforestation. Thus, they can be feasibly applied only in small areas and not for a nationwide wall-to-wall mapping of an entire country.

Any type of remote sensing still needs to be accompanied by terrestrial ground-truthing to check for the accuracy of remotely sensed deforestation estimates. A straight forward approach for REDD+ would be to deploy low or medium resolution imagery for the detection of broad deforestation patterns and high to very high resolution imagery for those areas that show frequent or high deforestation patterns. The first article to this thesis describes how remote sensing can be feasibly and sensibly applied in the scope of REDD+. It also demonstrates the connection to terrestrial inventories and ground-truth data (Plugge et al. 2010).

While remote sensing in combination with ground-truthing is the only feasible way to gain reliable data on national or global deforestation rates, it falls short in the detection of forest degradation (Baldauf et al. 2009). It is only recently that new types of sensors and methods show promising results to overcome this gap (Baldauf 2012, unpublished).

3.2 Forest Degradation

While defining, measuring, reporting and verifying deforestation is a feasible and well established task, none if this is the case for forest degradation. It is common sense that forest degradation can take place only in “forest land remaining forest land” (IPCC 2003b). However, defining forest degradation faces the problem that whether a forest is degraded or not depends on very subjective viewpoints. Simula and Mansur (2011) articulated this fact with the sentence: “One person’s degraded forest is another person’s livelihood”. Generally, forest degradation is much more subtle than deforestation and processes leading to forest degradation are manifold. This entails that a major proportion of forest degradation is due to local drivers like the collection of non-timber forest products, fuel- or construction wood or small scale charcoal production as well as human induced forest fires (Murdiyarso et al. 2008a). Selective logging is another driver of forest degradation that may occur in a broader context e.g. the illegal logging of precious wood species. The fact that degradation is more likely to be a small or medium-scale process should not lead to the conclusion that its overall impact is neglectable. ITTO (2002) estimated the total area of degraded forests in 77 tropical countries to be about 800 million hectares. However, due to the manifold processes and different intensities of forest degradation its proportion of the total GHG emissions remains unclear. Asner et al. (2005) estimated forest degradation in the Amazon region to be responsible for 20% of total emissions; Herold et al. (2008) compiled estimates for the proportion of emissions from degradation to those from deforestation ranging from 5% to 132%. Marklund and Schoene (2006) showed that from the total decrease of forest carbon stock of Indonesia from 1990 – 2005 two thirds can be related to forest degradation. These figures make ultimately clear that forest degradation has to be accounted for to design an effective and credible REDD+ mechanism. Neglecting forest degradation might lead to a broad shift of deforestation to forest degradation activities, thus depleting the forests without letting them fall out of the specific parameters of the forest definition (Bucki et al. 2012).

Measuring and reporting on forest degradation is more difficult than on deforestation (IPCC 2003b, UNFCCC 2011d). In particular the absence of a clear definition of forest degradation continues to hinder the development of consistent measuring and reporting protocols (GOFC-GOLD 2011). Despite many efforts towards defining forest degradation (IPCC 2003a, Simula 2009) and broad scientific discussion on the need for such a definition (Guariguata 2009, Sasaki and Putz 2009), the above presented definition (chapter 1.5.3) proposed by IPCC (2003a) lacks further description of the parameters used and is deemed unpractical (Penman 2008). These difficulties lead to a situation where countries tend to report no estimates on the impact of forest degradation on their carbon stocks. Marklund and Schoene (2006) compiled an analyses for FAO’s Forest Resource Assessment (FRA) 2005, showing that it is easier for countries to report on a change of their forest area (i.e. deforestation) than on a change of their forest carbon stocks (i.e. forest degradation) . In an updated version of this analysis, using data of FAO’s FRA 2010 (FAO 2010) this trend is confirmed (Figure 2).

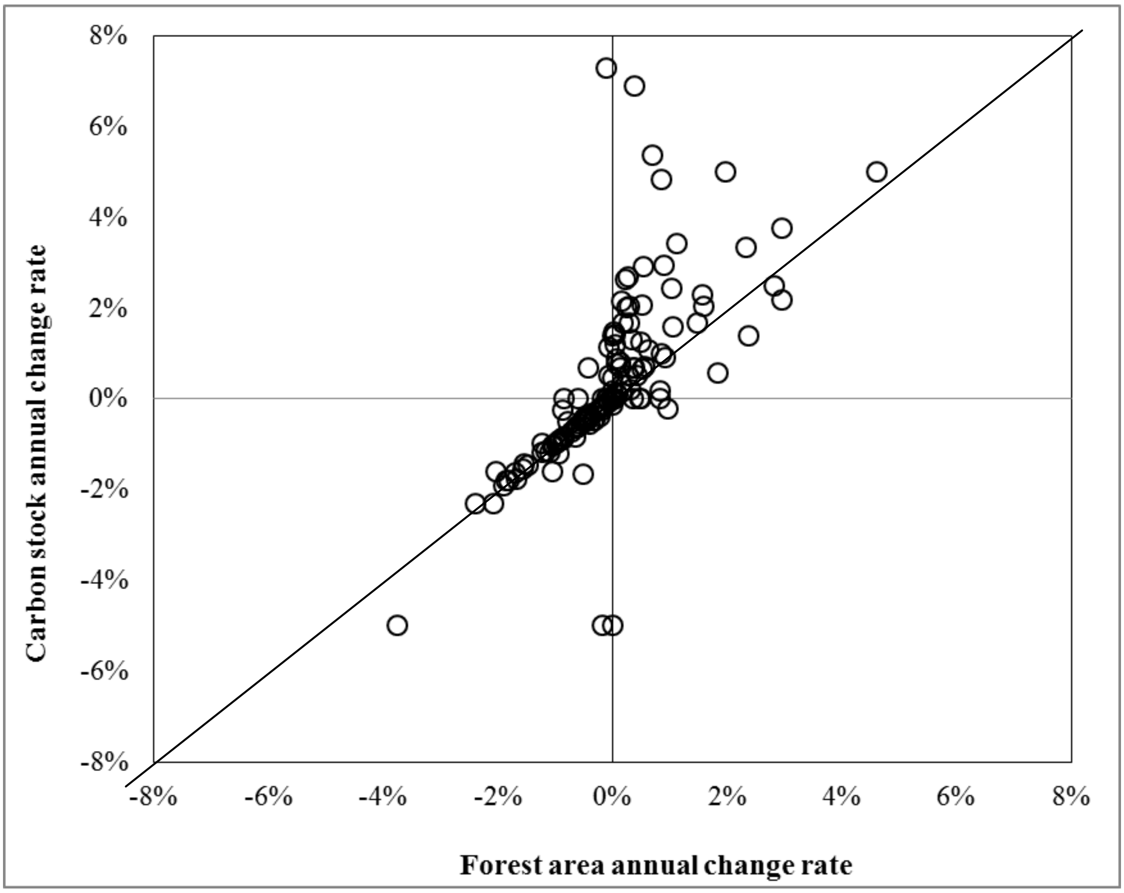

Figure 2: Change rates in carbon stock plotted against change rates in forest area. Data points falling on the diagonal represent countries where the same per-hectare values of carbon stock were applied to the forest area for all reporting years (1990 - 2010) (updated and adapted from Marklund and Schoene 2006 with data from FAO's FRA 2010)

It becomes obvious from Figure 2 that especially those countries reporting a negative change of their forest areas report no changes in their forest carbon stocks. However, it is likely that the countries that account for the major part of global deforestation also account for the majority of forest degradation (Mollicone et al. 2007). The lack of data on forest carbon stock changes and thus forest degradation can be interpreted as a lack of terrestrial inventory data. Nevertheless, terrestrial inventories are indispensable for an accurate estimation of degradation impacts. Omitting information on changes in forest carbon stocks is not an option for reporting under REDD+. It is therefore advised to find the best combination of remote sensing analyses to stratify a country's forests and terrestrial inventories for the assessment of changes in forest carbon stocks (Plugge et al. 2010). In the third publication to this thesis (Plugge and Köhl 2012) the importance of accurately identifying areas where forest degradation occurs and deriving reliable estimates of the impact of these activities is shown. Estimating the impact via in-situ assessments, however, is a time consuming and costly task especially in remote and hard to access areas. Thus, a thorough planning of these MRV activities is needed to render them cost effective (Köhl et al. 2011).

3.3 Measuring, Reporting and Verification for REDD+

The initial aim of REDD+ was to assign an economic value to tropical forests through the carbon that is stored in their biomass. The idea was that developing countries would commit themselves to a reduction of their historic deforestation rates and thus diminish the emissions that result mainly from the release of carbon dioxide when forests are cleared. The effective control of a countries commitment to the reduction of emissions is rendered possible via a MRV system. UNFCCC (2010) requests developing country parties to establish robust and transparent national forest monitoring systems that provide estimates that are transparent, consistent, accurate and suitable for review. Furthermore, it is requested that the MRV system applies a combination of remote sensing and ground based forest carbon inventory approaches to report on GHG emissions and removals, forest carbon stocks and forest area changes. This MRV system can thus be seen as a center-piece of a REDD+ mechanism. Regarding the growing complexity of REDD+, the requirements for a holistic MRV system, which actually may consist of several carefully harmonized systems in a nested approach, are rising. For the activities of sustainable management of forests, conservation and especially the monitoring of governance and the safeguards definitions and guidelines still need to be adapted to or developed for the REDD+ context.

The three articles of this thesis focus on the development, characteristics and specific features of a MRV system for REDD+ to assess changes in forest area and forest carbon stock and related emissions or removals. The SBSTA states that the data on these processes should be “transparent, consistent over time, robust, complete, comparable and be subject to quality assurance and quality control” (UNFCCC 2012b). For the fields of deforestation and forest degradation, as well as the enhancement of forest carbon stocks, the basis for a MRV system is provided via the Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG LULUCF) (IPCC 2003b) and the Guidelines for National Greenhouse Gas Inventories (IPCC 2006). According to these, five pools have to be considered for the assessment of changes of carbon stocks: (i) above-ground biomass, (ii) below-ground biomass, (iii) dead wood, (iv) litter and (v) soil organic matter. A MRV system for REDD+ needs to focus on two components (IPCC 2003b):

i) Assessing changes in forest area over time (activity data, AD), and

ii) assessing changes in the average carbon stock per unit area over time (emission factors, EF).

Assessing changes in AD and EF over time necessitates sampling on successive occasions (Ware and Cunia 1965) or the development of models to extrapolate data from one point in time to another (Hush et al. 2003), and needs to follow the prerequisites of continuous forest inventory systems (CFI) as further described in Köhl et al. (2006).

Besides the five pools and two components that are required by a MRV system, IPCC (2006) offers two alternative approaches for estimating carbon stock changes per unit area; the "Gain-Loss Method", based on estimates of annual change in biomass from estimates of biomass gain and loss, and the "Stock-Difference Method", which estimates the difference in total biomass carbon stock between two points in time (time 2 - time 1). Furthermore, IPCC (2006) provides three methodological tiers with varying complexity, from which countries can choose based on their national capacities and circumstances.

Tier 1 mainly utilizes default values given in the IPCC Guidelines and can even be applied if country specific AD is only available for some areas as there are globally available sources for AD. Therefore, Tier 1 is subject to high uncertainties, which are estimated to be in a magnitude of up to 70% or more of the mean (UNFCCC 2009a).

Tier 2 calls for country or region specific data on AD and EF, higher temporal and spatial resolution and less aggregated AD combined with country or region specific coefficients for the determination of carbon stocks and carbon stock changes. While Tier 2, in general, employs the same methods as Tier 1, it also increases the reliability of estimates with increasing resolution of the applied data.

Tier 3 includes higher order methods, such as models and successive inventory systems with high resolution activity data. It requires greater effort and capacities, but largely improves the reliability of estimates. The models need to be quality checked and validated.

To account for existing capabilities, a country is free to use a combination of different tiers for their reporting (e.g. Tier 2 for above-ground biomass and Tier 1 for soil organic matter). For so-called key categories, i.e. source or sink categories that contribute substantially to the overall national greenhouse gas inventory, Tier 2 or Tier 3 are required for reporting under IPCC (IPCC 2006).

After a country has successfully measured and estimated its carbon stocks and carbon stock changes, the specific data needs to be reported to the UNFCCC via a formalized data-transfer for inclusion into a harmonized REDD+ database. Together with data on further GHG emissions from other land uses and data on land use changes, matrices are developed to represent the changes between land uses and within the forest land (UN-REDD 2011).

The above describes opportunities and prerequisites for measuring and reporting under REDD+. Missing for a MRV system is the “V”, the verification. While measuring and reporting, after sufficient capacity development in the first two phases of REDD+, can be completely undertaken by a country’s authorized institutions, the verification has to be undertaken by an independent third party. The countercheck of the reported information is foreseen to be done by experts associated with the UNFCCC secretariat. However, since all reported data must be made publically available, the verification can also be completed by other institutions or the interested civil society. The verification process depends on three factors: (i) the degree to which reported data is capable of being verified; (ii) the actors conducting the verification; and (iii) the way in which verification is performed (UN-REDD 2011). Only a thorough verification process that is transparent and assessable by all concerned stakeholders can lead to a credible REDD+ mechanism.

3.4 Uncertainties

An important part of the reporting requirements and the verification process is the provision of quantified estimates of uncertainties aligned to the reported values for changes in forest area and carbon stocks. The UNFCCC (2008) requests the development of "means to deal with uncertainties in estimates aiming to ensure that reductions in emissions or increases in removals are not over-estimated, including those existing in IPCC guidance". To avoid over-estimations IPCC (2003b) proposes using the Reliable Minimum Estimate (RME) for the assessment of soil carbon stocks. Dawkins (1957) introduced the RME as the minimum quantity to be expected with a given probability. As such, it serves as a surrogate for the lower bound of a confidence interval. IPCC (2006) suggests applying the 95% confidence interval. However, confidence intervals are restricted to the precision of an estimate which includes sampling errors only, thus neglecting the significant impact of non-sampling errors. Lessler and Kalsbeek (1992) describe different types of non-sampling errors, e.g. frame errors, function errors, and measurement errors, which are likely to occur in any environmental survey (Gertner and Köhl 1992), including MRV for REDD+. While sampling errors can be controlled by the number of observations, i.e. increasing the number of observations will increase the precision of the estimate, non-sampling errors can be tackled previous to the survey or by analytical measures. To identify the reliability of an estimate, information on the precision, accuracy, bias and the mean square error (MSE) are needed. Cochran (1977) gives an extensive introduction into this field of sampling statistics. Grassi et al. (2008) proposed to apply the principle of conservativeness, i.e. the RME, to achieve robust and credible estimates for REDD+ activities.

As described above, using higher tiers reduces the uncertainties substantially while increasing costs and efforts required for the MRV process. However, applying more advanced methodologies and collecting more detailed date in higher tiers may also add uncertainties to MRV (WWF 2012). The negative impact on the accountability of reduced emissions via REDD+ activities, and thus the importance of respecting uncertainties in the MRV process, is discussed in the literature (e.g. Bucki et al. 2012, Grassi et al. 2008, Köhl et al. 2009, Pelletier et al. 2011, Plugge et al. 2011). Given temporal and monetary constraints, a country is urged to evaluate wisely which tiers and methods to use for their respective MRV system. A MRV system can be optimized by either improving the reliability of the estimates for a given cost, or reducing the costs for a given reliability (Köhl et al. 2011).

Most of the literature on uncertainties aligned to REDD+ estimates focus on uncertainties for one point in time (e.g. Grassi et al. 2008, Köhl et al. 2009, Plugge et al. 2011). The third article to this thesis considers the uncertainties of estimates at two points in time and shows that prior to the implementation of a REDD+ MRV system rules for the propagation of errors from one assessment to the next are essential (Plugge and Köhl 2012).

Part II. Integration of the articles into the thematic context

Part I shows how highly complex the proposed REDD+ mechanism has grown since the introduction of the original proposal into the international negotiations in 2005. The amendment of the initial idea by issues like the ‘plus-actions’ as well as the safeguards is undoubtedly meaningful for the construction of a credible REDD+ mechanism. Yet, these additional issues have exacerbated the challenges of finding practicable solutions to political, social, scientific and technical questions concerning the implementation of the mechanism. Nonetheless, as deforestation and forest degradation continue at an alarming rate (FAO 2010), it is widely accepted that the implementation of REDD+ must go forward, even if some issues have yet to be clarified (CIFOR 2010). Early implementation should focus on the core issues of deforestation and forest degradation and on developing and implementing an operational MRV system capable of providing reliable estimates on how successful reduction efforts have been.

These core issues are the overarching theme of the three articles that constitute this thesis. The following gives a summary of each article. The presented summaries are more detailed than the original summaries of the articles in order to better demonstrate the methods and results. However, for the sake of easy readability, only short summaries are presented. The methods and results are described in detail in the articles. After each summary a discussion of the article is presented to highlight the relations to the thematic context presented in Part I.

1 Plugge et al. (2010): "Combined biomass inventory in the scope of REDD [1] (Reducing Emissions from Deforestation and Forest Degradation)"

The first article that is part of this thesis was written by Daniel Plugge, Thomas Baldauf, Harifidy Rakoto Ratsimba, Gabrielle Rajoelison and Michael Köhl and published in the reviewed journal "Madagascar Conservation & Development" in June 2010. The specific journal was chosen to reach a broader public in Madagascar as the methods and results presented in the article were developed as part of a multi – institutional project in Madagascar (see also: Baldauf et al. 2010 and REDD-FORECA 2011).

1.1 Summary of the first article

This paper presents an approach for combined biomass inventories in the scope of a REDD regime. The focus is set on a sound and reliable method for measuring and monitoring the current state of carbon stocks and their changes over time. As set out in the chapters of the thematic context and further described in Plugge et al. (2011) a reliable framework for MRV is urgently needed to ensure the integrity and credibility of REDD. The proposed combined inventory approach was developed and successfully implemented in Madagascar within a multi - institutional REDD project, i.e. REDD - FORECA. It deploys a multi - temporal remote sensing approach incorporating satellite sensors from medium to very high resolution. In a first step a full coverage of the country's area (wall-to-wall map) is obtained by remote sensing imagery data. Together with auxiliary data on climate, topography and vegetation, broad regions are identified and further classified into non-forest and forest areas. Using archive and present data and applying change detection algorithms, those forest areas that show ample changes can be identified. Together with further socio-economic data (e.g. on accessibility or distance to settlements) deforestation and forest degradation hot-spots can be detected. In these hot-spots a terrestrial cluster sampling design, which is adaptable to the whole spectrum from highly fragmented to pristine forest areas, is implemented. On the sample plots of each cluster dendrometric variables like diameter at breast height, tree height or crown area, as well as auxiliary variables like signs of human impact, height above sea level or slope are assessed to deduce the above-ground biomass of a single tree. The combination of remote sensing and terrestrial inventory techniques is implemented in a multi - phase sampling approach. The inventory is designed for the prerequisites of a continuous forest inventory to facilitate the quantification of possible CO_2 reductions over time (see Figure 3).

[1] At the time of writing the article the term REDD+ was not completely adopted in the international negotiations. Referring to this article the terms REDD and REDD+ are used synonymously.

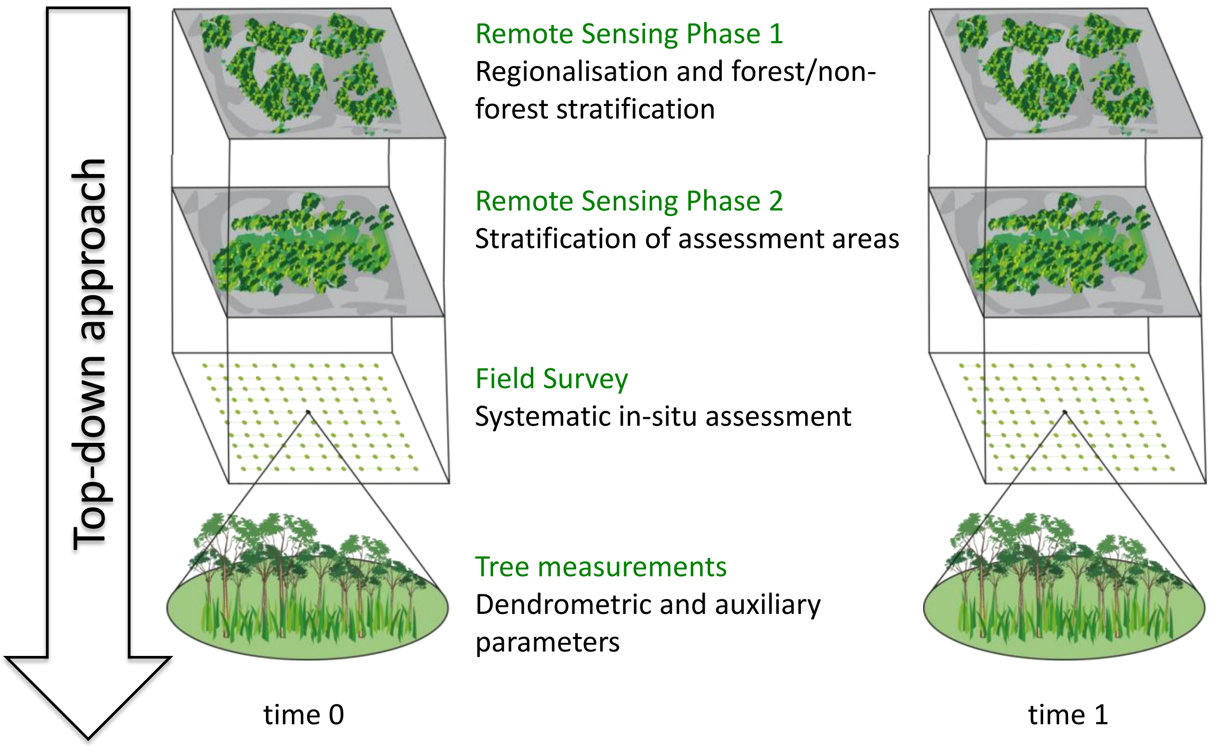

Figure 3: Top - down approach for a combined inventory on national scale (Plugge et al. 2010).

The field - assessments were accomplished in 2007 and 2008 at three different sites identified according to the selection process described above and representing three different forest formations (moist, deciduous, dry) as adapted from IPCC categories (IPCC 2003b). Following the physical implementation of the terrestrial inventory, statistical upscaling procedures were utilized to aggregate the resulting estimates on the above-ground biomass of single trees on several levels.

Table 4: Aggregation of estimates for forest formation and on country level (adapted from Plugge et al. 2010)

Forest formation	AB total [t]	SE of AB total [%]	Mean AB [t/ha]	SE of mean AB [%]
Moist forest	9,461,790	10.2	272.5	25.5
Deciduous forest	302,471	20	163.7	23.9
Dry forest	2,763,880	11.6	98.9	18.5
Madagascar			194.2	20.1

SE = standard error; AB = above-ground biomass; t = ton; ha = hectar

The results show that the developed and applied methodology is operational for the whole spectrum of forest formations as well as different states of forest fragmentation. All values on above-ground biomass meet the ranges of values given in the IPCC GPG (IPCC 2003b). It is thus applicable for the implementation of a REDD+ MRV system on national as well as project based or sub-national level in a nested approach and leads to reliable estimates of carbon stocks of different tropical forest formations.

1.2 Discussion of the first article in the thematic context

The first article refers mainly to the request of UNFCCC to develop robust and transparent national forest monitoring systems that provide estimates that are transparent, consistent, accurate and suitable for review (UNFCCC 2010, UNFCCC 2012b). It deploys a combination of remote sensing and ground-based inventory techniques as requested by UNFCCC (2010) and discussed by a multitude of other authors (e.g. Brown 1997, Gibbs et al. 2007, GOFC-GOLD 2011, Köhl et al. 2006).

In the context of uncertainties, the presented methodology is capable of quantifying the uncertainty of each estimate as requested for higher tier approaches (IPCC 2006) and under this aspect allows for reporting on the key categories of deforestation and forest degradation. The relatively high uncertainties are due to the pilot-character of the project, not allowing for full scale inventories. As the proposed method fully complies with the recent IPCC guidance and guidelines it is likely to be transferable to other countries while requesting some adaptation to country specific circumstances as demanded by e.g. Murdiyarso et al. (2008b) or Maniatis and Mollicone (2010). This implicates that the methodology requires a high level of capacity for the application in a specific country. Among others Hardcastle and Baird (2008) and Romijn et al. (2012) have analyzed the capacities and the needed development in countries that may introduce REDD+ activities. Their findings render the implementation of a MRV system as presented in this article possible.

The article shows that it is feasible to estimate changes in carbon stocks in forest land remaining forest land, i.e. forest degradation or enhancement of carbon stocks, when applying an adaptive sampling design. Herold and Skutsch (2011) and Bucki et al. (2012) call for a MRV approach that focusses on areas where human activities in forest land take place to avoid costly measurements in areas where there is no significant change in AD and EF. The selection of hot-spots, as presented in the article, fully complies with such a system. Accordingly, the article is a valuable input into the political and scientific discussion on the development and implementation of a robust, transparent and practicable MRV system in the REDD+ context. However, capacity development and terrestrial inventories in hard to access and remote areas demand a sensible allocation of available funds prior to the implementation of a national REDD+ strategy. Köhl et al. (2011) present options for optimizing sampling design with regard to their cost efficiency.

The aspects of the identification of drivers of deforestation and forest degradation and the development of reference levels were also part of the project on which this article is based and can be found in Baldauf et al. (2010) and REDD-FORECA (2011).

2 Plugge et al. (2012): “The global climate change mitigation strategy REDD [1] : monitoring costs and uncertainties jeopardize economic benefits”

The second article of the cumulative thesis was written by Daniel Plugge, Thomas Baldauf and Michael Köhl and published online with open access in the reviewed Springer journal “Climatic Change” in June 2012. The core ideas of this article were presented at the poster session of the Forest Day 4 that took place during the COP16 in Cancun, Mexico. After being published online the article was chosen as a ‘Research Highlight’ by the editors of Nature’s ‘Climate Change’ journal (Brown 2012).

2.1 Summary of the second article

The article highlights the influence of the costs and errors associated with the implementation of a MRV system. It focuses on the estimation of reduced emissions from deforestation, nonetheless, the assigned costs and errors hold for a comprehensive MRV system, operational to detect both deforestation and forest degradation as presented in the first article. The emphasis of this paper is set on the potential of countries to generate economic benefits from REDD. A simulation study for five countries was conducted showing high to low deforestation rates and high to low forest cover. Thus, these countries represent different states in the forest transition theory (FT) as described in chapter 2.4.

Table 5: Countries selected for the simulation study (data source FAO 2010, adapted from Plugge et al. 2012)

Country	Forest area 2010 [1000 ha]	Forest area change [1000 ha/year]	Carbon stock 2010		Carbon stock reduction 2000 – 2010 in [%]
			[MtC]	[tC/ha]	
Ghana	4,940	-115	381	77	-23.36
Cameroon	19,916	-220	2,966	135	-11.05
Indonesia	94,432	-498	13,017	138	-5.27
Colombia	60,499	-101	6,805	112	-1.67
Suriname	14,758	-2	3,165	214	-0.12

The study applied a realistic range of total errors (1% to 10%) for the estimation of the carbon stocks at the end of the assessment period for analyzing the impact of uncertainties and costs of a MRV system. In addition, the costs for the MRV system were divided into fixed monitoring costs and variable monitoring costs; the latter are dependent on the size of the forest area and on the design of the MRV system. Therefore, they are represented by a range of values (0.01 US$/ha to 5 US$/ha) in the simulation study. As described in chapter 2.3, a rational decision about the adoption of a REDD regime is driven on the one hand by the potential benefits, and on the other by the costs of implementing an operational and sound monitoring system. The cost benefit analysis of this article compares the potential benefits to the expected monitoring costs. Comparing benefits with costs allows the break-even point (BEP) to be calculated, where the former equals the latter. Using the values of the five selected countries presented in Table 5, as well as the different ranges for the costs and the errors in the simulation, it is possible to calculate the emission reduction that is needed to reach the BEP (table 2 in Plugge et al. 2012). Furthermore, it is possible to identify the maximum total

[1] At the time of writing the first draft of the article the term REDD+ was not completely adopted in the international negotiations. Referring to this article the terms REDD and REDD+ are used synonymously.

error of the MRV system that allows for the generation of economic benefits under a chosen emission reduction scenario (table 3 in Plugge et al. 2012).

The benefits achievable by emission reductions are a function of the price that is paid per ton of carbon dioxide (tCO_2). The higher the price for one ton CO_2, the higher the potential benefit. However, the simulation study showed that this logic consequence is only true as long as the total error is carefully controlled and can be kept lower than a threshold value (see Figure 4).

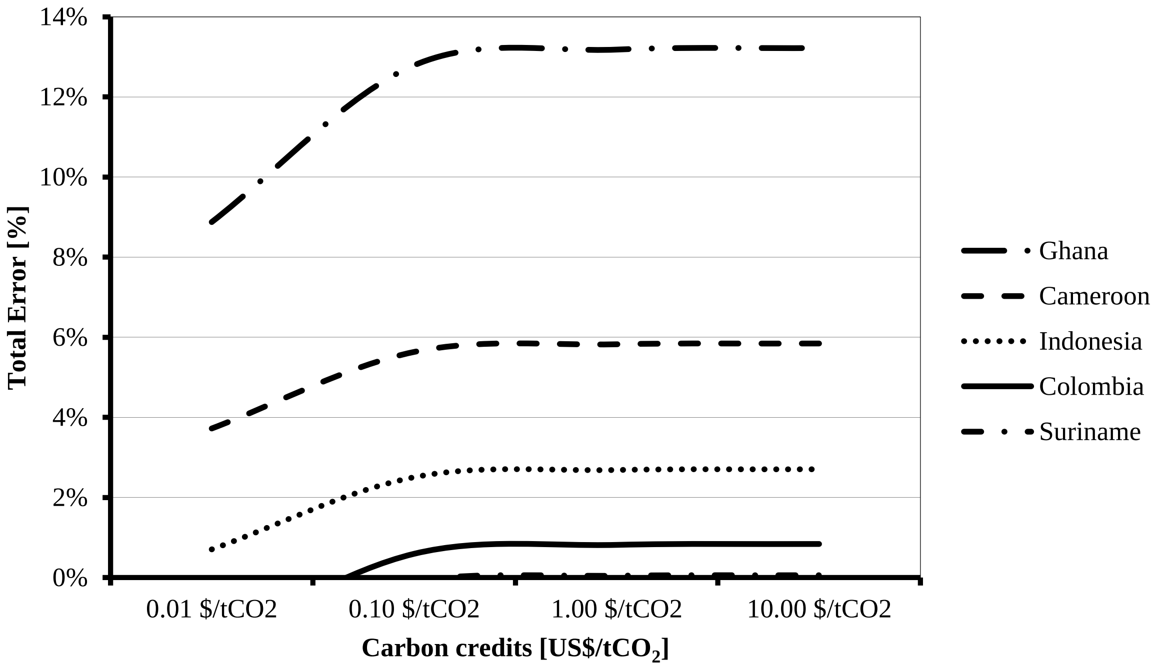

Figure 4: Maximum total error percentages at given inventory costs (i.e. fixed costs, MF, were set to 100,000 US$ and variable costs, Mha, to 0.1 US$/ha) over increasing carbon prices (Plugge et al. 2012).

The results of this article demonstrate that the potential for generating benefits from REDD greatly depends on the magnitude of the total error, while assessment costs and the price of carbon credits play a minor role. Consequently, under the assumptions of this article, REDD is obviously not an option for generating benefits for countries with low deforestation rates as they would need to implement monitoring systems that are able to estimate carbon stock changes with a total error well below 1%. Total errors feasible under operational monitoring systems are only sufficient to gain revenues from REDD-regimes under high deforestation rates.

2.2 Discussion of the second article in the thematic context

The second article refers to three major topics in the thematic context of this cumulative dissertation. The first aspect concerns the setup of reference levels against which emission reductions are set off, the second is the aspect of uncertainties aligned to a MRV system, the third are the financial aspects of REDD+.

The first aspect referring to the context of this thesis is the decision in favor of the RL made in the article. It may be argued that by applying a reference level different to the 'business-as-usual' scenario as chosen in the simulation study for those countries that show low deforestation rates, the potential for gaining benefits might be improved. This aspect is already reflected in the conclusions of the article. However, taking into account the ideas of a crediting baseline or incentive benchmark (Angelsen 2012) the obstacles of achieving accountable emission reductions for countries with low deforestation rates would increase. A special accounting system for these countries seems indispensable if they are not to be excluded from a REDD+ mechanism.

For the second aspect the importance of including uncertainties into the MRV requirements as requested by UNFCCC (2008) and discussed by e.g. Grassi et al. (2008) and Waggoner (2009), is clearly shown by this article. Furthermore, the expectation that uncertainties may outweigh successful efforts towards reducing deforestation and forest degradation (e.g. Bucki et al. 2012, Köhl et al. 2009, Pelletier et al. 2011) is confirmed. It may be argued that a correlation of the errors at two points in time, as can be expected under an operational MRV system that follows the prerequisites of CFI (Grassi et al. 2008, Köhl et al. 2006), is not considered in the simulation study. Consideration of this error correlation would lower the negative impact that the application of the principle of conservativeness has on the accountable emission reductions. However, for the data that is used in this article (FAO's FRA 2010) no information on the type of assessment is given. Thus, a correlation of assessment errors could only be assumed but not verified. Furthermore, the intention of the article was to raise awareness for the major influence that errors may have on the accountability of emission reductions. In an editorial comment that will be published together with this article in the same volume of 'Climatic Change' Knoke assesses the effect that a correlation of errors would have on the presented findings. While applying a different methodology the general consequence that high uncertainties may outweigh successful REDD+ efforts is confirmed (Knoke 2012, unpublished).

For the third topic, i.e. the financial aspects of REDD+, this article shows that a reasonable part of the funds that are available to countries in the readiness and the policy reform phase should be spent on the development of methodologies and capacities for the implementation of a MRV system. This finding is confirmed and estimates for the costs are presented in e.g. Hardcastle and Baird (2008) and UNFCCC (2009a). The World Bank (2011) provides a manual for the upfront calculation of all costs associated with the implementation of a national REDD+ mechanism. Furthermore, the article shows that the undoubtedly important discussion on the influence of carbon credits issued via REDD+ on the carbon market (Bosetti et al. 2009, Lubowski 2008) has to be seen in the light of the accountability of emission reductions. The results of the article show that the price paid per carbon credit is only of importance as long as the total error of the implemented MRV system allows for issuing carbon credits from REDD+ activities.

3 Plugge and Köhl (2012): "Estimating carbon emissions from forest degradation: implications of uncertainties and area sizes for a REDD+ MRV system"

The third article of this thesis was written by Daniel Plugge and Michael Köhl and was accepted by the Canadian Journal of Forest Research on 17th August 2012. It was published online with open access on 12th November 2012.

3.1 Summary of the third article

This article concentrates on measuring and reporting the emissions and emission reductions from forest degradation. On the basis of data from the FAO's FRA 2010, the influence of uncertainties that are aligned to the estimation of emission reductions from forest degradation, i.e. in the IPCC land use category forest land remaining forest land is shown. Three countries representing small to large forest areas and low to high carbon stocks are selected for the conduction of a simulation study. As in Plugge et al. (2012) these countries show different states in the forest transition theory (see chapter 2.4). Furthermore, the countries were selected from the entity of countries that reported data to the FRA 2010 according to: (i) that they have reported a negative change in their forest carbon stock from 1990 to 2000 (reference period) and 2000 to 2010 (assessment period) and (ii) that they have been successful in reducing the negative change in forest carbon stocks between the two periods.

Table 6: FRA 2010 data for the three selected countries on total forest area (A) in thousand hectares [1000ha], total C-stock (C) in teragrams carbon [TgC] and C-stock per hectare (C/ha) in megagram per hectare [Mg ha-1] in the years 1990 (t_0), 2000 (t_1) and 2010 (t_2) (Plugge and Köhl 2012)

Country	A_{t_0} [1000ha]	A_{t_1} [1000ha]	A_{t_2} [1000ha]	C_{t_0} [TgC]	C_{t_1} [TgC]	C_{t_2} [TgC]	C/ha_{t_0} [Mg ha^{-1}]	C/ha_{t_1} [Mg ha^{-1}]	C/ha_{t_2} [Mg ha^{-1}]
Brunei	413	397	380	81	76	72	196.1	191.4	189.5
Cambodia	12 944	11 546	10 094	609	537	464	47.0	46.5	46.0
Pakistan	2 527	2 116	1 687	330	271	213	130.6	128.1	126.3

On the basis of the data presented in Table 6, three different approaches for the inclusion of the uncertainties of estimates for the two periods are analyzed. The uncertainties were included in the simulation by a range of realistic errors (0% to 10%), accordingly including the idealistic assumption that estimates can be achieved with an error-free true mean. The approaches represent different scenarios for possible correlations of uncertainties between the two periods (see Figure 5). A full correlation of the uncertainties is, however, not part of the simulation as no information is available on the methods used for data collection on forest degradation (i.e. the changes in C/ha) for the FRA 2010. Whether these data are positively correlated (Approach C) or negatively correlated (Approach A), which is likely for degradation areas, cannot be deduced from the dataset. To show the disparate influences of the different types of correlations, the data of 1990, 2000 and 2010 were treated as completely independent datasets.

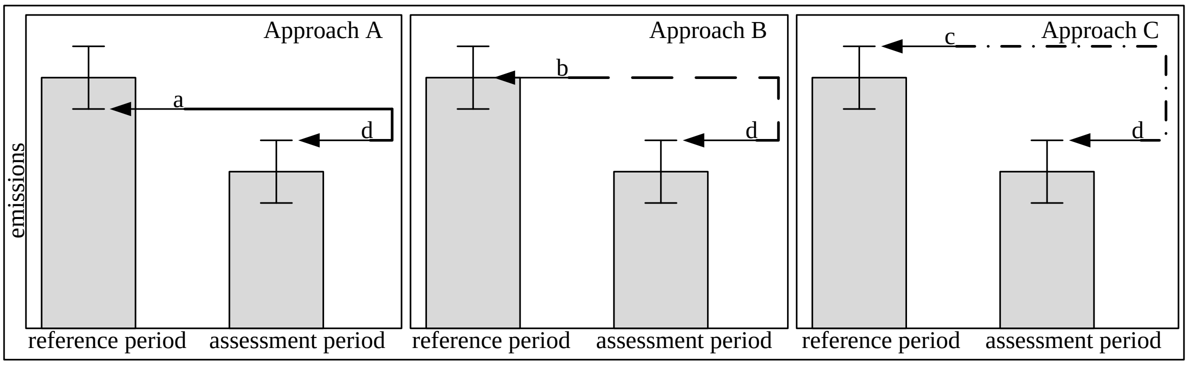

Figure 5: The three approaches analyzed in this study. Approach A (a-d) conservatively considers the uncertainties in both periods. Approach B (b-d) only takes into account the uncertainties at the end of the assessment period. Approach C (c-d) is oriented on the conservative estimate of the emissions in the reference period (upper bound of the error interval) (Plugge and Köhl 2012).

To analyze the sensitivity of the estimated emission reductions with respect to the size of areas where forest degradation takes place, the simulation includes three different sizes of these areas, i.e. 10%, 20% and 50% of the total forest area. The data presented in Table 6 allow for identifying the amount of carbon that is lost due to degradation activities in both periods. For each different size of the degradation areas a reference level (or baseline) can be constructed. For simplicity a business as usual baseline is assumed. Table 7 shows that the emission reduction is independent from the size of the degradation area.

Table 7: C-stock change per hectare for the reference and the assessment period in total values [Mg ha^{-1}] and in percent [%] for the three selected sizes of the area of degradation (A_{deg}) in thousand hectares for each country, as well as the proportional reduction of the carbon stock change between the periods in percent [%]. The values for the reference period represent the values for the baseline (adapted from Plugge and Köhl 2012).

			reference period (ΔC_{BL})		assessment period		emission reduction*
	Country	A_{deg} [1000ha]	[Mg ha^{-1}]	[%]	[Mg ha^{-1}]	[%]	[%]
area of degradation 10%	Brunei	39.7	-46.9	-23.9	-16.8	-11.2	-64.2
	Cambodia	1 154.6	-5.4	-11.5	-4.1	-9.7	-24.7
	Pakistan	211.6	-25.2	-19.3	-9.3	-8.9	-62.9
area of degradation 20%	Brunei	79.4	-23.5	-12.0	-8.4	-4.9	-64.2
	Cambodia	2 309.2	-2.7	-5.7	-2.0	-4.6	-24.7
	Pakistan	423.2	-12.6	-9.6	-4.7	-4.0	-62.9
area of degradation 50%	Brunei	198.5	-9.4	-4.8	-3.4	-1.8	-64.2
	Cambodia	5 773.0	-1.1	-2.3	-0.8	-1.8	-24.7
	Pakistan	1 058.0	-5.0	-3.9	-1.9	-1.5	-62.9

* from the reference to the assessment period

The analyses of the simulation study focused on two points: (i) the influence of uncertainties for both periods on the accountability of emission reductions from forest degradation, and (ii) the sensitivity of the accountable emission reduction to different sizes of areas where forest degradation takes place. For the first point, the results showed the negative influence of high uncertainties on the accountability of emission reductions for the Approaches A and B. The higher the uncertainties at the end of the reference period, the lower is the amount of accountable emission reductions for Approach A. However, if uncertainties are better controlled in the assessment period, higher emission reductions can be reported than with maintaining the level of uncertainty from the reference to the assessment period. For Approach B, that assumes an error-free mean in the reference period, the reportable emission reduction decrease with increasing uncertainties in the assessment period. For Approach C the results for the first part of the analyses showed that this approach towards including the uncertainties for both periods is likely to create an incentive for estimating emissions in the reference period with a high total error. As this is not an option for a reliable and acceptable REDD+ MRV system, Approach C was not considered for the second part of the analyses.

In the second part the results demonstrated that the accountability of emission reductions is sensitive to the area sizes for degradation activities. Increasing area sizes reduce the possibilities of a country to report successful emission reductions and amplify the negative effect of the uncertainties (see Figure 6 for the example of Brunei).

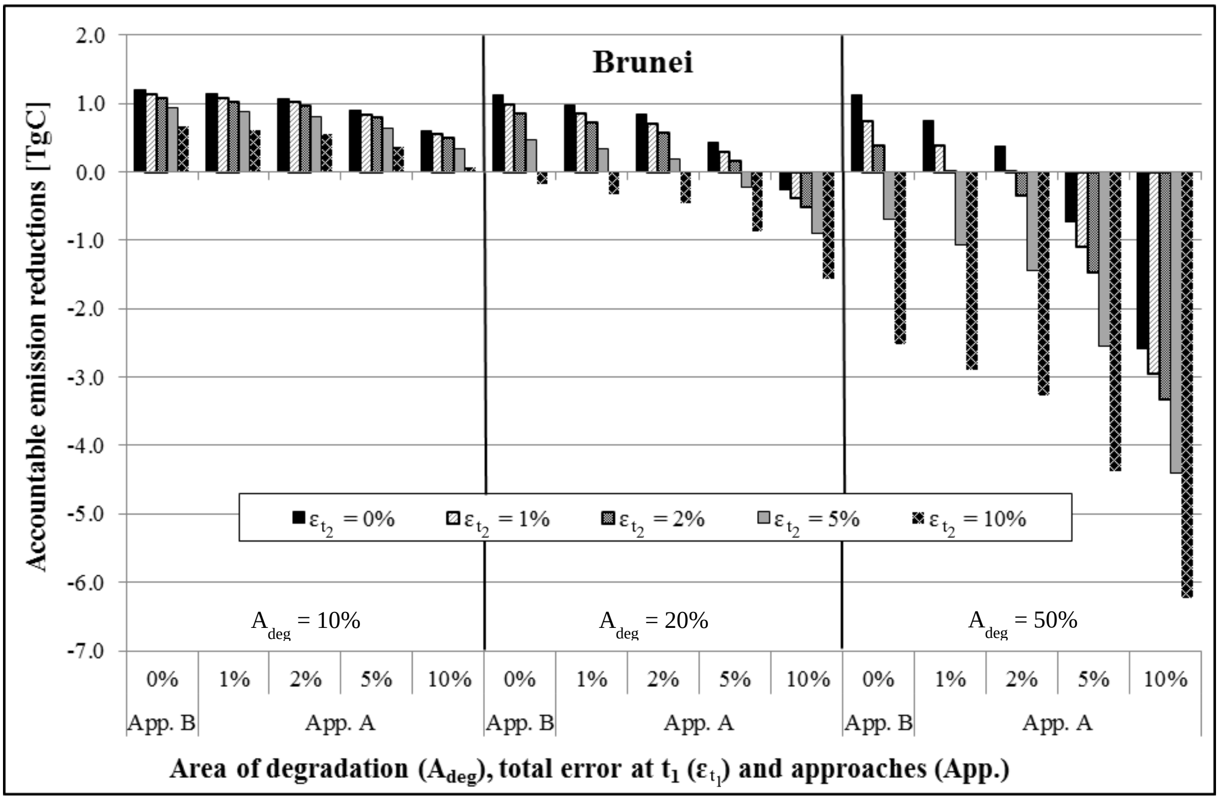

Figure 6: Accountable emission reductions in teragrams carbon for Brunei (TgC, y-axis) for Approach A and B and different areas of degradation (A_{deg} = 10%, left; A_{deg} = 20%, center; A_{deg} = 50%, right). The x-axis shows ε_{t_1} of the estimates in percent, with Approach B = ε_{t_1} of 0% and Approach A with ε_{t_1} = 1% - 10%. The graphs depict the resulting accountable emission reductions for the different error levels at t_2 (ε_{t_2}). Positive values of TgC show accountable emission reductions, negative values imply that no emission reduction can be reported (Plugge and Köhl 2012).

The results of the study highlight the importance of identifying feasible options of including uncertainties for different periods into a MRV system to avoid windfall profits from REDD+. Similar to the case of deforestation, countries that already show low forest degradation rates are obliged to develop and apply MRV systems that are able to assess emission reductions with low total errors to be in a situation to generate benefits from a REDD+ mechanism. Moreover, it is demonstrated that an as accurate as possible identification of the areas where forest degradation takes place is decisive on the amount of benefits achievable from a REDD+ mechanism for a country. As forest degradation is a dynamic process a MRV system for REDD+ needs to be adaptive to the dynamics of the process and allow for adaption of the monitoring activities over time.

3.2 Discussion of the third article in the thematic context

The third article concentrates on three main aspects of the thematic context. First, it gives input to the discussion on the construction of reference levels for REDD+ activities. Second, it considers the issue of MRV for forest degradation, and third it reflects the issue of uncertainties especially for forest degradation.

With regard to the construction of reference levels, the findings of the third article confirm the considerations on alternative possibilities for the construction of baselines, as given in e.g. Meridian Institute (2011b) and discussed in Plugge et al. (2012), not only for the case of deforestation, but also forest degradation. Furthermore, it might appear sensible to construct different reference levels for the two processes as the relation of the impact of deforestation and forest degradation depends on factors such as the state of a country in the forest transition curve, the size of the forest area, or the amount of forest fragmentation (Murdiyarso et al. 2008a). Thus, granting developing countries the opportunity to deploy sub-national baselines, as put forward by UNFCCC (2012c), appears to be sensible.

For the second aspect, the article clearly shows that considering forest degradation in a REDD+ mechanism demands tailored methodologies. This demand is also reflected in several other publications (e.g. FAO 2009, GOFC-GOLD 2011, Simula 2009). Monitoring forest degradation is generally seen as more difficult than monitoring deforestation (IPCC 2003b, UNFCCC 2011d). Even though methodologies for reporting on forest degradation at higher tiers are available (e.g. IPCC 2006, Köhl et al. 2006, Plugge et al. 2010) this may not be feasible for some developing countries in the first phase of REDD+. It is therefore proposed to allow using proxies for forest degradation (UNFCCC 2011d) and to further allow developing countries to follow a step-wise approach in the development of their MRV systems to cope with national capacities and circumstances and move to higher tiers when feasible (UNFCCC 2012a). Omitting the measuring and reporting of forest degradation is not an option, especially since the introduction of the enhancement of forest carbon stocks the from REDD+ activities (Herold and Skutsch 2011). The article relates forest degradation to a certain area, i.e. no spatial shift of degradation activities occurs and degraded areas are not deforested. This can be assumed at least for some degraded forests (Herold and Skutsch 2011, Murdiyarso et al. 2008a). However, forest degradation is a dynamic process and can also be seen as a precursor to deforestation (Asner et al. 2005). Thus, it is concluded from the article that a MRV system that entails forest degradation needs to be dynamic and could follow the prerequisites of sampling with partial replacement as introduced by Ware and Cunia (1965) or Scott and Köhl (1994). Furthermore, forest could be stratified using proxies for the risk of degradation such as accessibility or distance to settlements. This type of stratification is already included in the methodology presented in the first article (Plugge et al. 2010) and can be supported and enhanced through advances in remote sensing technologies and methodologies (Baldauf 2012, unpublished). Such stratification could clearly help with identifying areas where degradation activities take place. The presented article shows the great importance of a precise delineation of degradation areas for a credible MRV system as well as for the possibility of a country to gain benefits from REDD+ activities.

For the aspect of uncertainties, the third article confirms the findings that have been issued in publications regarding deforestation (e.g. Köhl et al. 2009, Pelletier et al. 2011, Plugge et al. 2011, Plugge et al. 2012) for the topic of forest degradation. However, the article extends beyond most of the named publications as it considers the uncertainties of more than on period. It clearly shows that not only it is necessary to consider the uncertainties at one point in time as already requested by UNFCCC (2012b), but that clear provisions also have to be made for the propagation of errors between several different periods to avoid false incentives or windfall profits.

4 Conclusions of the cumulative dissertation

4.1 Capabilities of terrestrial forest inventory systems in the assessment of forest degradation in the scope of REDD+

Forest degradation is estimated to affect 100 million hectares globally per year, thus outweighing the area that is deforested - 13 million hectares per year - by nearly eight times (FAO 2006). In the scope of REDD+, forest degradation focusses on the loss of carbon in the IPCC land use category 'forest land remaining forest land'. Terrestrial inventory systems are momentarily the only readily available opportunity to estimate changes in carbon stocks in this land use category with suitable reliability. In particularly the second (Plugge et al. 2012) and the third article (Plugge and Köhl 2012) of this dissertation demonstrate that reliable estimates are decisive for gaining benefits from a possible REDD+ mechanism and outweigh the influence of the price paid for each ton of reduced carbon emissions. Only when errors are carefully controlled are countries that do not show historically high deforestation rates in a position to report successful reductions of their emissions from deforestation and forest degradation. Thus, any such country is advised to distribute financial resources in the readiness and the policy reform phase to the development of a forest inventory system that is capable of providing adequate reliable estimates. Especially for the case of forest degradation this is rendered possible by applying terrestrial inventory techniques as laid out in the first article (Plugge et al. 2010). Uncertainties in ground based surveys can be quantified and identified. Hence they can be tackled by alterations in the general sampling design or by analytical measures for non-sampling errors and the number of samples taken for sampling errors. This enables a country to optimize its MRV system towards a higher reliability. A terrestrial inventory design as part of a MRV system for REDD+ will need to be deployed under the prerequisites of a continuous forest inventory (CFI). In a CFI system the uncertainties are correlated (see Plugge and Köhl 2012) and thus the application of the principle of conservativeness, as already introduced by UNFCCC, does not lead to overly negative effects in the ability to report emission reductions. The first article demonstrates that terrestrial forest inventory systems can be designed to be adaptive to different forest formations (i.e. dry, deciduous, moist) and different states of forests (i.e. from highly fragmented to pristine), while providing reliable estimates on sub-national and national level. As described in the third article, terrestrial forest inventories can also be designed to consider the dynamic processes of forest degradation, i.e. a spatial shift in degradation patterns. Thus, a country has the flexibility to adapt the inventory design of a MRV system for REDD+ to its specific circumstances while providing high levels of estimate reliability. Furthermore, the effects of the enhancement of forest carbon stocks and the sustainable management of forests, i.e. emissions and removals, as included in the '+' of REDD+ are just as accurately or easily measurable and reportable with such a flexible inventory design. Thus, terrestrial forest inventory systems are readily capable of being tailored to: (i) answer the demand for higher tier levels for reporting under UNFCCC for the key category forest degradation; (ii) give information on the enhancement of forest carbon stocks and the sustainable management of forests; (iii) implement a MRV system that is transparent, consistent, robust, comparable and controllable; and (iv) gain economic benefits from REDD+.

4.2 Deficiencies of terrestrial forest inventory systems in the assessment of forest degradation in the scope of REDD+

Whether a country participates in a REDD+ mechanism or not will be decided by the potential to generate economic benefits from introducing REDD+ activities (WWF 2012). Terrestrial forest inventories are costly and time consuming and cannot be applied for a national wall-to-wall assessment of deforestation and forest degradation activities. This renders sample based inventory approaches necessary. Sample based approaches, however, do not stand the demand for completeness as issued by the SBSTA (UNFCCC 2012b) or Grassi et al. (2008). This means that a sample based terrestrial inventory is not capable of reporting on the entity and the spatial extent of deforestation or forest degradation processes regardless of the allocated resources. The needed resources, i.e. the costs of sample based forest inventories are design dependent and there is a general trade-off between the money invested, i.e. the number of terrestrial samples that can be taken, and the reliability of the estimates (Köhl et al. 2011). When applied properly, i.e. in a manner that allows for estimates with a suitable reliability allowing for gaining benefits, significant costs are added to the MRV system for all REDD+ activities. However, there is no sample based inventory design that is able to produce estimates that are free of uncertainties. This is due to natural variability on the one hand, and design effects on the other. Design effects include the impracticability of a nation-wide terrestrial inventory system that is able to report on even small changes in forest carbon stocks. The costs associated with these assessments may outweigh the gains in accuracy, particularly in areas that are remote and hard to access. Furthermore, the necessary build-up of capacities for national in-situ assessments of carbon stocks requires great temporal and monetary efforts (Hardcastle and Baird 2008) and terrestrial forest inventory systems gather a multitude of data that needs to be processed, stored and verified. In their latest session, the SBSTA proposed a biennial reporting for activities related to REDD+ (UNFCCC 2012a). Even if a biennial reporting does not imply a biennial inventory and given a CFI system where not all permanent sampling plots need to be revisited, the reporting obligations call for a time effective implementation of a MRV system with a high number of staff, thus increasing costs.

Implementing an inventory system that answers the demand for higher tiers for key categories requires the assessment of an increasing number of parameters. Especially in the assessment of forest degradation impacts some of these additional parameters are associated with high uncertainties that cannot be easily reduced. Such parameters involve the estimation of the carbon stock loss due to illegal logging when only stumps are left in the forests and the major part of the tree is not measurable. Another example is the estimation of carbon stock losses due to the frequent collection of fuel-wood or non-timber forest products. The uncertainty of each parameter has to be combined with the uncertainties of every other parameter to quantify the overall uncertainty of the estimate of carbon stock loss due to degradation activities. Additional parameters with high uncertainties may, in the end, lead to an increased uncertainty of higher tier methods compared to lower tier methods (WWF 2012). Thus, countries that already show low rates of deforestation and forest degradation are facing especially high obstacles in developing and implementing a terrestrial inventory system capable of producing estimates with a sufficient reliability. The opportunity of gaining benefits from reducing forest degradation for these countries is generally low due to a constrained reduction potential. These countries would then have an incentive for not reporting on forest degradation activities due to the high costs associated with terrestrial forest inventory systems and the resulting chance of no or only very few benefits.

4.3 General conclusions and ways to overcome the deficiencies of terrestrial forest inventory systems in the assessment of forest degradation in the scope of REDD+

UNFCCC (2010) recommends implementing terrestrial forest inventory techniques as an indispensable part of a robust, transparent and credible MRV system for REDD+ activities. The first part of the conclusions shows that terrestrial forest inventory techniques are capable and indispensable for assessing and estimating forest degradation. These techniques are readily available for the implementation of a transparent, consistent, robust, comparable and controllable MRV system. The second part shows that there are some deficiencies in the applicability of these techniques under specific circumstances and that terrestrial forest inventories alone cannot provide the needed completeness for a credible MRV system.

To overcome these deficiencies the second complementary part to terrestrial forest inventories in an operational, robust, transparent and credible MRV system for REDD+ are remote sensing techniques. The capabilities and advantages of applying remote sensing imagery for tracking the process of deforestation are well known. In fact, on a national, regional and global level an efficient monitoring of deforestation is only possible via remote sensing. In this case terrestrial surveys are merely needed to check for the accuracy of the estimates made.

For the case of assessing the impacts of forest degradation, the enhancement of forest carbon stocks and the sustainable management of forests, i.e. changes in carbon stocks in forest land remaining forest land, the relation between remote sensing and terrestrial forest inventories is somewhat different. The development of remote sensing technologies and methodologies for the detection of changes in forest carbons stocks are evolving (Baldauf 2012, unpublished) and have lowered the cost of terrestrial inventories substantially, especially when combined with auxiliary socio-economic data like accessibility or distance to settlements. Thereby in-situ assessments can be directed to those areas where actual human induced degradation activities occur (Plugge et al. 2010). Moreover, this allows for a relatively accurate estimate of the area where human induced activities take place, as needed to answer the constrained completeness of terrestrial inventories. In addition, the delineation of degradation areas is decisive for the generation of benefits from REDD+ as shown in Plugge and Köhl (2012). This is of special importance for areas that are not under a forest management scheme or where degradation processes are due to illegal activities like fires or the logging of precious trees, i.e. where no data exist on the potential of a forest area to undergo changes. However, detecting changes in forest carbon stocks via remote sensing still needs high to very high resolution data and, especially when there is no distinct impact on the canopy cover, active sensors have to be applied (Baldauf 2009). Furthermore, processing and interpreting remotely sensed data is associated with the work force of highly competent personal with advanced training. Both, high to very high resolution imagery and capacity development, are associated with high costs. Beyond this, detecting and analyzing changes in forest carbon stocks via remote sensing is still related to high levels of uncertainty. Hence, the appropriate combination of different remote sensing techniques and terrestrial forest inventories that assess changes in forest carbon stocks are vital for a cost effective MRV system. The first article (Plugge et al. 2010) shows how to deploy remote sensing imagery of different resolution in order to minimize the area where very high resolution imagery is needed and to guide and support the terrestrial inventories. Köhl et al. (2011) analyzed different combinations of remote sensing technologies and in-situ assessments to show ways of optimizing the cost efficiency of such approaches. The cost-effective design of a MRV system for a specific country must not only be scientifically sound, but also has to take into account the major drivers of deforestation and forest degradation, the combination of the processes that lead to a change of forest carbon stocks, as well as the existing capacities available for processing and analyzing the data and for the physical assessment on the ground. The best source of information on the drivers of change, their spatial allocation, and their impact are local communities that are involved in managing their own forest land (community based forest management). Incorporating this information leads to a valuable gain in knowledge for the country-specific design of a MRV system. The direct involvement of local people in the terrestrial assessments results in a better understanding of the issues related to REDD+. This helps bring about the desired multiple benefits from REDD+. When designed and implemented properly, terrestrial forest inventories will thus not only serve as an indispensable part of an operational, robust, transparent and credible MRV system, but also provide an efficient benefit transfer to those communities that are affected the most by REDD+ activities.

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Annex I:
Scientific articles and personal contribution

Combined biomass inventory in the scope of REDD (Reducing Emissions from Deforestation and Forest Degradation)

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ABSTRACT

This paper presents an approach for combined biomass inventories in the scope of future REDD regimes. The focus is set on a sound and reliable method for measuring and monitoring the current state of carbon stocks and their changes over time. A reliable framework for measuring, reporting and verification is urgently needed to ensure the integrity and credibility of REDD efforts in general and REDD in the post-2012 agreement which is assumed to be approved at COP 16 in Mexico in December 2010. The proposed approach was developed and successfully implemented in Madagascar within a multi-institutional REDD project, i.e., REDD-FORECA. It combines a multi-temporal remote sensing approach incorporating satellite sensors from medium to very high resolution with a terrestrial cluster sampling design, which proved to be operational for the whole spectrum from highly fragmented to pristine forest areas. This combination was implemented by a multi-phase sampling approach. The inventory is designed for the prerequisites of a continuous forest inventory to facilitate the quantification of possible CO_2 reductions over time. The first field-assessments were accomplished in 2007 and 2008, and resulted in estimates of aboveground biomass on single tree level. Statistical upscaling procedures were utilised to aggregate these estimates on several levels. The results of the introduced methodology are presented and discussed.

RÉSUMÉ

Cet article présente une approche concernant les inventaires de biomasse combinés dans le cadre des futurs régimes REDD. Elle porte sur une méthode fiable et avérée pour mesurer et contrôler l'état actuel des stocks de carbone et leur évolution dans le temps. Un système fiable de mesure, de suivi et de vérification est nécessaire pour garantir l'intégrité et la crédibilité des efforts investis dans REDD en général d'une part et du mécanisme REDD dans les accords post-2012 devant être approuvé à Mexico en décembre 2010 lors de la COP 16, d'autre part.

Dans la mesure où REDD doit pouvoir être appliqué par l'ensemble des pays en voie de développement, l'accent a été mis en particulier sur la possibilité de transférer la méthode en tenant compte des particularités nationales et régionales des divers pays concernés. L'approche proposée a été développée et mise en œuvre à Madagascar avec succès dans le cadre d'un projet REDD (REDD-FORECA) impliquant plusieurs institutions. Elle associe une approche basée sur la télédétection multi-temporelle, intégrant des capteurs de moyenne à très haute résolution avec un plan d'échantillonnage terrestre en 'cluster'. Elle s'est avérée opérationnelle sur l'intégralité du spectre des surfaces forestières, depuis les parcelles extrêmement fragmentées aux forêts intactes. Cette possibilité d'adapter la méthode à une large variété d'états de la forêt a été testée et vérifiée. Cet article met de plus en lumière la possibilité de détecter et de quantifier le déboisement et la dégradation des forêts. La méthode présentée permet d'estimer de manière fiable la biomasse forestière et son évolution dans le temps, à un coût total et avec des erreurs d'échantillonnage raisonnables. Cela a été possible grâce à une démarche d'échantillonnage à plusieurs phases en combinant des phases de télédétection avec une phase terrestre d'inventaire. Un contrôle rigoureux des erreurs d'échantillonnage lors de chacune de ces phases est essentiel pour générer des bénéfices dans un mécanisme REDD. L'inventaire est conçu de façon à remplir les pré-requis de tout inventaire forestier continu afin de faciliter la quantification des éventuelles réductions de CO_2. Les premières mesures sur le terrain qui se sont déroulés en 2007 et en 2008 ont permis d'estimer la biomasse au-dessus du niveau du sol. Pour dériver ces estimations à des niveaux d'agrégation plus élevés, des procédures ascendantes (upscaling) ont été utilisées. Les résultats de la méthodologie employée sont présentés et discutés.

KEYWORDS: Combined inventory, remote sensing, biomass, Reducing Emissions from Deforestation and Forest Degradation (REDD), Madagascar.

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MOTS CLEFS : inventaire combine, télédétection, biomasse, réduction des émissions du déboisement et la dégradation forestière (REDD), Madagascar.

INTRODUCTION

According to estimates of the Intergovernmental Panel on Climate Change (IPCC) an annual total of 1.6 billion tons of carbon are released worldwide by land-use change activities, of which a major part results from deforestation and forest degradation (Denman et al. 2007). Following the Stern Report (Stern 2007) carbon emissions from land-use change accumulate to nearly one-fifth of today's total annual emissions, most of which can be traced back to tropical deforestation. The avoidance of deforestation and forest degradation is not accepted so far as an eligible action in the current commitment period of the Kyoto Protocol, i.e., 2008-2012. In 2005 the Eleventh Session of the Conference of Parties (COP 11) to the United Nations Framework Convention on Climate Change (UNFCCC) initiated a process for considering a policy for reduced emissions from deforestation and forest degradation (REDD).

REDUCING EMISSIONS FROM DEFORESTATION AND FOREST DEGRADATION (REDD). Some economical incentives for reducing the emissions of greenhouse gases (GHG) exist in the Kyoto Protocol. In the articles 3.3 and 3.4 the benefit of forests as carbon sinks are considered (UNFCCC 1998) and in the Clean Development Mechanism measures for afforestation and reforestation can be accounted for generation of credits. These financial measures reward the function of forests as carbon sinks or carbon sequestration by local to regional re- or afforestation activities. In contrast, REDD focuses mainly on the maintenance of forest carbon stocks through compensation of potential direct or indirect economic benefits of deforestation and forest degradation on a national level. As developing countries, sheltering the major part of the existing tropical forests, have shown high rates of deforestation in the recent past, the process REDD is expected to become an important element for reduction of GHG emissions into the atmosphere. However, effective incentives leading to a reduction of deforestation and forest degradation are still a topic of ongoing discussions. To ensure the integrity and credibility of REDD efforts in general and REDD in the post-2012 agreement a reliable framework for measuring, reporting and verification is urgently needed (UNFCCC 2007). As a consequence thereof, the parties at COP 15 in Copenhagen acknowledged a decision on the methodological guidance for activities relating to REDD and therein request the establishment of robust and transparent national forest monitoring systems (UNFCCC 2009). It is assumed that a legally binding agreement on REDD will be integrated in a post-2012 agreement at COP 16 in Mexico in December 2010. Nevertheless, each country choosing REDD as an option for mitigating GHG emissions needs to set up its own national strategy and monitoring system that has to adhere UNFCCC standards. Implementing a viable REDD regime involves several steps:

(1) Initiating a system for the assessment of forest carbon stocks and their change over time;
(2) quantifying the amount of reduced CO_2 emissions, which qualifies for accounting;
(3) identifying and ranking of the relevant causes for human impact on forests in order to derive effective measures to combat the degradation of forests;
(4) definition of a reference level (i.e., baseline), against which the changes of carbon stocks in forests are set off; and
(5) implementing a scheme for the transfer of benefits to local actors.

PILOT PROJECT REDD-FORECA. REDD-FORECA is a multi-partnership pilot project in Madagascar that was set up to develop methodological approaches to monitor accountable reductions of GHG emissions due to deforestation and forest degradation activities, to develop possible incentives to realise these reductions, and to integrate the results into the political decision-making process of Madagascar. In REDD-FORECA the German von Thünen-Institute (vTI) and the Malagasy scientific partner ESSA Forêts collaborate with the 'Swiss Foundation for Development and International Cooperation' (Intercooperation) and the 'Gesellschaft für Technische Zusammenarbeit' (GTZ), as well as with various cooperation partners in Madagascar, i.e., inter alia local and national forest authorities. The focal point of the pilot project was set on natural forests as plantations or managed forests are not likely to be a part of REDD.

CARBON FLUXES. As REDD focuses on the maintenance of already existing carbon stocks in natural forests five major carbon pools are to be considered: (1) Aboveground biomass, (2) below-ground biomass, (3) dead wood, (4) litter, and (5) soil organic matter (IPCC 2006). By increasing at least one pool, while maintaining the other pools forests become a carbon sink. However, respecting the complexity of natural systems, all these five carbon pools are highly interdependent and in a steady state of flux (Longdoz et al. 2004, Nabuurs 2004).

Currently there is a contradictory debate on the amount of carbon transferred by the decay of living biomass, i.e., pools 1 and 2, to the atmosphere and to soils, i.e., pool 5. Despite growing interest on this topic, there are no long-term studies in tropical areas on soil carbon fluxes that could allow reliable inferences to the scope of REDD. Thus, the following brief overview on different positions in this debate concentrates on studies from temperate regions. While some publications suggest an increase of organic soil components and thus an increase of carbon sequestered by soils (Freibauer et al. 2009), others report no significant changes in soil carbon or even a release of soil carbon to the atmosphere. Schlesinger and Lichter (2001) studied soil carbon in *Pinus taeda* stands and found high transfer rates of organic carbon in the litter layer, i.e., pool 4, but an absence of carbon accumulation in the mineral soil. They conclude that a significant, long-term net carbon sequestration in soils is an unlikely event. Bellamy et al. (2005) analysed data of the National Soil Inventory in England and Wales, which were assessed between 1978 and 2003. They report a mean annual release of 0.6 percent of the existing soil carbon stock, which compensates with high probability the carbon sequestration by soils. In accordance with the IPCC Good Practice Guidance for National Greenhouse Gas Inventories (IPCC 2006) it was assumed that carbon uptake and carbon release by soils is at equilibrium and that it is justifiable to exclude this pool from accounting. Furthermore, we assume that the carbon sequestration by living biomass in natural forests is on the long run in balance with the carbon offset by the decay of dead organic matter. Thus, natural forests are neither a carbon sink nor a carbon source.

For these reasons the presented methodology will focus on the quantification of living aboveground biomass, which can be subsequently transformed into carbon stock. Changes of the carbon stock are induced by either a total loss of biomass due to deforestation and associated land-use changes or by a net-reduction of biomass stock, i.e., forest degradation. Hence the REDD-FORECA project in Madagascar had inter alia the objective to assess changes of forest area and changes of living biomass stock.

A multitude of methods exist to fulfil this objective. This article illustrates both the development of a methodology for the assessment of forest carbon stocks and their changes over time, and the possibilities of quantification of the amount of reduced CO_2 emissions, which qualifies for accounting. Furthermore, the results after the methodology's appliance are presented and discussed.

INTRODUCTION INTO THE METHODOLOGY

To assess changes in forest area and of living biomass on a national scale combined inventories, i.e., the combination of remote sensing (RS) data and in-situ assessments, have been advised by IPCC (IPCC 2006) and proven to be cost efficient and operational on the one hand and to lead to reliable results on the other hand (Bowden et al. 1979, Scott and Köhl 1994, Achard et al. 2002, IPCC 2003). For this purpose the top-down approach is a commonly used and operational methodology on national level. In the following paragraphs the subsequent steps of this multi-phase approach, as illustrated in Figure 1, are outlined.

In a first step a full coverage of the country's area (wall-to-wall map) can be obtained by remote sensing imagery data. The quality of such data depends on its spatial, spectral, radiometric and temporal resolutions. The wide variety of RS sensors and their specific characteristics have been classified by DeFries et al. (2006) for the particular needs of REDD (Table 1).

The information of the wall-to-wall map can be specified by the usage of sensible auxiliary data on e.g., climate, topography or vegetation classes to derive broad regions of the country's area. Within these regions thematic classes, i.e., non-forest and forest areas can be obtained in a second step by further classifying the remote sensing data. The non-forest and forest areas are considered to be homogeneous groups or strata (Remote Sensing Phase 1, in Figure 1). In general the stratification of an area of interest into sub-areas or strata has the objective to form homogenous sub-units. In most situations, stratified probability sampling is likely to yield more precise population estimates (i.e., estimates with smaller standard errors) than non-stratified probability sampling with the same sample size.

To obtain information on the development of a country's forest area the changes over time between the forest and non-forest areas have to be analysed by applying change detection algorithms for archive and present data (time 0, time 1, in Figure 1).

In contrast to a national forest inventory (NFI), a combined inventory in the scope of REDD needs to concentrate mainly on forest areas that show ample changes in their spatial extent. The use of change detection algorithms integrated in multi-tem-

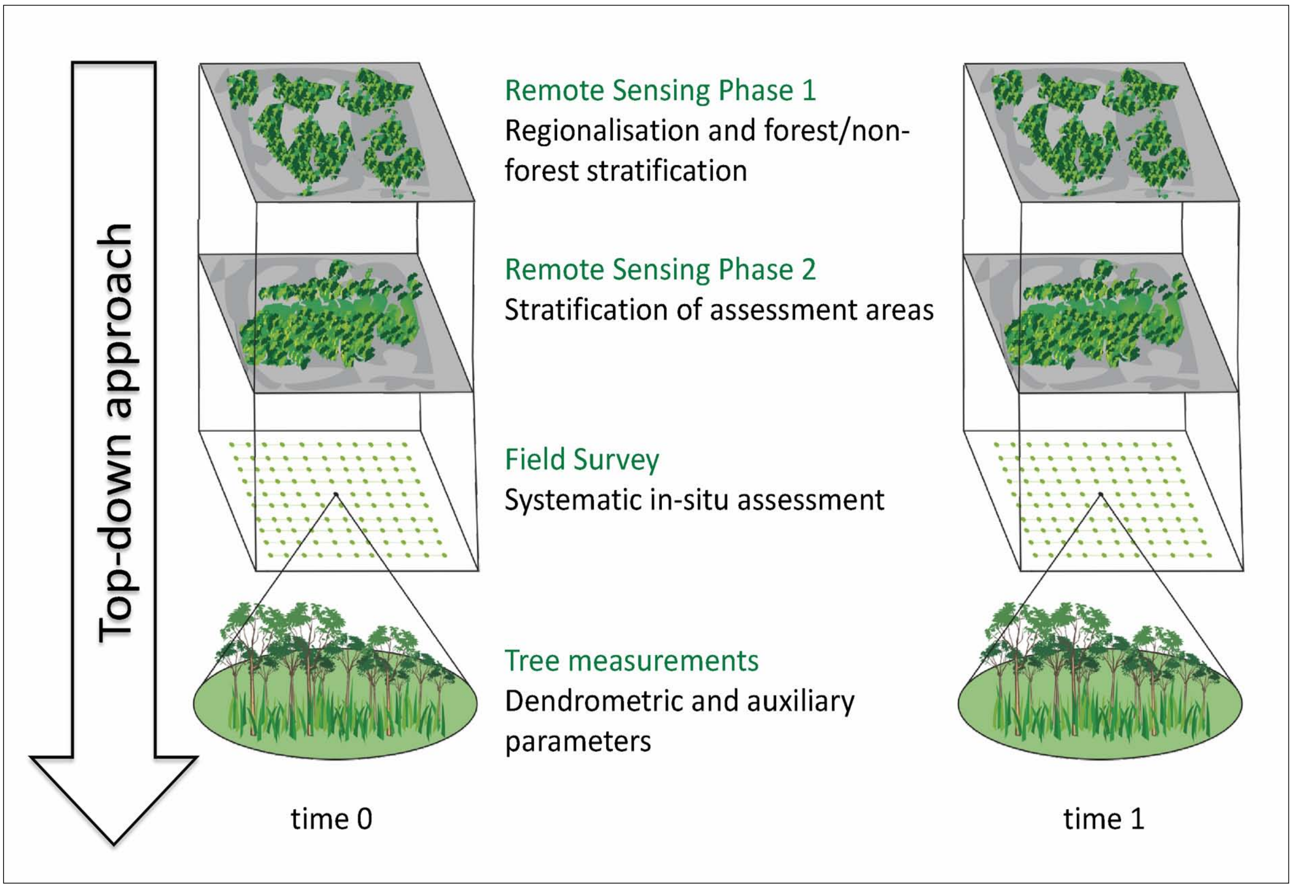

FIGURE 1. Top-down approach for a combined inventory on national scale.

TABLE 1. Utility of optical sensors with different resolutions in deforestation monitoring (after DeFries 2006).

Sensor Resolution	Examples of Current Sensors	Utility for Monitoring	Cost
Very high (< 5 m)	IKONOS, Quickbird	Validation over small areas of results from coarser resolution analysis	Very high
High (10-60 m)	Landsat, SPOT HRV, AWiFsLISS III, CBERS	Primary tool to identify deforestation	Low/medium (historical) to medium high (recent)
Medium (250-1000 m)	MODIS, SPOT Vegetation	Consistent global annual monitoring to identify large clearings (>10-20 ha) and locate "hotspots" for further analysis with high resolution	Low or free
Data from optical sensors have been widely used for deforestation monitoring. Data from Lidar and Radar (Ers 1/2 SAR, JERS-1, ENVISAT-ASAR and ALOS PALSAR) have demonstrated to be useful in project studies, however, so far are not widely used operationally for tropical deforestation monitoring. An exception is the use of SRTM data, which were acquired by an active RADAR sensor.			

poral data can be combined with socio-economic data (e.g., accessibility, number and distribution of settlements), which allows detecting both possible 'hot spots' with high rates of deforestation and forest degradation, and undisturbed areas. Assessment areas, where the in-situ assessments are carried out, can be selected from these hot spots following specified criteria.

In a third step the assessment areas can be further analysed to identify different strata inside the forest area (e.g., closed forest, open forest) through the utilization of high or very high resolution imagery. The combination of different sensors on different scales for this purpose is commonly utilized and proposed by e.g., FAO (2007).

In a next step the design of the in-situ assessment has to be chosen. A multitude of options for the allocation of sample plots (SP) within the strata, like for example, simple random sampling or systematic random sampling, exist and can be found in the specific literature (Loetsch et al. 1973, Synnott 1979, Adlard 1990, IPCC 2006, Köhl et al. 2006). Nevertheless, especially for pilot assessments, where little is known on the characteristics of the forest, a systematic sampling design of the in-situ phase is advised (Saket et al. 2002). Here the sample plots are allocated on a systematic grid in each stratum, thus facilitating the assessment of dendrometric and auxiliary data to obtain information on living aboveground biomass.

To enhance the cost efficiency and feasibility of this approach and taking into account the difficulties of hard to access, remote areas of tropical forests, it is advised to apply cluster sampling. An introduction into the methods and statistical peculiarities of cluster sampling can be found in the literature (Loetsch et al. 1973, Cochran 1977, Köhl et al. 2006, Mandallaz 2008). A measure for the efficiency of cluster sampling is the intra-cluster-correlation coefficient (ICC), which is presented for each of the assessment areas in the results chapter (see Results).

APPLIED METHODOLOGY

For the present pilot project in Madagascar an assessment method for monitoring current state and changes of forest carbon stock has been developed and applied. This method combines the capacities of remote sensing techniques to assess spatial data on forest areas with the potential of sample based field surveys to capture even small changes in forest carbon stock. A detailed illustration of this applied methodology is shown in the Supplementary Material.

To assess natural forest carbon stocks and their changes over time it is indispensable to define 'forest'. From the several existing definitions (UNFCCC 2001, Schoene et al. 2007) the minimum benchmarks defined in the Marrakesh Accords were chosen, in order to realise the inclusion of small forest fragments severely threatened to be finally deforested as well as the dry forests in southern Madagascar. These are (i) a minimum area of 0.05 hectare, (ii) a tree crown cover of more than 10 % and, (iii) the potential to present trees that reach at least two meters height in-situ. To the knowledge of the authors Madagascar itself has not yet decided on a definition of forest for the scope of REDD.

Figure 1 shows the subsequent steps of the applied top-down approach. The implementations of these steps in Madagascar are described in the following.

REGIONALISATION OF THE LAND AREA OF MADAGASCAR.

There are a number of factors influencing the amount of aboveground biomass stocks in forests, resulting in a broad range of these in a single country. However, only some factors are feasible for breaking down a country's land area into homogeneous groups, thus dividing the whole range of possible forest aboveground biomass (AB) into specific, consistent compartments. The aim of the regionalisation in this project was to reduce cost and to increase the accuracy of field assessments. Within the 'Good Practice Guidance for Land Use, Land-Use Change and Forestry' (GPG-LULUCF) (IPCC 2003) stratification rules for broad forest categories related to aboveground biomass stocks are presented, which can be applied worldwide. These rules are shown in Table 2 for tropical forests.

In order to assign these IPCC categories to Madagascar the following input data have been used (see Figure 2): (i) Data of the Moderate Resolution Imaging Spectroradiometer (MODIS), (ii) data of the Shuttle Radar Topography Mission (SRTM) and, (iii) information on climate.

A regionalisation of Madagascar was performed using a supervised classification of these data. This common technique uses RS-data with terrestrial reference data in order to assign discrete or continuous classes to areas. Within the classification process, in this case a maximum likelihood classifier was used, statistical parameters were derived from the RS-data and resultant features thereof (Lillesand et al. 2004).

RS-data generally has to be pre-processed before performing analyses, i.e., geometric and radiometric corrections. These processes lower the estimated errors in the results. Additionally, the use of passive sensors demands, especially in the tropics, the masking of clouds and shadows in RS-data, as these areas cannot be further processed.

Time series of MODIS data were applied for the monitoring of forest cover changes by deforestation on large areas and the identification of hot spots. In doing so, the use of expensive, very

TABLE 2. Aboveground biomass stock in tons per hectare per forest formation (adapted from IPCC 2003).

Tropical Forests						
	Wet	Moist with Short Dry Season	Moist with Long Dry Season	Dry	Montane Moist	Montane Dry
	P > 2000	2000 > P > 1000		P < 1000	P > 1000	P < 1000
Africa	310 (131-513)	260 (159-433)	123 (120-130)	72 (16-195)	191	40
Asia & Oceania:						
Continental	275 (123-683)	182 (10-562)	127 (100-155)	60	222 (81-310)	50
Insular	348 (280-520)	290	160	70	362 (330-505)	50
America	347 (118-860)	217 (212-278)	212 (202-406)	78 (45-90)	234 (48-348)	60
Note: Data are given in mean value and as range of possible values (in parentheses)						
P: Annual Precipitation						

high resolution remote sensing data could thus be restricted to small hot spots to get detailed insight in the spatial development of forest cover. While high resolution sensors provide information on forest cover for small areas, the very high cost associated with their application renders their use on extensive areas not feasible. Regarding the needs for the REDD-FORECA project, sensors with different spatial resolutions needed to be integrated in order to provide a manageable and affordable spatial database.

In the recent past the capabilities of the sensor MODIS regarding the classification of forests have been intensively tested and discussed (Kleinn 2002, Bucha and Stibig 2008, Andersson and Richards 2009, FAO 2009). Hansen et al. (2008) used MODIS data to generate a regional forest / non-forest cover map in the Congo Basin. Moat and Smith (2007) produced an atlas of the vegetation of Madagascar based on MODIS data. Despite the fact, that this data source has a spatial resolution of 250 m and thereby does not allow for exact area and area change calculations due to the mixed pixel issue, FAO proposes its use for monitoring in an integrated approach with higher resolution data (FAO 2007). This integration was implemented in the applied top-down approach.

In addition, Shuttle Radar Topography Mission (SRTM) data were used. This active sensor provides data on topographic information. Data from this sensor are available from the U.S. Geological Survey (USGS) free of charge and have been used since 2000 (Toutin and Gray 2000, van Zyl 2001). An adequate source on climatic information for Madagascar is the classification in climate zones by Cornet (1974). Unfortunately, available national forest inventory (NFI) results of the 1990s were only of limited use, as neither complete original data sets could be obtained nor did the available data fulfil the requirements for REDD.

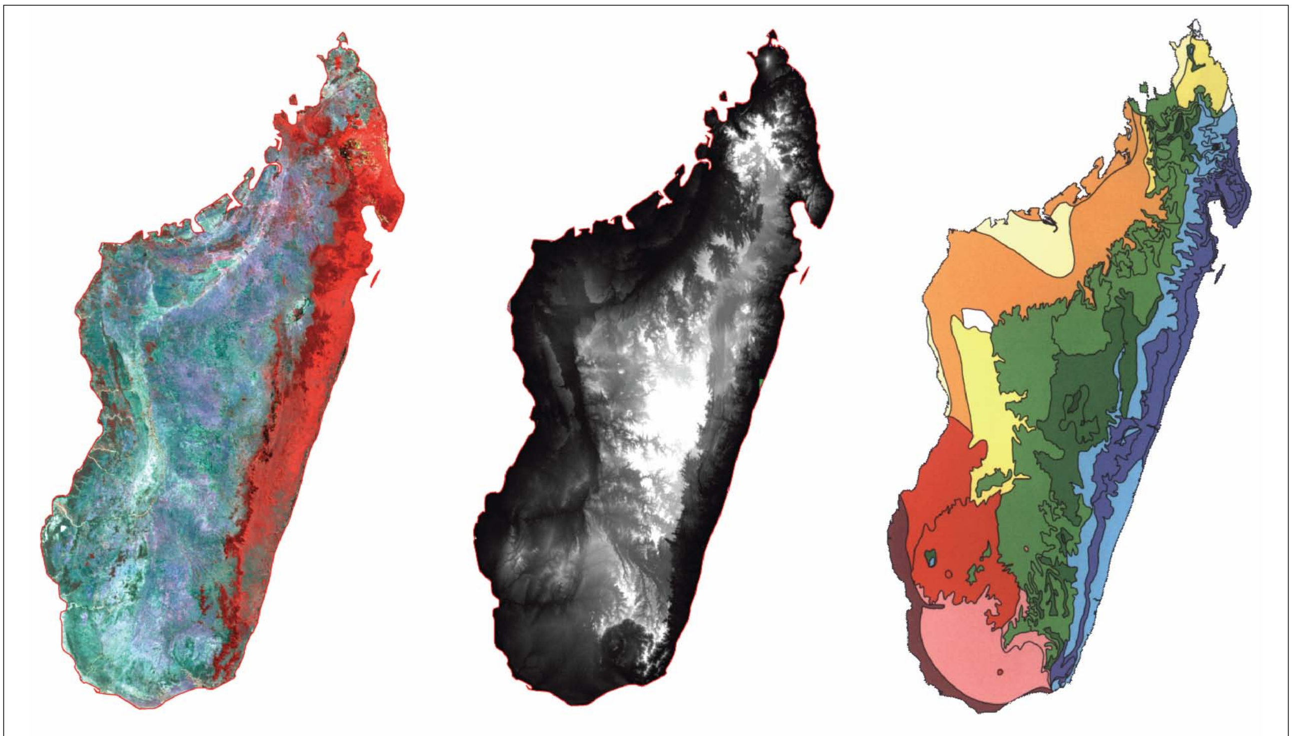

FIGURE 2. Input data for the supervised classification (from left to right): Layer stack of MODIS_13q1 (2-3-1) dated 2007-08-29, SRTM-data (darker spots represent lower areas), climate map based on Cornet (1974).

Furthermore, a criteria list was developed to identify assessment areas. In this list the prerequisites for the selection of an assessment area were defined according to their importance. First, the assessment area has to be representative for the above derived regions. Second, the derived results should be transferable to areas with similar characteristics in other tropical countries. Third, the assessment area has to exhibit different intensities of deforestation and forest degradation. Furthermore, criteria like infrastructure, accessibility and temporal feasibility were included. Considering the above named criteria and due to time restrictions a further aggregation of the categories proposed by IPCC to only three categories was realised and resulted in the following regionalisation of the country and subsequent identification of three assessment areas (see Figure 3 and Table 3).

STRATIFICATION OF ASSESSMENT AREAS. In a next step forest areas within the assessment areas had to be identified. Here, an unsupervised classification algorithm, where RS-data is classified into spectrally similar clusters, was applied. This classification method is performed automatically, and in contrast to the above illustrated supervised classification, no reference data is used for the procedures. As a result, the RS-data is divided into a selected number of categories with similar characteristics of their radiometric information. In order to determine the number of radiometric separable classes for the assessment areas, scatter diagrams were used, where the combination of applied spectral bands of the RS-data was examined.

This classification based on the assessment areas has a high potential for error reduction as the classification results were used for stratification. The aim of this stratification was to identify forest and non-forest areas in the assessment areas. Data of the passive, high resolution SPOT 4 and SPOT 5 sensors were used. Both sensors record four spectral bands, i.e., green, red, near infra-red and short-wavelength infrared light.

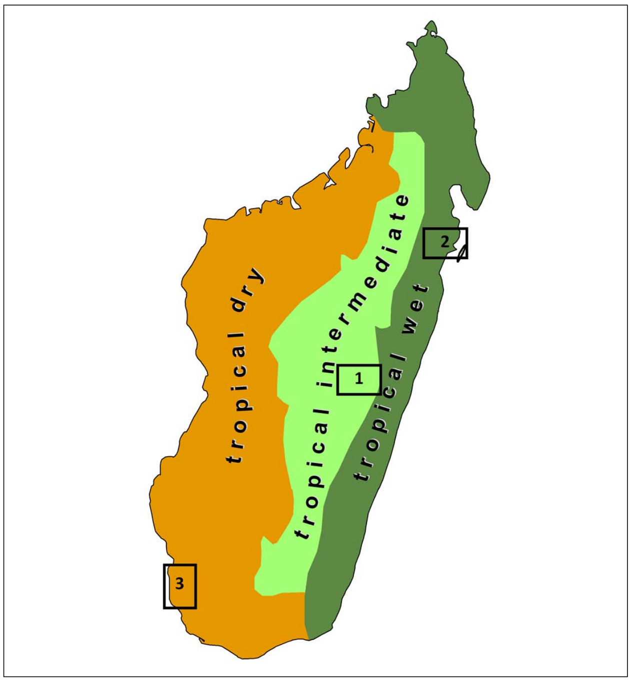

FIGURE 3. Regionalisation of Madagascar's land area based on aggregated IPCC categories; black boxes show the identified assessment areas: No. 1 Tsinjoarivo, No. 2 Manompana and No. 3 Tsimanampetsotsa.

The assessments of both forest area and carbon stock changes over time demands for repeated successive assessments. This was realised by the acquisition of remote sensing imagery from two points in time and a subsequent multi-temporal image analysis. In medium and high resolution imagery changes of the spatial distribution of forest areas were identified, while very high resolution imagery facilitated the identification of advanced stages of forest degradation. Performing a change detection analysis for the archive and the present data permitted statements on the development of these forest areas.

The primarily result was a number of intermediate classes in these forest areas, which in a second step had to be fused into the classes forest and non-forest following the parameters of the chosen forest definition. It was detected that in Madagascar two diverse types of forest fragments exist. Firstly, contiguous or almost contiguous forest areas, i.e., nearly one large forest fragment, could be detected. Secondly, small, more fragmented forest areas were identified. These circumstances gave the reason for the need for a flexible methodology, in order to keep total errors in the inventory low. Keeping errors in a reasonable scale generally requires more expenses for the field assessment. These fragments of forest were subsequently inventoried within the in-situ assessment, which was implemented in order to get sensitive information on forest degradation, i.e., the development of forest carbon stock, and to be able to quantify the loss of biomass due to deforestation activities.

IN-SITU ASSESSMENT. Cluster sampling was applied to facilitate the acquisition of field data in remote and hard to access areas on the one hand and to lower the cost of the field survey on the other hand. In more fragmented forest areas cluster sampling yields the flexibility to be adapted to area specific conditions. Two different cluster layouts for the identified assessment areas (see Figure 4) were applied. In general, different cluster layouts may also be applied for different strata within one assessment area but not within a single stratum. On the sample plots (SPs) of these clusters a multitude of data was assessed during the in-situ assessments from September 2007 to October 2008. These included dendrometric data, such as DBH (diameter at breast height, 1.30m), d7 (diameter at 7 meters height), total height and crown parameters. Furthermore, auxiliary data on the structure and status of the forest, the SP-location and its topographic characteristics as well as on possible human induced impacts were collected. Data on young forest or regeneration were obtained on special plots (small squares in Figure 4).

POST-STRATIFICATION. Using the data of the entity of sample plots (dendrometric and auxiliary) a post-stratification was applied to the population. Post-stratifications generally aim

TABLE 3. Description of the three assessment areas.

1: Tsinjoarivo (TJV)	2: Manompana (MPA)	3:Tsimanampetsotsa (TMP)
Semi-decidous rainforest located in the 'Haute Plateau' of Madagascar	Wet rainforest at the east-coast of Madagascar	Dry forest in the south-west of Madagascar
Total area: 32,272 hectares	Total area: 46,095 hectares	Total area: 43,296 hectares
In-situ assessment from October to November 2007	In-situ assessment from April to May 2008	In-situ assessment conducted from September to October 2008

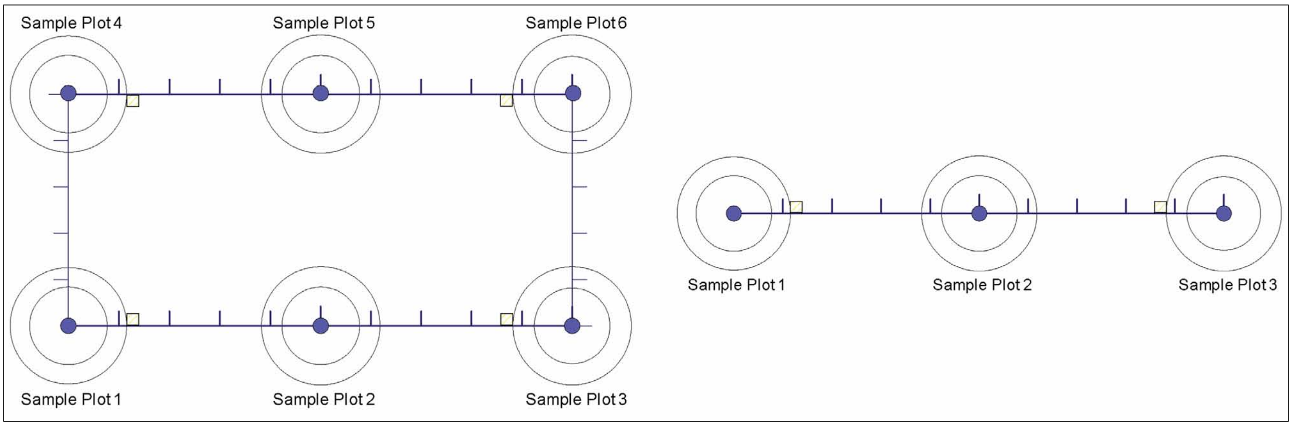

FIGURE 4. Cluster layouts applied in the REDD project in Madagascar; left for nearly pristine forests; right for highly fragmented forests. Distances between sample plots and sample plot size may also be adapted.

at producing sampling estimates with a lower sampling error for each stratum. While strata are physically connected, domains can be described as groups with specific characteristics that are found throughout the whole population, i.e., members of different domains can be found on one single SP. In the presented survey a distinction between different domains was achieved.

Nevertheless, a valid post-stratification is depending on the discriminability of the collected and examined data and can not be forced. Hence, this step is not an indispensable prerequisite for the following.

ABOVEGROUND BIOMASS. The combined inventory focuses on the calculation of living aboveground biomass (AB). There are numerous ways to derive AB depending on the scale of the inventory, i.e., local, regional, or national, or the data available for a specific scale (Köhl 1998, IPCC 2006, Somogyi et al. 2007).

In the presented study, single tree volume was derived via segmentation of each tree and the appliance of domain-specific taper functions. The tree was divided into three parts: main stem (bole), the top, and the stump section. While the stump and the top represent just one single segment, the bole itself can have multiple segments, each with a different taper. Calculation of the volume of each part is presented here for the example of the second assessment area, but was similarly done in the other assessment areas with alterations regarding the area specific domains.

Volume of the bole (V_{bole}):

$$V_{bole} = \sum_{s=1}^{n} \left(\frac{\pi * l_{Sn} * d_{Sn}^2}{12} \right) + \left(\frac{d_{Sn} * d_{Sn+1}}{4} \right) + \left(\frac{d_{Sn+1}^2}{4} \right)$$

with

$$d_{Sn+1} = d_{Sn} * \left(\frac{100 - e^{\alpha + \frac{\beta}{d_{Sn}}}}{100} \right)$$

with

α and β = domain-specific parameters

d_{Sn} = diameter at the beginning of segment n

d_{Sn+1} = diameter at the end of segment n

l_{Sn} = length of segment n

Volume of the top (V_{top}):

$$V_{top} = \left(\frac{\pi * d_{Sn}^2 * (h_{tot} - h_{bh} - n_s * l_s)}{12} \right)$$

with

h_{tot} = total height of the tree

n_s = number of segments of the tree

h_{bh} = breast height

Volume of the stump (V_{stump}):

$$V_{stump} = \left(\frac{h_{bh}}{4} \right) * \left(\left(\frac{\pi * d_{Sn-1}^2}{4} \right) + \left(\left(\frac{\pi * d_{Sn-1}}{4} \right)^2 * \left(\sqrt[3]{\frac{\pi * d_{Sn}^2}{4}} \right) \right) + \left(\left(\frac{\pi * d_{Sn}}{4} \right)^2 * \left(\sqrt[3]{\frac{\pi * d_{Sn-1}^2}{4}} \right) \right) + \left(\frac{\pi * d_{Sn}^2}{4} \right) \right)$$

with

$$d_{Sn-1} = \frac{d_{Sn}}{\left(\frac{100 - e^{\alpha + \frac{\beta}{h_{bh}}}}{100} \right)}$$

with

α and β = domain-specific parameters

d_{Sn-1} = diameter on ground level

The aboveground biomass of a single tree (AB_{tree}) was derived using the above formulas as an input for:

$$AB_{tree} = (V_{stump} + V_{bole} + V_{top}) * BF$$

with:

BF = species specific biomass factor.

The species specific biomass factor (BF) was taken from existing literature, such as Brown (1997) or IPCC (2006). Otherwise default values for tropical hard- or softwoods provided by IPCC (2006) have been applied.

Conversion of biomass into carbon can likewise be done by means of equation factors. The more specific these equation factors are for different regions, the more elaborate the results will be. If no detailed information is available or the collection of a reasonable number of samples for wood density is too laborious, IPCC (2006) provides default values to convert biomass into carbon.

UPSCALING PROCEDURES. The aboveground biomass (AB) for a single tree was obtained by the equations described above. The sum of the AB for all trees of one sample plot (SP) results in the total AB for this SP. The sum of all SPs of one cluster as well as the associated variance and sampling error are derived on the basis of the single tree values. This holds as long as the cluster size is kept constant. Procedures to derive variances and sampling errors for unequal cluster sizes are described in Cochran (1977). Upscaling procedures expand cluster data to area related estimates resulting in an aggregation of the respective values, variances, and errors on different scales (e.g., forest fragments, strata, or country). Details of the applied upscaling procedures are described in Riedel (2008). After appliance of these procedures sound and sensitive estimates of forest biomass were derived.

QUANTIFYING THE AMOUNT OF REDUCED CO_2 EMISSIONS.

Quantification of the amount of reduced CO_2 emissions is essential to any country that wants to commit itself to a REDD regime. This includes two important components: (1) There has to be a reference level (i.e., a baseline), against which the changes of carbon stocks in forests are set off. Different possibilities for the construction of reference scenarios are given in the specific literature (Griscom et al. 2009, Krug et al. 2009). (2) There has to be a monitoring of the development of the carbon stocks. This is provided by the presented methodology. The amount of reduced emissions can then be derived with the difference between the assumed carbon stock at the end of the commitment period referring to the selected reference level and the carbon stock estimation derived from the applied methodology.

RESULTS

Based on the IPCC categories for the zone 'Tropical Forests' a stratification in 'wet', 'intermediate' and 'dry' was achieved using a forest cover change detection algorithm (see section Regionalisation of the land area of Madagascar) and for each strata an assessment area was identified (see Table 3 and Figure 3). Combined inventories were carried out in all three assessment areas. The following table (Table 4) presents the results for the assessment areas, derived with the above described methodology. Three different domains were identified, i.e., 'Closed Forest' (crown cover ≥ 20 %), 'Open Forest' (crown cover ≥ 10 % and < 20 %) and 'Non Forest' (crown cover < 10 %). The estimated means of the first two domains were tested for statistical significant differences on the 95 % confidence level using a t-test. Furthermore, these estimates are combined in the domain 'Forest total'. As only clusters within forest or forest fragments were included in the field survey, there is no further terrestrial information on the domain 'Non Forest' assuming that there is no considerable amount of biomass.

For the Tsinjoarivo assessment area (see Figure 3, No. 1), the values for the mean aboveground biomass (AB) for 'Closed Forest' and 'Open Forest' are not significantly different (190.3 to 154.0 t / ha) from each other. The area fraction for 'Closed Forest' is small; the intra-cluster-correlation coefficients (ICCs) for all domains of this assessment area are relatively high. The 'Non Forest' area is disproportionately high. The estimate for mean AB for the combined domain 'Forest total' is 163.7 t / ha.

For the assessment area of Manompana (see Figure 3, No. 2) the differences between the mean AB of 'Closed Forest' (293.2 t / ha) and 'Open Forest' (184.0 t / ha) are significant. The amount of sample plots in 'Closed Forest' is considerably higher than in 'Open Forest'. The ICC ranges from 0.18-0.28. The 'Non Forest' area accounts for 25 % of the total area. The resulting estimate for 'Forest total' is 272.5 t / ha.

The mean AB in the domain 'Closed Forest' in Tsimanampetsotsa (see Figure 3, No. 3) is 136.1 t / ha and significantly different to the estimate for the domain 'Open Forest' (mean AB 87.7 t / ha). More than one third of the sample plots is in the domain 'Non Forest'. The ICC ranges from 0.15-0.32. The estimate for 'Forest total' in Tsimanampetsotsa is 98.9 t / ha.

TABLE 4. Estimates for each of the three assessment areas.

Tsinjoarivo								
Domain	n_SP	AF (ha)	SE of AF (%)	AB total (t)	SE of AB total (%)	Mean AB (t / ha)	SE of mean AB (%)	ICC
Closed Forest	15	495	31.0	94,169	31.7	190.3	34.2	0.72
Open Forest	41	1,353	18.9	208,302	19.8	154.0	23.7	0.73
Forest total	56	1,848	19.0	302,471	20.0	163.7	23.9	0.78
Non Forest	922	30,424	1.2					
Manompana								
Domain	n_SP	AF (ha)	SE of AF (%)	AB total (t)	SE of AB total (%)	Mean AB (t / ha)	SE of mean AB (%)	ICC
Closed Forest	47	28,136	12.4	8,250,251	13.1	293.2	29.5	0.27
Open Forest	11	6,585	32.4	1,211,540	32.0	184.0	43.0	0.18
Forest total	58	34,721	9.4	9,461,790	10.2	272.5	25.5	0.28
Non Forest	19	11,374	28.8					
Tsimanampetsotsa								
Domain	n_SP	AF (ha)	SE of AF (%)	AB total (t)	SE of AB total (%)	Mean AB (t / ha)	SE of mean AB (%)	ICC
Closed Forest	21	6,448	23.8	877,889	27.5	136.1	34.7	0.22
Open Forest	70	21,494	9.1	1,885,991	9.5	87.7	23.0	0.15
Forest total	91	27,943	8.7	2,763,880	11.6	98.9	18.5	0.32
Non Forest	50	15,353	15.9					

n_SP = number of sample plots; AF = area fraction; SE = standard error; AB = aboveground biomass; ICC = Intra-Cluster-Correlation-Coefficient; t = ton; ha = hectar

TABLE 5. Aggregation of estimates on country level.

Madagascar							
Domain	n_SP	AF (ha)	SE of AF (%)	AB total (t)	SE of AB total (%)	Mean AB (t / ha)	SE of mean AB (%)
Closed Forest	83	35,079	10.9	9,222,309	12.0	262.9	26.6
Open Forest	122	29,432	9.9	3,305,832	13.0	112.3	20.6
Forest total	205	64,512	6.4	12,528,141	8.2	194.2	20.1
Non Forest	991	57,151	7.2				
n_SP = number of sample plots; AF = area fraction; SE = standard error; AB = aboveground biomass; t = ton; ha = hectar							

Table 5 shows the aggregation of the estimates for the three assessment areas as presented above on country level for Madagascar. Consequently the apportionment into three domains ('Closed Forest', 'Open Forest', 'Non Forest') and the combination of 'Closed Forest' and 'Open Forest' as 'Forest total' again is applied. For the aggregation on country level no ICC as a measure of the efficiency of cluster sampling is calculated, because sensible results can only be expected for the assessment area level.

The estimates for 'Closed Forest' (262.9 t / ha) and 'Open Forest' (112.3 t / ha) on national scale are significantly different from each other. The estimate for mean aboveground biomass for the combined domain 'Forest total' is 194.2 t / ha. The overall sampling error (SE of mean AB) ranges from 26.6 % to 20.1 % decreasing with increasing sample size.

DISCUSSION

The applied methodology displays the adaptation of fully operational and respected methods to the particular needs of a possible REDD regime for Madagascar. The application of remote sensing analyses for the top-down approach using medium resolution imagery and sensible auxiliary data forthe regionalisation of the land area of Madagascar and a first stratification into forest and non-forest areas proved to be feasible. The identification of hot spots of deforestation utilizing change detection analysis with different points in time led to a sound and sensible selection of appropriate assessment areas. A further stratification of these areas e.g., into the strata closed forest and open forest, could have been possible by means of very high resolution imagery. However, this was not feasible in this project due to disadvantageous RS-data quality. Nevertheless, utilizing expensive, very high resolution imagery not for the entire country but only for the identified assessment areas helps to keep costs at a manageable level.

The systematic sampling approach incorporating cluster sampling for the in-situ assessment proved to be operational for remote and hard to access as well as highly fragmented forest areas. The physical conduction of the in-situ method and the subsequent calculation of single tree biomass as well as the applied upscaling methods led to sound and reliable estimates on aboveground biomass for each of the assessment areas which are discussed in the following.

ESTIMATES FOR THE THREE ASSESSMENT AREAS.

The non-significance in the difference of the estimates for mean aboveground biomass (AB) (see Table 4) in the assessment area Tsinjoarivo as well as the high intra-cluster-correlation coefficient (ICC) is caused by the high fragmentation and degradation of the forest. The high amount of sample plots in the domain 'Non Forest' is owed to the same reason and enhanced by the fact that at the time of planning only outdated data from the national forest inventory (NFI) from 1996 were available as reference. This resulted in a conservative layout of the sampling grid (1 km x 2 km). The estimate for the combined domain 'Forest total' meets the IPCC values for the adapted category 'intermediate (semi-dry / semi-wet)' forests (see Table 2).

The ICC for the assessment area Manompana is justifiable in the scope of a pilot project. The estimate for the domain 'Forest total' is within the range of possible values for the adapted IPCC category 'wet' (310 to 272.5 t / ha). The sampling error could be reduced significantly if the applied method would be adjusted to a national scale inventory, thus augmenting the sampling intensity in this category.

The ICC in the assessment area of Tsimanampetsotsa is acceptable for a pilot project. The estimate for the adapted IPCC category is well within the range of possible values (see Table 2). The error of the estimates in this area is also acceptable for a pilot project.

The estimate aggregated on country level for the domain 'Forest total' (194.2 t / ha) meets the default value for aboveground biomass content in forest in 2000 given by IPCC in table 3A.1.4 of the GPGLULUCF for Madagascar (194 t / ha) (IPCC 2003). The sampling error for the mean AB in this domain is acceptable for a pilot project but is likely to be reduced if the applied assessment scheme would be extended on a national scale. This would imply an extension of the in-situ assessment to more than the three selected assessment areas, resulting in higher costs for the combined inventory.

RELIABILITY OF ESTIMATES. The assessment of carbon stock and carbon stock changes is associated with uncertainties. The IPCC GPG LULUCF (IPCC 2003) addresses this problem by offering parties to use three different tiers (i.e., levels of reliability) for their national greenhouse gas reporting. Where parties want to generate carbon credits by participating in REDD, the reliable minimum estimate (RME) for carbon stock changes needs to be presented in order to follow the broadly accepted principle of conservativeness (Grassi et al. 2008). A point estimate of the carbon stock or its change rate over time needs to be supplemented by a quantitative measure of its reliability. The point estimate is reduced by the reliability measure resulting in the RME; not the point estimate but the RME qualifies for accounting. Therefore parties are obliged to report on the errors associated with any carbon estimate and need to implement assessment methods that result in estimates with high reliability to render possible the generation of benefits from REDD (Köhl et al. 2009). The reliability of forest area changes is quantified via the accuracy of remote sensing classifications, while the reliability of biomass estimates results from the calculation of sampling error estimates. Errors associated with the assessment of individual tree biomass and its conversion into carbon contents are to be obtained by empirical studies. All different error sources can be combined via an error budget (Gertner and Köhl 1992) and allow for a consistent and accepted quantification of the reliability of carbon stocks and carbon stock changes.

COMBINATION OF REMOTE SENSING DATA AND IN-SITU ASSESSMENTS. The use of satellite imagery and remote sensing techniques has been widely described as an efficient tool to monitor forest area changes (Bowden et al. 1979, UN-ECE/FAO 2000). Remote sensing provides spatially explicit data on forest areas and allows for multi-temporal approaches on forest area changes and can thereby be used in the scope of REDD (GOFC-GOLD 2009).

Apart from detectable and quantifiable deforestation in the applied remote sensing phase the applied in-situ methodology-allows to gather sensitive information on forest degradation, as well. The importance of including degradation in REDD is stated in international discussions (UNFCCC 2008).

Variable extents of forest degradation still make its assessment a challenging task (Baldauf et al. 2009, FAO 2009). In addition, optical remote sensing sensors fall short when it comes to the assessment of minor changes in standing woody biomass (Scott and Köhl 1994). Especially in natural forests in the tropics and subtropics, which are characterised by heterogenic vertical stand structures and contiguous canopy covers, degradation can only be detected, when the formerly closed canopy cover is dissolved. Otherwise, if the forest is degraded affecting the canopy cover in a minor extent only, the degradation remains stealthy for optical remote sensing sensors (see Figure 5). So far, this stealthy degradation can only be assessed by field surveys.

Although clear definitions of degradation are yet missing, the applied methodology is designed to be flexible enough for adaptation to a finally agreed definition of forest degradation.

CONCLUSION

On the one hand the applied methodology depends largely on capacities which have to be available or which have to be build up in a country applying for REDD. Not later than at the end of the first commitment period all capacities should be available in the specific country so that there is no urgent need for broad scale consultancy. On the other hand country specific knowledge is indispensable when generating such an approach. The applied methodology was developed in close collaboration of the Forest Institute of the University of Antananarivo (ESSA Forêts) and the Institute for World Forestry at the vTI in Hamburg, thus guaranteeing the incorporation of country specific knowledge.

A broadly accepted challenge lies in the most effective combination of remote sensing and terrestrial inventories. For the RS-data and further additional data, e.g., national forest inventory (NFI), data availability will differ from country to country. Therefore, the applied methodology uses RS-data that is available worldwide, e.g., MODIS, or identifies sensor categories, i.e., medium, high and very high resolution data.

The results of this pilot study show that the applied combined inventory and the upscaling methods are capable of producing reliable results on a national level. Regarding the need for successive inventories in the scope of REDD the in-situ design can be further optimised for each of the adapted IPCC categories on the basis of the presented results to fully exploit the advantages of a systematic stratified cluster sampling design.

Concerning the detection of degradation areas, problems arise from the small scale differences in RS-data. The availability of cloudless very high resolution data can be considered as a big challenge, especially in the tropics. Presently, there are some projects using high resolution RADAR data (i.e., TerraSAR-X), which could possibly overcome these challenges.

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DP, TB and MK developed the methodology and statistical background aligned to it. DP carried out the terrestrial implementation of the methodology, TB conducted the remote sensing analyses. HRR and GR adapted the methodology to the specific conditions found in Madagascar.

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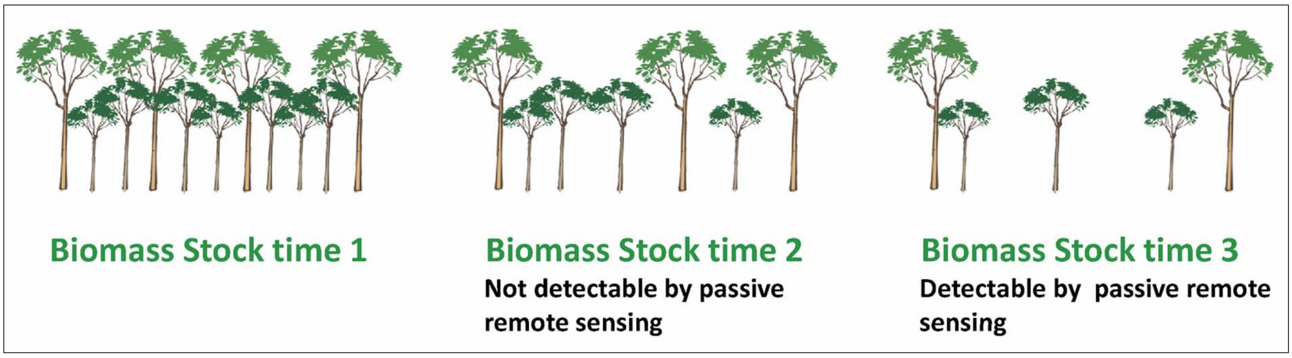

FIGURE 5. Different status of forest degradation and potential of detection by optical remote sensing techniques (Baldauf et al. 2009).

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SUPPLEMENTARY MATERIAL.

AVAILABLE ONLINE ONLY.

Overview of methodology of combined inventory, detailed illustration of the applied combined inventory methodology showing the top-down and bottom-up approaches.

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The global climate change mitigation strategy REDD: monitoring costs and uncertainties jeopardize economic benefits

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Abstract REDD (Reducing Emissions from Deforestation and Forest Degradation) has been suggested as a climate change mitigation strategy that is based on the philosophy to reward countries for reducing their deforestation and forest degradation by financial benefits via the generation of carbon credits. While the potential of REDD has been widely discussed, minor attention has been drawn to the implication of uncertainties and costs associated with the estimation of carbon stock changes. To raise awareness of these issues, we conducted a simulation study for a set of countries that show high to low deforestation rates, which demonstrates that the potential to generate benefits from REDD depends highly on the magnitude of the total error while assessment costs and the price of carbon credits play a minor role. For countries with low deforestation rates REDD is obviously not an option for generating benefits as they would need to implement monitoring systems that are able to estimate carbon stock changes with a total error well below 1 %. Total errors feasible under operational monitoring systems are only sufficient to gain revenues from REDD-regimes under high deforestation rates.

1 Background

According to UN-FAO's Forest Resources Assessment (FRA) 2010 (FAO 2010), the world's forests store 289 gigatonnes (Gt) of carbon in their biomass. The FRA 2010 however also shows that the destruction of forests releases 0.5 Gt of carbon annually between 1990 and 2010. The Stern-Review (Stern 2007) identified that "emissions from deforestation are very significant". The emissions from deforestation are estimated to represent between 12 %

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and 20 % of global emissions (van der Werf et al. 2009; IPCC 2007), which calls for urgent activities to maintain the remaining areas of natural forests.

As part of a global climate change mitigation strategy REDD should support developing countries to take additional actions that reduce emissions from deforestation and forest degradation by mobilization and distribution of financial resources (UNFCCC 2008). A basic concern on the finance mechanisms for REDD is whether the generated financial resources should be public or private, or a mixture of both (ITTO 2009). It can be argued that short-term economic profits from deforestation and degradation offset the long-term benefits of forests (EfB 2011). REDD mechanisms aim at generating credits for maintaining current forest carbon stocks by avoiding deforestation and forest degradation. Currently, those credits are only eligible on voluntary carbon markets, but in a post-2012 climate agreement they may enter regulatory Kyoto carbon markets.

EcoSecurities (2007) presented estimates which indicate that a 50 % reduction in the world's deforestation rate could generate between 7.6 and 45.9 Billion US$ each year depending on the monetary value per ton carbon credits. While EcoSecurities aimed at the obtainable market volumes and focussed on the potential benefits, Grieg-Gran (2008) estimated the global costs of cutting the rate of deforestation in eight countries (i.e. Bolivia, Brazil, Cameroon, DRC, Ghana, Indonesia and PNG) responsible for about 50 % of the world wide deforestation. Grieg-Gran used the simplifying assumptions that a national scheme to avoid deforestation is implemented and has 100 % additionality and no leakage, and that the alternative to deforestation is forest conservation without any exploitation of timber. She identified three cost components that need to be covered to avoid deforestation at the country level:

- the value of the economic activity that leads to deforestation, e.g. agriculture or mining;
- the administration, monitoring and enforcement costs for the government, and
- an incentive element.

Grieg-Gran (2008) utilized the net present value of returns from land uses as the total costs of avoided deforestation. If foregone returns from selective logging are included the annual total cost for controlling deforestation in the eight selected countries would be between US$ 6.5 billion and US$ 8 billion.

A country that intends to participate in a future REDD mechanism has to demonstrate that it has substantial capacity of monitoring and accounting carbon emissions from forests in the future. Thus, a reliable framework for measuring, reporting and verification is urgently needed to ensure the integrity and credibility of REDD efforts in general and REDD in the post-2012 negotiation under the UNFCCC in particular (Plugge et al. 2011). While approaches for monitoring and reporting as well as financing mechanisms including the allocation of incentives have been intensively discussed (GOFC-GOLD 2010; Eliasch 2008), little attention has so far been paid to the costs and uncertainties of such operational REDD monitoring systems. In the following we compare cost and uncertainties involved in implementing a REDD monitoring system with the potential financial benefits generated by a REDD regime.

1.1 Monitoring costs

No universal inventory concept exists for REDD monitoring. A cost-efficient inventory concept needs to be adapted to the specific conditions of the inventory area and include choices on data sources utilized, in-situ assessment methods, models, sampling concepts, sampling intensity, stratification rules, time intervals for updating, or methods for quantifying errors (Köhl et al. 2006). Generally several alternative inventory concepts can be found for a specific situation, and choosing the most cost-efficient alternative is a matter of optimization (Köhl et al. 2011). Two objective functions exist in the optimization process: (1) minimizing error for given costs, or (2) minimizing cost for a desired error (Scott and Köhl 1993). The total costs of an inventory is made up of fixed and variable costs. Fixed costs do not change with the area to be monitored, e.g. expenses for developing a survey design, or for computer equipment and software development. Variable costs are expenses that change in proportion to the inventory area and the number of field plots assessed. The optimization process takes into account only variable costs.

Hardcastle and Baird (2008) studied the readiness of 25 tropical countries for monitoring forests and reporting on REDD. For each country cost estimates are provided for implementing REDD monitoring and reporting systems, the major drivers of costs being forest extent, stratification, and the appropriate choice of estimation method (Tier). They present the initial and recurrent cost separately for four alternatives:

Tier 2, Approach A: an accurate land-cover map is available, 300 sample plots are assessed in-situ, all carbon measurements are performed once at the beginning of the programme, future monitoring is focused on the assessment of human activities (activity data, AD), such as area changes by remote sensing data, and requires only minimal field work.

Tier 2, Approach B: no accurate land-cover map is available, in-situ assessments are performed when activity monitoring by remote sensing identifies locations under change, the in-situ sampling intensity is considerably lower than under Tier 2, Approach A.

Tier 3, ignoring degradation: AD und emissions per unit of the activity (emission factors, EF) are assessed as under alternative 1 (Tier 2 Approach A), but re-measurements are made in permanent in-situ sample plots (about 1/3 of the original sample locations).

Tier 3, including degradation: alternative 3 is enhanced by further stratification of forests into the two classes “intact forests” and “non-intact forests”, the number of field plots is moderately increased.

The inventory concepts applied by Hardcastle and Baird (2008) are generic rather than case-specific, as they do not result from a sound inventory design and optimization process on the individual national levels. However, they are used for an approximate comparison of cost required to implement an operational REDD monitoring and reporting scheme on the national level. Figure 1 presents the respective costs for the four alternatives over forest area. The cost per unit area decreases with increasing forest area, as the share of fixed costs in total costs decreases.

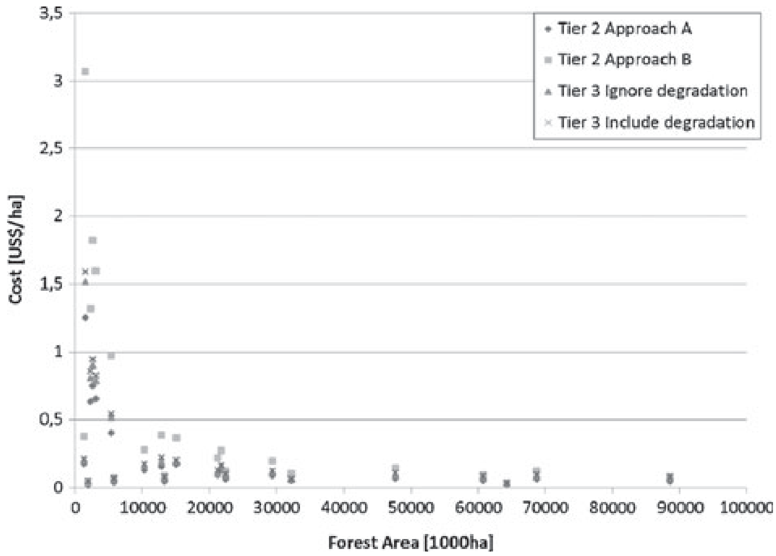


Fig. 1 Cost estimates [US$/ha] for implementing annual forest monitoring systems in relation to forest area (source data: Hardcastle and Baird 2008) for a 5-year commitment period

1.2 Uncertainties

The principle of conservativeness, which has been reflected in several UNFCCC documents, for example in the context of afforestation and reforestation activities under the Clean Development Mechanism (CDM) (UNFCCC 2006a, b), was proposed by Grassi et al. (2008) in order to "address the potential incompleteness and high uncertainties of REDD estimates".

According to Grassi et al. (2008), the completeness principle depends on "the processes, pools and gases that need to be reported and on the forest-related definitions". For quantifying carbon stock changes under REDD activities both uncertainties and incompleteness need to be considered. The IPCC-Good Practice Guidance suggests in the context of the assessment of changes in soil carbon the use of the Reliable Minimum Estimate (RME) to address uncertainties (IPCC 2003). The RME was originally introduced by Dawkins (1957) as the minimum quantity to be expected with a given probability and served as a surrogate for the lower bound of a confidence interval.

However, from a statistical point of view the principle of the RME is different from the lower bound of the confidence interval that is suggested by several authors (e.g. GOFC-GOLD 2010). Where the confidence interval is used, only sampling errors are considered. The RME is based on a holistic treatment of uncertainties and includes in addition to sampling errors other error sources. Köhl et al. (2009) describe the components of the total survey error such as model and prediction errors, measurement errors, frame errors, or classification errors. In the scope of REDD, the RME is the difference between the lower error interval at the reference period (time 1) and the upper bound of the error interval at the commitment period (time 2) and can be treated as a conservative estimate that qualifies for accounting. The resulting magnitude of emission reduction is considerably smaller for an RME than for a confidence interval, which only takes sampling errors into account.

2 Methods

A rational decision about the adoption of a REDD regime is driven by the potential benefits on the one hand, and the costs for implementing an operational and sound monitoring system on the other. Comparing benefits with costs allows for calculating the break-even point (BEP), where potential benefits equal the expected monitoring costs.

The potential benefit generated by a REDD regime at the end of a commitment period, t_2, is subject to the amount of carbon stock qualifying for accounting, C_{t2REDD}, and the prices paid per ton of CO_2. C_{t2REDD} is calculated as the difference between the expected carbon stock under a baseline scenario without any efforts to avoid deforestation and degradation, C_{t2BL}, and the real carbon stock observed at time 2, C_{t2real}. Under the conservativeness approach (Grassi et al. 2008) uncertainties associated with the estimation of C_{t2REDD} need to be considered in order to obtain the RME of the carbon stock at time 2, C_{t2RME} (Köhl et al. 2009). Thus, the amount of reduced carbon emissions qualifying for accounting, $\hat{C}_{t2REDD}$ is obtained by:

$$\begin{aligned}\widehat{C}_{t2REDD} &= C_{t2RME} - C_{t2BL} \\ &= \left(C_{t1}(1-E_{t2})(1+\Delta_{real})\right) - C_{t1}(1+\Delta_{BL}) \\ &= C_{t1}\left((1-E_{t2})(1+\Delta_{real}) - (1+\Delta_{BL})\right)\end{aligned} \tag{1}$$

where

C_{t2RME} carbon stock at time 2 qualifying for accounting
C_{t2BL} expected carbon stock at time 2 according to a baseline scenario

Δ_{real} proportion of real carbon stock change between time 1 and time 2, {-1,1}
Δ_{BL} proportion of carbon stock change between time 1 and time 2 according to the baseline, {-1,1}
C_{t1} carbon stock at time 1
E_{t2} total error at time 2

Among other factors the amount of carbon stock qualifying for accounting, $\hat{C}_{t2REDD}$, is affected by the proportion of the real change of carbon stocks between time 1 and time 2, Δ_{real}. Human induced activities lead to either an increase or a decrease of carbon losses with respect to Δ_{BL}. Where efforts to reduce degradation and deforestation are successful, the real change, Δ_{real}, is smaller than the change according to the baseline, $\Delta_{BL,}$ and an emission reduction is obtained. Where deforestation and degradation exceed prior rates, emissions are increased. $\Delta_{\,real}$ is given by

$$\Delta_{real} = \Delta_{BL} + (\Delta_{desired}|\Delta_{BL}|) \tag{2}$$

where

$\Delta_{desired}$ the proportional reduction of the change between time 1 and time 2 according to the baseline (i.e. negative values for $\Delta_{desired}$ indicate a successful reduction of past emission patterns)

The possible financial earnings by means of a REDD regime result from the emission reductions, $\hat{C}_{t2REDD}$, multiplied by the potential value of carbon credits, P_C, and need to be larger than the cost for implementing and maintaining the monitoring system, M, in order to produce benefits. A breakeven-point is reached when revenues equal costs.

$$\widehat{C}_{t2REDD}{}^{*}P_C = M \tag{3}$$

where

$\hat{C}_{t2REDD}$ amount of carbon stock qualifying for accounting, incorporating uncertainties
P_C value of carbon credits
M monitoring costs

With Equations (1) and (2) Equation (3) can be transformed (see Appendix) to show the amount of reduction, $\Delta_{desired}$ that is needed to reach a breakeven-point between revenues and costs:

$$\Delta_{desired} = \frac{\frac{C_{t1}(1+\Delta_{BL})+\frac{M}{P_C}}{C_{t1}(1-E_{t2})} - 1 - \Delta_{BL}}{|\Delta_{BL}|} \tag{4}$$

The monitoring cost can be further segregated into variable (M_V) and fixed inventory costs (M_F) (Scott and Köhl 1993; Wöhe et al. 2005; Hardcastle and Baird 2008). While fixed costs, such as for administration or remote sensing imagery, are design independent, the variable costs vary with sample size, as shown in formula (5).

$$\begin{aligned} M &= M_V + M_F \\ &= A^{*}M_{ha} + M_F \end{aligned} \tag{5}$$

where

M_V Variable inventory costs
M_F Fixed inventory costs

A Forest area [ha]
M_{ha} Assessment costs per hectare forest

Under the constraint that no degradation and only deforestation takes place and thereby the carbon stock per unit area remains constant, i.e. $\overline{C}_{t2} = \overline{C}_{t1}$, and with

$$A = \frac{C_{t2REAL}}{\overline{C}_{t2}} \tag{6}$$

where
$\overline{C}_{t2}$ is the carbon stock per hectare at time 2
rearranging Eq. (6) produces

$$A = \frac{(C_{t1}(1 + (\Delta_{BL} + (\Delta_{desired}|\Delta_{BL}|))))}{\overline{C}_{t1}} \tag{7}$$

Equations (5) and (7) were used to transform Eq. (4):

$$\Delta_{desired} = \frac{\left(\frac{P_C\ C_{t1}(1+\Delta_{BL})+M_F}{\left(P_C\ C_{t1}(1-E_{t2})-\frac{M_{ha}\ C_{t1}}{\overline{C}_{t1}}\right)} - 1 - \Delta_{BL}\right)}{|\Delta_{BL}|} \tag{8}$$

2.1 Simulation study

To show the effect of the inclusion of uncertainties and monitoring costs in REDD estimates, a simulation study was conducted. The rate of deforestation between 2000 and 2010 was utilised to construct the baseline and thereby predict the carbon stock at the end of the commitment period under a business-as-usual (BAU) development. The objective function utilized was the amount of reduction of deforestation with respect to the baseline scenario needed for reaching a break-even point between revenues gained from a REDD scheme and the costs of the underlying monitoring system.

FAO's Global Forest Resources Assessment (FAO 2010) was utilized to select five countries, which show small to large forest areas and low (−0.12 %) to high (−23.36 %) deforestation rates. Table 1 presents the corresponding data as given in FRA 2010 on forest area and carbon stock, which were used to calculate the proportional changes between time 1 and time 2 (reference period = 10 years) according to the baseline, Δ_{BL}.

Table 1 Countries selected for simulation study (source: FAO 2010)

Country	Forest area 2010 [1,000 ha]	Forest area change [1,000 ha/year]	Carbon stock at time 1, C_{t1}		Carbon stock change according to baseline, Δ_{BL} [%]
			[MtC]	[tC/ha]	
Ghana	4,940	−115	381	77	−23.36 %
Cameroon	19,916	−220	2,696	135	−11.05 %
Indonesia	94,432	−498	13,017	138	−5.27 %
Colombia	60,499	−101	6,805	112	−1.67 %
Suriname	14,758	−2	3,165	214	−0.12 %

For simulating the impacts of monitoring costs and uncertainties realistic ranges for total errors, E_{t2}, and per hectare monitoring costs, M_{ha}, had to be defined. For total errors, E_{t2}, a range between 1 % and 10 % (1 %, 2 %, 5 %, 10 %) was chosen, for the variable monitoring costs, M_{ha}, a range between 5US$/ha to 0.01US$/ha (5US$/ha, 1US$/ha, 0.1US$/ha, 0.01US$/ha). Fixed monitoring costs, M_F, were set to 100,000US$ and include inter alia the costs for remote sensing imagery. The total cost of the monitoring system was calculated by the product of the national forest area and the respective per ha assessment costs plus the fixed monitoring costs. Under these conditions the fixed costs are well below 2 % of the total costs, if the per ha assessment costs, M_{ha}, are 1US$/ha or higher. For assessment costs of 0.1US$/ha they vary between 1.1 % (Indonesia) to 16.8 % (Ghana) and 9.6 % (Indonesia) and 66 % (Ghana) for 0.01US$/ha. The price paid per ton of carbon credit, P_C, was set to 10 US$/t$CO_2$.

3 Results

For each of the five selected countries Eq. (8) was applied using the figures presented in Table 1 and the value ranges for errors and costs given above in order to predict the associated proportional reduction of the carbon stock change between time 1 and time 2 with respect to the baseline, $\Delta_{desired}$, that is needed to reach a break-even point between assessment costs and revenues from REDD. The results for $\Delta_{desired}$ are presented in Table 2

Table 2 Proportional reduction of the change between carbon stock at time 1 and time 2 ($\Delta_{desired}$) according to the baseline (Δ_{BL}) for four error (E_{t2}) scenarios required for the break-even point of revenues and costs when the value of carbon credit is 10 US$/t$CO_2$

	Cost [US$/ha]	Error E_{t2}			
		1 %	2 %	5 %	10 %
Ghana Δ_{BL} = −23.36 %	5.00	3.90 %	7.29 %	17.88 %	37.10 %
	1.00	3.43 %	6.82 %	17.39 %	36.59 %
	0.10	3.33 %	6.71 %	17.28 %	36.47 %
	0.01	3.32 %	6.70 %	17.27 %	36.46 %
Cameroon Δ_{BL} = −11.05 %	5.00	8.96 %	17.26 %	43.24 %	90.38 %
	1.00	8.30 %	16.60 %	42.55 %	89.66 %
	0.10	8.15 %	16.45 %	42.40 %	89.49 %
	0.01	8.14 %	16.44 %	42.39 %	89.48 %
Indonesia Δ_{BL} = −5.27 %	5.00	19.95 %	38.50 %	96.47 %	201.69 %
	1.00	18.52 %	37.04 %	94.97 %	200.10 %
	0.10	18.19 %	36.72 %	94.64 %	199.75 %
	0.01	18.16 %	36.69 %	94.60 %	199.71 %
Colombia Δ_{BL} = −1.67 %	5.00	66.72 %	127.51 %	317.53 %	662.40 %
	1.00	60.94 %	121.67 %	311.51 %	656.04 %
	0.10	59.64 %	120.35 %	310.15 %	654.61 %
	0.01	59.51 %	120.22 %	310.02 %	654.46 %
Suriname Δ_{BL} = −0.12 %	5.00	879.90 %	1724.48 %	4364.90 %	9156.77 %
	1.00	837.76 %	1681.91 %	4320.99 %	9110.42 %
	0.10	828.28 %	1672.34 %	4311.11 %	9100.00 %
	0.01	827.34 %	1671.38 %	4310.13 %	9098.96 %

and show under the given cost and total error scenarios the reduction of past deforestation rates (Δ_{BL}) that is needed to just cover the assessment costs by revenues from reduced deforestation. Under given cost and total errors gains are produced where $\Delta_{desired}$ is larger than the respective value shown in Table 2.

Where table cells in Table 2 show values for $\Delta_{desired}$ larger than 100 % a country cannot realize benefits from reduced deforestation only but would additionally need to increase its forest area in the commitment period in order to at least cover the assessment costs. The results given in Table 2 show that Ghana and Cameroon as the two countries with the highest deforestation rates (Δ_{BL} = −23.36 % and −11.05 % respectively) can benefit in all error/cost constellations from REDD without increasing its forest area. While for total errors of 1 % to 2 % even a moderate reduction of the deforestation with respect to the baseline would yield benefits from REDD for these two countries, the deforestation of Cameroon would need to be almost halted for a 10 % total error.

Indonesia, with a high forest area and a medium deforestation rate (Δ_{BL} = −5.27 %), is in a position to benefit from a REDD scheme only under the first two simulated error scenarios (i.e. 1 % and 2 %). With a total error of 5 % Indonesia would need to nearly halt its deforestation, while for a total error of 10 % the forest area would have to be doubled during the commitment period (resulting in total forest area values of 199.71 % to 201.69 % relative to the beginning of the commitment period) to reach a breakeven-point of costs and revenues.

The outcomes of the simulation study for Colombia, a country with high forest area and low deforestation rate (Δ_{BL} = −1.67 %), show that only under a scenario where the deforestation rate is more than halved and the total error is well below 2 % benefits from REDD can be achieved without increasing the forest area.

Suriname as the country with the lowest deforestation rate in our simulation study (Δ_{BL} = −0.12 %) is under none of the simulated error and cost scenarios in a position to benefit from a REDD scheme. On the contrary Suriname would need to increase its forest area substantially (i.e. at least by 727.34 %) to reach a breakeven-point of costs and revenues. This however is not even hypothetically possible, as this would exceed the total land area of Suriname itself.

On the whole, Table 2 obviously demonstrates two major findings on the potential to generate benefits from REDD. One is case specific for this study, as we have chosen a simple business-as-usual baseline scenario. Under this scenario past deforestation rates have a strong effect on the potential to generate benefits from REDD. The second finding is a more generic one. The impacts of the total error are much higher than the influence of the assessment costs per hectare. Thus countries in the readiness phase of REDD need to put uttermost attention and efforts in developing assessments schemes that minimize total errors and produce reliable results.

Benefits from REDD can only be generated where the RME of the carbon stock at time 2, C_{t2RME}, is larger than the carbon stock defined by the baseline, C_{t2BL}. Table 3 presents the

Table 3 Total error needed to meet breakeven-point of reduced (halved) deforestation rate ($\Delta_{desired}$ = 50 %) and baseline: $C_{t2RME} = C_{t2BL}$

	$\Delta_{desired}$ = 50 %
Country	E_{t2}
Ghana	13.22 %
Cameroon	5.85 %
Indonesia	2.71 %
Colombia	0.84 %
Suriname	0.06 %

threshold values for total errors at which C_{t2RME} equals C_{t2BL} under the assumption that the deforestation was halved ($\Delta_{desired}$ = 50 %). Countries with low deforestation rates (i.e. Colombia and Suriname) would need to implement monitoring systems that are able to estimate carbon stock changes with a total error well below 1 %. Only under high deforestation rates total errors feasible under operational monitoring systems are sufficient to cover the assessment costs. As the thresholds for C_{t2RME} refer solely to the consideration of errors, they elude influence by either assessment costs or carbon prices.

The incorporation of assessment costs, M, into this calculation would decrease the threshold values for total errors. The limited influence of the value of carbon credits, P_C, on the potential benefits generated from REDD can be seen in Fig. 2, where thresholds for total errors of each country are presented as a function of P_C, and assessment cost as shown in formula (9). It becomes evident that the more the values of C_{t2RME} and C_{t2BL} converge (however still $C_{t2RME} > C_{t2BL}$), the influence of the value of carbon credits on a possible compensation of assessment costs vanishes.

$$P_C{}^*(C_{t2RME} - C_{t2BL}) = M_F + A^* M_{ha} \tag{9}$$

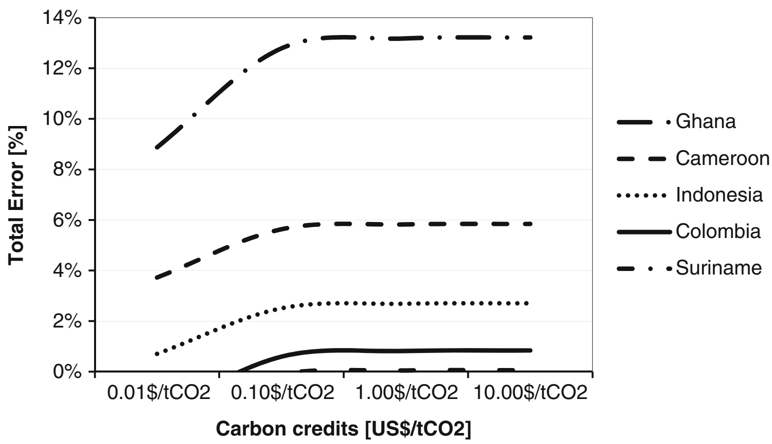
Equations (1) and (7) were used to transform Eq. (9):

$$E_{t2} = 1 - \frac{\frac{\frac{(M_{ha}\, C_{t1}\,(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))))}{C_{t1}} + M_F}{P_C} + C_{t1}(1 + \Delta_{BL})}{C_{t1}(1 + (\Delta_{BL} + (\Delta_{desired}|\Delta_{BL}|)))} \tag{10}$$

For the calculations fixed costs, M_F, were set to 100.000 US\$ and variable costs, M_{ha}, to 0.1 US\$/ha. Figure 2 presents the total error percentages over carbon prices. For higher values of carbon credits, P_C, a larger error can be accepted for estimating the carbon stock at time 2 in order to balance the expenses for assessments and the revenues by carbon credits. However, an increase of P_C from 0.01\$/tCO_2 to 10\$/tCO_2 results in a situation where any of the threshold values presented in Table 3 are reached. Figure 2 clearly shows that under the above described preconditions for each country an asymptote for the Eq. 10 exists. This means that for Eq. 10 there is no significant effect of P_C for a value of carbon credits higher than 1\$/tCO_2. Thus, increasing the value of carbon credits can only show a restricted contribution to a possible generation of benefits from REDD, as not values of carbon credits and assessment costs but the total errors of carbon stock assessment are the limiting factors.

It is still arguable which magnitude of total errors can be reached in REDD monitoring systems. Germany, for example, has a sophisticated national forest inventory and reports a

Fig. 2 Maximum total error percentages at given inventory costs (i.e. fixed costs, M_F, were set to 100,000 US\$ and variable costs, M_{ha}, to 0.1 US\$/ha) over increasing carbon prices



1.4 % sampling error for estimating the growing stock (BMELV 2011). Gertner and Köhl (1992) showed for the example of the Swiss national forest inventory that the inclusion of non-sampling errors and bias can inflate the total error of growing stock estimates substantially. According to Waggoner (2009) a 1 % level of total error for the estimation of carbon stock changes will be extremely difficult to be met.

4 Discussion

Generally, the potential to generate benefits from REDD depends on the deforestation rate of the respective country, the assessment costs and the uncertainties associated with the estimation of the carbon stock at the end of the reference period, time 2. The simulation study conducted showed that countries with already low deforestation rates are not in an easy position to gain benefits from REDD. On the contrary, those countries would be forced to increase their forest area in order to meet the reduction goals when the total error of the estimate of the carbon stock at time 2 is taken into account.

However, it was demonstrated that in fact the potential to generate benefits from REDD depends highly on the magnitude of the total error, while assessment costs and the values of carbon credits play a minor role. Nevertheless, the influence of assessment costs should not be peculated. There are a number of possibilities to optimize the cost-effectiveness of an assessment scheme (Köhl et al. 2011). Furthermore there are numerous case studies of indigenous participation in scientific data collection projects which are helpful in reducing assessment costs with the application of Participatory Forest Carbon Assessments (Galloway McLean 2010).

However, under the preconditions set for this simulation study it becomes obvious that for countries with low deforestation rates (i.e. Colombia and Suriname) REDD is not an option for generating benefits as they would need to implement monitoring systems that are able to estimate carbon stock changes with a total error well below 1 %. By larger error levels no RME for the carbon stock at the end of the reference period (time 2) above the carbon stock level as indicated by the baseline can be achieved. As the underlying functional relationships depend only on possible sources of error, no improvements can be achieved by reducing assessment costs or realizing higher values of carbon credits. Total errors feasible under operational monitoring systems are sufficient to gain revenues from REDD-regimes only under high deforestation rates.

5 Conclusions

Uncertainties associated with the quantification of carbon stocks and carbon stock changes exert a dominant influence on the generation of carbon credits under a REDD regime. The operational implementation of REDD as a global climate change mitigation strategy renders mandatory regulations for the assessment and accounting of errors necessary. Otherwise countries would be discriminated against on accord of sound monitoring and reporting methods.

When the principle of conservativeness is not reflected in REDD accounting regulations, countries would be well advised to apply imprecise and inaccurate monitoring systems.

Countries in the readiness phase of REDD need to put uttermost attention and efforts in developing assessments schemes that minimize total errors and produce reliable results. This holds especially true for countries that have already reached a situation where deforestation rates are low. The need for capacity building and the development of cost-efficient monitoring systems that produce estimates with high reliability is crucial for the successful implementation of REDD.

Countries showing low deforestation rates are discriminated against the generation of REDD benefits; they meet improvements with respect to national baselines only when their monitoring systems are able to produce results with extremely low total errors. In order not to exclude those countries per se from REDD, several alternatives for establishing national baselines have been proposed. Among those alternatives are:

- the discrimination between countries with high and low deforestation rates and the introduction of a "global" baseline rate for the latter (Mollicone et al. 2007),
- the allocation of credits to an individual country by applying a formula that combines a measure of individual country performance against their own historic emissions' baseline, and performance against a global emissions' baseline (Strassburg et al. 2009),
- the allocation of credits to countries as a function of both reduced emissions from deforestation - as compared with historical rate-, and as dividends for maintaining carbon stocks–as a proportion of global forest carbon stocks (Cattaneo 2008; Cattaneo 2010),
- a separate system not based on carbon stock changes but rewarding conservation activities or sustainable management of forests by evaluating policies and measures undertaken and achieved (Meridian Institute 2011).

Those alternatives have to be examined against the background of uncertainties in order to provide comparable and equitable accounting schemes and to avoid windfall profits for countries with unsophisticated assessment systems.

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Appendix

Proportional reduction of change between time 1 and time 2 according to the baseline, $\Delta_{desired}$

$$\widehat{C}_{t2REDD}{}^{*}P_C = M$$
$$(C_{t2RME} - C_{t2BL})^{*}P_C = M$$
$$C_{t2RME}{}^{*}P_C - C_{t2BL}{}^{*}P_C = M$$
$$C_{t2BL}{}^{*}P_C = C_{t2RME}{}^{*}P_C - M$$
$$P_C{}^{*}C_{t1}(1 + \Delta_{BL}) = (C_{t1}(1 - E_{t2})(1 + \Delta real))^{*}P_C - M$$
$$P_C{}^{*}C_{t1}(1 + \Delta_{BL}) = (C_{t1}(1 - E_{t2})(1 + (\Delta_{BL} + (\Delta_{desired}|\Delta_{BL}|))))^{*}P_C - M$$
$$\frac{P_C{}^{*}C_{t1}(1+\Delta_{BL})+M}{P_C} = C_{t1}(1 - E_{t2})(1 + (\Delta_{BL} + (\Delta_{desired}|\Delta_{BL}|)))$$
$$C_{t1}(1 + \Delta_{BL}) + \frac{M}{P_C} = C_{t1}(1 - E_{t2})(1 + (\Delta_{BL}(\Delta_{desired}|\Delta_{BL}|)))$$
$$\frac{C_{t1}(1+\Delta_{BL})+\frac{M}{P_C}}{C_{t1}(1-E_{t2})} - 1 = (\Delta_{BL} + (\Delta_{desired}|\Delta_{BL}|))$$
$$\Delta_{desired} = \frac{\frac{C_{t1}(1+\Delta_{BL})+\frac{M}{P_C}}{C_{t1}(1-E_{t2})} - 1 - \Delta_{BL}}{|\Delta_{BL}|}$$

$\Delta_{\mathrm{desired}}$ under cost constraints

$$
\begin{aligned}
&P_C(C_{t2RME} - C_{t2BL}) = M\\
&P_C(C_{t2RME} - C_{t2BL}) = M_V + M_F\\
&P_C(C_{t2RME} - C_{t2BL}) = A^{*}M_{ha} + M_F\\
&P_C(C_{t2RME} - C_{t2BL}) = A^{*}M_{ha} + M_F\\
&P_C(C_{t2RME} - C_{t2BL}) = \frac{C_{t2REAL}}{\bar{C}_{t1}}M_{ha} + M_F\\
&P_C((C_{t1}(1-E_{t2})(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|)))) - C_{t1}(1+\Delta_{BL})) = \frac{(C_{t1}(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))))}{\bar{C}_{t1}}M_{ha} + M_F\\
&P_C(C_{t1}(1-E_{t2})(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|)))) - P_C(C_{t1}(1+\Delta_{BL})) = \frac{(C_{t1}(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))))}{\bar{C}_{t1}}M_{ha} + M_F\\
&P_C(C_{t1}(1-E_{t2})(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|)))) = \frac{(C_{t1}(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))))}{\bar{C}_{t1}}M_{ha} + M_F + P_C(C_{t1}(1+\Delta_{BL}))\\
&(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))) * \left(P_C C_{t1}(1-E_{t2}) - \frac{C_{t1}M_{ha}}{\bar{C}_{t1}}\right) = M_F + P_C(C_{t1}(1+\Delta_{BL}))\\
&(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))) = \frac{M_F + P_C C_{t1}(1+\Delta_{BL})}{\left(P_C C_{t1}(1-E_{t2}) - \frac{C_{t1}M_{ha}}{\bar{C}_{t1}}\right)}\\
&\Delta_{desired}|\Delta_{BL}| = \frac{M_F + P_C C_{t1}(1+\Delta_{BL})}{\left(P_C C_{t1}(1-E_{t2}) - \frac{C_{t1}M_{ha}}{\bar{C}_{t1}}\right)} - 1 - \Delta_{BL}\\
&\Delta_{desired} = \frac{\frac{M_F + P_C C_{t1}(1+\Delta_{BL})}{\left(P_C C_{t1}(1-E_{t2}) - \frac{C_{t1}M_{ha}}{\bar{C}_{t1}}\right)} - 1 - \Delta_{BL}}{|\Delta_{BL}|}
\end{aligned}
$$

E_{t2} Breakeven

$$
\begin{aligned}
&P_C(C_{t2RME} - C_{t2BL}) = A^{*}M_{ha} + M_F\\
&P_C((C_{t1}(1-E_{t2})(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|)))) - C_{t1}(1+\Delta_{BL})) = A * M_{ha} + M_F\\
&P_C((C_{t1}(1-E_{t2})(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|)))) - C_{t1}(1+\Delta_{BL})) = \frac{(C_{t1}(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))))}{\bar{C}_{t1}} {}^{*}M_{ha} + M_F\\
&((C_{t1}(1-E_{t2})(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|)))) - C_{t1}(1+\Delta_{BL})) = \frac{\frac{(C_{t1}(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))))}{\bar{C}_{t1}} {}^{*}M_{ha} + M_F}{P_C}\\
&(C_{t1}(1-E_{t2})(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|)))) = \frac{\frac{(C_{t1}(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))))}{\bar{C}_{t1}} {}^{*}M_{ha} + M_F}{P_C} + C_{t1}(1+\Delta_{BL})\\
&E_{t2} = 1 - \frac{\frac{\frac{(M_{ha}\, C_{t1}(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|))))}{\bar{C}_{t1}} + M_F}{P_C}}{C_{t1}(1+(\Delta_{BL}+(\Delta_{desired}|\Delta_{BL}|)))} + C_{t1}(1+\Delta_{BL})
\end{aligned}
$$

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Estimating carbon emissions from forest degradation: implications of uncertainties and area sizes for a REDD+ MRV system

Daniel Plugge and Michael Köhl

Abstract: Under the United Nations Framework Convention on Climate Change (UNFCCC), the mechanism Reducing Emissions from Deforestation and Forest Degradation (REDD) has become an important option to create a financial value for the carbon stored in forests by reducing the emissions from forested lands. Thus far, many studies deal with the detectability of emissions resulting from deforestation. This study concentrates on the emissions and emission reductions from forest degradation. We show, based on data from the United Nations Food and Agricultural Organization's (FAO) Global Forest Resources Assessment 2010, the influence of uncertainties aligned to the estimation of emission reductions from forest degradation. On the example of three countries representing small to large forest areas and low to high carbon stocks, three different approaches for the inclusion of the uncertainties of estimates for two periods are analyzed. Furthermore, by simulating different sizes of areas where forest degradation takes place, the sensitivity of the estimated emission reductions with respect to the size of these areas is shown. The results of the study highlight the importance of identifying sound options of including uncertainties for different periods into a Measuring, Reporting, and Verification (MRV) system to avoid windfall profits from REDD. Moreover, it is demonstrated that an as accurate as possible identification of the areas where forest degradation takes place is decisive for the amount of REDD benefits achievable for a country.

Résumé : Selon la Convention cadre des Nations Unies sur les changements climatiques (CCNUCC), le mécanisme de réduction des émissions provenant de la déforestation et de la dégradation des forêts (REDD) est devenu une option importante pour générer une valeur financière grâce au carbone emmagasiné dans les forêts, en réduisant les émissions provenant des forêts. Jusqu'à maintenant, plusieurs études ont porté sur la détectabilité des émissions causées par la déforestation. Cette étude se concentre sur les émissions et la réduction des émissions dues à la dégradation de la forêt. En se basant sur des données de l'évaluation des ressources forestières mondiales 2010 de l'Organisation des Nations-Unies pour l'alimentation et l'agriculture (FAO), nous mettons en évidence l'influence des incertitudes reliées à l'estimation de la réduction des émissions provenant de la dégradation des forêts. Prenant comme exemple trois pays représentatifs de régions forestières allant de petites à vastes et de stocks de carbone variant de faibles à élevés, nous avons analysé trois approches différentes pour inclure les incertitudes des estimations pour deux périodes. De plus, en simulant des régions de différentes dimensions où la forêt se dégrade, on met en évidence la sensibilité de la réduction estimée des émissions en fonction de la dimension de ces régions. Les résultats de l'étude font ressortir l'importance d'identifier des façons valables d'inclure les incertitudes pour différentes périodes dans un système de mesure, de rapport et de vérification (MRV) afin d'éviter les bénéfices exceptionnels générés par la REDD. De plus, on démontre qu'une identification aussi précise que possible des régions où il y a de la dégradation est décisive quant à l'ampleur des bénéfices générés par la REDD que peut obtenir un pays.

[Traduit par la Rédaction]

Introduction

The destruction of tropical forests has raised the concern of the international community for a long time. Even though there have been many attempts to slow down deforestation, the United Nations Food and Agricultural Organization (FAO) estimates that 13 million hectares of tropical forests are lost annually (FAO 2010*a*), contributing 12%–20% of the anthropogenic global greenhouse gas emissions (UN-REDD 2008).

As a new attempt to reduce deforestation and forest degradation, Reducing Emissions from Deforestation and Forest Degradation (REDD) was introduced into the international political discussions by the Coalition of Rainforest Nations on the United Nations Framework Convention on Climate Change's (UNFCCC) 11th Conference of the Parties (COP11) in 2005 in Montreal (UNFCCC 2005). The reduction of deforestation and forest degradation was identified to be the most cost effective way to combat climate change (Stern 2007). Since the first submission, many political and scientific discussions have taken place to insure the integrity of a possible REDD mechanism. This broadened the topic of REDD by including the enhancement of forest carbon stocks, the conservation of forests, and the sustainable management of forests (Forest Carbon Partnership Facility 2011), indicated by the term REDD+. Furthermore, UNFCCC (2011*a*)

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decided that a country willing to participate in a REDD+ mechanism has to implement the necessary measures in a phased approach. This includes, inter alia, the buildup of sufficient capacities for a robust Measuring, Reporting, and Verification (MRV) system to be able to report changes of its deforestation and forest degradation rate (UNFCCC 2011*a*). Approaches for MRV systems are discussed widely (Eliasch 2008) and are constantly updated (GOFC-GOLD 2011).

Background

Defining deforestation and forest degradation

Most of the publications dealing with the implementation of REDD+ MRV systems focus on deforestation. This is mainly due to the fact that measuring and reporting of deforestation is deemed easier than of forest degradation (DeFries et al. 2006) and that internationally agreed definitions for forest (e.g., UNEP/CBD 2001; UNFCCC 2001; FAO 2006) and related forest land (IPCC 2003*a*) are available. The forest definitions commonly use an array of parameters within a given range (e.g., UNFCCC (2001): minimum area 0.05–1.0 ha, crown cover 10%–30%, and minimum height 2–5 m). Out of these ranges, a country can choose its specific combination of parameter thresholds to define forests. This may lead to a situation where countries have the same area of forest but do report different areas due to selecting different parameter thresholds (Köhl et al. 2000).

Following IPCC (2003*a*), deforestation is "the direct human-induced conversion of forested land to non-forested land". Whenever one of the parameters falls below the selected threshold, this land no longer qualifies as forest. In terms of a MRV system, forest area and crown cover are readily detectable via remote sensing. The manifold improvements in this field of forest monitoring increase the reliability of estimations of area changes and resulting carbon stock losses (Goetz and Dubayah 2011).

The situation becomes different for forest degradation. In terms of the IPCC (2003*b*), forest degradation is a process that occurs in "forest land remaining forest land". Hence, degradation may entail, e.g., a forest area with a crown cover between 100% and 10%. Especially for those forests with a closed crown cover, many degradation activities may occur unaccounted for by remote sensing. The multitude of processes that may lead to forest degradation like, e.g., illegal logging, fuelwood collection, and expansion of agriculture or grazing, render the measuring, reporting, and verification much more complex. Consequently, the process of forest degradation is, besides much effort (IPCC 2003*b*), still not finally defined (Simula 2009). In the scope of REDD+, forest degradation focuses on carbon loss. IPCC (2003*b*) proposed to define forest degradation as "...a direct human-induced long-term loss (persisting for *X* years or more) of at least *Y* % of forest carbon stocks (and forest values) since time *T* and not qualifying as deforestation or an elected activity under Article 3.4 of the Kyoto Protocol". However, none of the thresholds (*X*, *Y*, *T*) have been further defined and the practicability of the proposed definition is doubted (Penman 2008). Moreover, including the enhancement of forest carbon stocks, sustainable management of forests and the conservation of forest into REDD+ might exacerbate the finding of a suitable definition. However, these open questions hinder the development of a consistent MRV system (GOFC-GOLD 2011) as demanded in the acknowledgments of COP15 (Draft decision 4/15) (UNFCCC 2009).

MRV systems for REDD+

To comply with the accounting and reporting guidelines issued by UNFCCC (2011*b*), five major carbon pools in forests have to be considered (IPCC 2003*a*): (1) aboveground biomass, (2) belowground biomass, (3) dead wood, (4) litter, and (5) soil organic matter. A MRV system for REDD+ needs to focus on two components (IPCC 2003*a*): (*i*) assessing changes in forest area over time (activity data (AD)) and (*ii*) assessing changes in the average carbon stock per unit area over time (emission factors (EFs)).

To assess changes in AD and EF over time renders sampling on successive occasions (Ware and Cunia 1965) or the development of models to extrapolate data from one point in time to another (Hush et al. 2003) necessary. On large areas, cost and time efficient monitoring suggests concentrating on the aboveground biomass (Murdiyarso et al. 2008). Remote sensing techniques facilitate the monitoring of spatially explicit AD (Gibbs et al. 2007) but often are not sensitive enough to provide reliable information of in situ changes (Baldauf et al. 2009). This implies possible noncompliance with the standards for a MRV system, as a considerable fraction of forest degradation might remain undetected and the proportion of emissions from forest degradation in relation to deforestation can be concealed. Herold et al. (2008) compiled estimates for this relation ranging from 5% for the world's humid tropics to 25%–42% for tropical Asia and to 132% for tropical Africa. Therefore, a combination of remote sensing data and sample-based terrestrial in situ assessments on successive occasions is preferred to monitor aboveground biomass (UNFCCC 2009). To improve the effectiveness and reliability of the estimates, forests can be arranged in homogenous subgroups via remote sensing, enhanced by proxies for the likelihood of a specific forest area to undergo changes (Schreuder et al. 1993).

IPCC (2006) provides three methodological tiers for the estimation of carbon stock changes that countries can choose from regarding their national capacities and circumstances. While Tier 1 mainly utilizes default values and is therefore subject to high uncertainties, Tier 2 and Tier 3 require increasing efforts and improve the reliability of estimates. For most of the countries involved in REDD+ demonstration and readiness activities, deforestation and forest degradation can be assumed to be a key category (Maniatis and Mollicone 2010) requiring Tier 2 or Tier 3. This demands a thorough evaluation of alternatives for a MRV system to reduce uncertainties by choosing either the best reliability for a given budget or a given reliability for the least costs (Köhl et al. 2011).

While data on the change of forest area are provided for most of the countries reporting to FAO's Forest Resource Assessment (FRA), only for some countries are data on biomass or carbon stock changes available. Marklund and Schoene (2006) concluded for FAO's FRA 2005 that one third of all reporting countries gave information on either an increase or a decrease of the growing stock per hectare in their forests, whereas the other two thirds reported a change in their forest area while reporting no change in the growing stock per hectare. This tendency holds true for the data of FRA 2010, implying that trends on carbon stocks are rarely available for countries showing a decrease in their forest area. At any rate, it is the same set of countries that account for the large majority of forest degradation (Mollicone et al. 2007). Omitting data on the change of forest carbon stock per hectare is not a viable option for a MRV system for REDD+.

Uncertainties

UNFCCC (2008) stipulated, inter alia, that “means to deal with uncertainties in estimates aiming to ensure that reductions in emissions or increases in removals are not over-estimated, including those existing in IPCC guidance” need to be developed. Underlying uncertainties are intrinsically bound to any assessment or estimation methodology and are inevitable when estimating activity data and emission factors. IPCC (2003*a*) proposed to address uncertainties by the use of the reliable minimum estimate (RME) for the assessment of soil carbon stock changes, introduced by Dawkins (1957) as the minimum quantity to be expected with a given probability. The implications of the RME on a MRV system for REDD+ are described in more detail in Köhl et al. (2009) and Plugge et al. (2011). To “address the potential incompleteness and the high uncertainty of REDD estimates”, Grassi et al. (2008) proposed to apply the principle of conservativeness already introduced in several UNFCCC documents (UNFCCC 2006*a*, 2006*b*). They concluded that incorporating the RME in the calculation of REDD estimates results in a practicable, robust, and credible REDD mechanism.

Objectives and hypotheses of the study

Thus far, many studies have dealt with the detectability of emissions resulting from deforestation. This study concentrates on the emissions and emission reductions from forest degradation. Utilizing data from FAO’s FRA 2010 (FAO 2010*b*), our first objective is to test the hypothesis that uncertainties aligned to the estimation of emission reductions from forest degradation have an influence on the reporting of a country. Our second objective is to test the hypothesis that the estimated emission reductions are sensitive to the size of areas where degradation takes place.

Data and methods

FAO’s global forest resources assessment

This study utilizes data from FAO’s FRA 2010 on forest areas and carbon stocks for the years 1990, 2000, and 2010. Data from 2005 were not considered, as we assigned 1990–2000 as the reference period, while 2000–2010 is defined as the assessment period. In the reference period, the initial data for the construction of the reference level are gathered. In the assessment period, information on AD and EFs are collected. For the present study, we only consider carbon emissions. Emissions of other greenhouse gases are not included in our analyses.

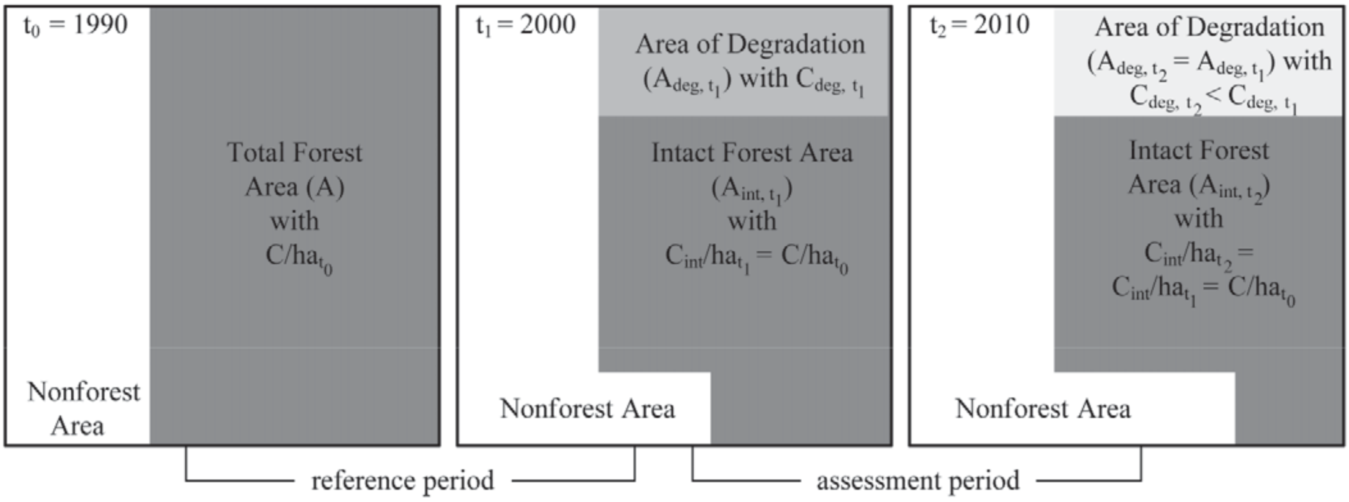
Creating scenarios

From the set of countries that reported changes in their per hectare forest carbon stocks in FRA 2010, we selected Brunei Darussalam (Brunei hereafter), Cambodia, and Pakistan

Table 1. FRA 2010 data for the three selected countries on total forest area (*A*), total carbon stock (*C*), and carbon stock per hectare (*C*/ha) in the years 1990 (t_0), 2000 (t_1), and 2010 (t_2).

Country	A_{t_0} (1000 ha)	A_{t_1} (1000 ha)	A_{t_2} (1000 ha)	C_{t_0} (Tg C)	C_{t_1} (Tg C)	C_{t_2} (Tg C)	C/ha_{t_0} (Mg·ha^{-1})	C/ha_{t_1} (Mg·ha^{-1})	C/ha_{t_2} (Mg·ha^{-1})
Brunei	413	397	380	81	76	72	196.1	191.4	189.5
Cambodia	12944	11546	10094	609	537	464	47.0	46.5	46.0
Pakistan	2527	2116	1687	330	271	213	130.6	128.1	126.3

Fig. 1. Schematic display of the methodological assumptions. The development of a hypothetical forest (dark grey) and nonforest area (white) from the reference (1990–2000) to the assessment period (2000–2010) is depicted. The development of the intact forest area (A_{int}) (dark grey) and its carbon stock per hectare (C/ha) as well as the areas of degradation (A_{deg}) (shaded grey and light grey) and its carbon stock (C_{deg}) are displayed for t_1 and t_2.



with respect to their average carbon stock per hectare (high to low), their forest area (small to large), as well as their performance in reducing forest degradation from the reference to the assessment period. For the purpose of this study, it is assumed that these countries already applied measures to reduce their rates of deforestation and forest degradation from the reference (1990–2000) to the assessment period (2000–2010). Table 1 shows the respective data of the FRA 2010 (FAO 2010*b*) for the forest area, the total carbon stock, and the carbon stock per hectare for each country and year.

While a decrease in the total forest area inherently decreases the total carbon stock of a country, it does not necessarily decrease the carbon stock per hectare of the remaining forest of a country. The decrease per hectare is due either to a generally lower carbon stock or to degradation processes in the remaining forest area. As the exact cause of the decrease cannot be verified by the available data, we assign the decrease of carbon stock per hectare to the process of forest degradation. The probability of changes in carbon stocks is generally higher in forest areas that are more prone to degradation due to different factors like accessibility, distance to villages, or the provision of high-value timber (Brown 1997). Consequently, degradation activities will not occur simultaneously or with the same impact on the total forest area of a country but only on those area fractions that show at least one of the factors that facilitate human-induced changes in forest carbon stocks. The respective sizes are, however, not deducible from FRA data. As this study aims to analyze whether different sizes have an influence on the reporting of a country, we selected three different area fractions, $p \in \{0.1, 0.2, 0.5\}$, of the total forest area, A, where degradation is assumed to happen. These areas are henceforth called areas of degradation (A_{deg}), while those areas where the carbon stock stays constant are called intact forest areas (A_{int}). Assigning the decrease of carbon stock per hectare as displayed in the FRA data (see Table 1) to a specific area size of A_{deg} ($A_{deg} = \{0.1A, 0.2A, 0.5A\}$) allows for analyzing the influence of different area sizes and uncertainties on the estimation of emissions from forest degradation. Figure 1 illustrates the development of a hypothetical forest area with deforestation and forest degradation activities.

Corresponding to the FRA 2010 data, the initial year of the study (1990, t_0) is considered to be the beginning of the reference period. The following assumptions apply for t_0 (Fig. 1, left). A_{deg} is set to zero and the carbon stock per hectare (C/ha_{t_0}) is equally distributed over the forest area, as no other distribution (e.g., primary forest with high carbon stock and secondary forest with low carbon stock) can be deduced from FRA data. From t_0 onwards, deforestation as well as forest degradation take place. For the end of the reference period (2000, t_1) the following assumptions are made (Fig. 1, center). The total forest area has decreased due to deforestation. For the selected countries, this decrease corresponds to the FRA data (see Table 1). The remaining forest area is divided into an area of degradation ($A_{deg,\,t_1}$) where a carbon stock change occurred and an intact forest area ($A_{int,\,t_1}$) without degradation activities, resulting in an unchanged per hectare carbon stock ($C_{int}/\mathrm{ha}_{t_1} = C/\mathrm{ha}_{t_0}$). $A_{deg,\,t_1}$ is calculated with reference to the total forest area at t_1 (A_{t_1}) and the area fractions (p):

[1] $$A_{deg,\,t_1} = A_{t_1} \times p$$

The carbon stock on $A_{int,\,t_1}$ is calculated as

[2] $$C_{int,\,t_1} = A_{int,\,t_1} \times C/\mathrm{ha}_{t_0}$$

The carbon stock on $A_{deg,\,t_1}$ is then given by

[3] $$C_{deg,\,t_1} = C_{t_1} - C_{int,\,t_1}$$

For the end of the assessment period (2010, t_2) further assumptions are made (Fig. 1, right). Even though those areas that are already degraded are more prone to be finally deforested, we set the simplifying assumption that deforestation takes only place on intact forest areas (A_{int}) and not on degradation areas (A_{deg}). Otherwise, it would be necessary to introduce variables for the area of degraded forest that is finally deforested, the area of degraded forest that is further degraded but not finally deforested and the amount of this de-

Table 2. Values of the three selected countries for the total change in carbon stock in the reference period ($\Delta C_{t_0-t_1}$) and the assessment period ($\Delta C_{t_1-t_2}$) and partition of the change in carbon stock due to the processes of deforestation (ΔC_{def}) and forest degradation (ΔC_{deg}).

	Reference period (1990–2000)			Assessment period (2000–2010)		
Country	$\Delta C_{t_0-t_1}$ (Tg C)	ΔC_{def} (Tg C)	ΔC_{deg} (Tg C)	$\Delta C_{t_1-t_2}$ (Tg C)	ΔC_{def} (Tg C)	ΔC_{deg} (Tg C)
Brunei	5.0	3.1	1.9	4.0	3.3	0.7
Cambodia	72.0	65.8	6.2	73.0	68.3	4.7
Pakistan	59.0	53.7	5.3	58.0	56.0	2.0

gradation, and the area of previous intact forest that is degraded and the amount of this degradation. To avoid a high level of complexity and to allow showing some general effects of the size of degradation areas and aligned errors in estimating emission reductions, A_{deg} is kept constant ($A_{\mathrm{deg},\,t_1} = A_{\mathrm{deg},\,t_2}$). Consequently, the carbon stock change that is due to forest degradation (ΔC_{deg}) is fully assigned to this area. The total forest area A_{t_2} and, respectively, the area of intact forests $A_{\mathrm{int},\,t_2}$ change according to FRA data. The change of the forest area (A) during the assessment period ($\Delta A_{t_1-t_2}$) is considered via

$$[4] \qquad \Delta A_{t_1-t_2} = A_{t_1} - A_{t_2}$$

The carbon stock per hectare on A_{int} does not change from the reference to the assessment period; thus, the aligned carbon stock change due to deforestation (ΔC_{def}) is calculated as follows:

$$[5] \qquad \Delta C_{\mathrm{def}} = \Delta A_{t_1-t_2} \times C/\mathrm{ha}_{t_0}$$

The carbon stock change due to forest degradation (ΔC_{deg}) is

$$[6] \qquad \Delta C_{\mathrm{deg}} = \Delta C_{t_1-t_2} - \Delta C_{\mathrm{def}}$$

Subsequently, the remaining carbon stock on A_{deg} ($C_{\mathrm{deg},\,t_2}$) is calculated as

$$[7] \qquad C_{\mathrm{deg},\,t_2} = C_{\mathrm{deg},\,t_1} - \Delta C_{\mathrm{deg}}$$

Table 2 presents the total change of carbon stock in the reference period ($\Delta C_{t_0-t_1}$, 1990–2000) and the assessment period ($\Delta C_{t_1-t_2}$, 2000–2010) for the three selected countries and the corresponding partitions of carbon stock changes due to deforestation (ΔC_{def}) and forest degradation (ΔC_{deg}).

Incorporating uncertainties into the scenarios

The approach presented so far allows for the calculations of the carbon stock changes due to forest degradation without uncertainties. However, any assessment of carbon stocks or carbon stock changes is bound to several sources of errors that affect the reliability of estimates.

Grassi et al. (2008) introduced two groups of approaches for handling uncertainties of REDD estimates. One group focuses on the uncertainties associated with the difference of emissions between the reference and the assessment period and utilizes the uncertainty of a trend. A trend uncertainty is highly dependent on the potential correlation of the uncertainties between the two periods. Assuming that the data for the estimation of the emissions are gathered under the prerequisites of a continuous forest inventory (CFI), i.e., among others, that the same set of terrestrial inventory plots is used for deriving the data at both points in time, the standard approach for respecting the correlation of the uncertainties from two points in time is the combination of the corresponding standard errors while also respecting their covariance. A good overview on CFI and the handling of uncertainties is given in Köhl et al. (2006). One of the major advantages of CFI is that the standard error will be generally lower compared with, e.g., two completely independent surveys. Grassi et al. (2008) assumed full correlation of the uncertainties of EFs for the case of deforestation. However, they introduced a second group of approaches for handling uncertainties of REDD estimates that focus on utilizing the RME for both the emissions of the reference and the assessment period. This group becomes important whenever the correlation of uncertainties becomes unclear or is simply unknown. They concluded that the correlation of the uncertainties of the EF and the AD depends highly on the type of assessment used for the acquisition of data. In this study, we have no information on the methods used for data collection on forest degradation (i.e., the changes in carbon stock per hectare) for the FRA 2010. Whether these data are positively correlated, as it would be expected with CFI, or negatively correlated, as may be the case in heterogeneous environments with frequent disturbances (likely for degradation areas) (Köhl et al. 2006), cannot be deduced from the data set. To show the disparate influences of the different types of correlations, we decided to treat the data of 1990, 2000, and 2010 as completely independent data sets.

To estimate the influence of the possible correlations of uncertainties on the reporting of a specific country on the one hand and to signify the importance of the thorough design of a MRV system for REDD+ on the other, we introduce three different approaches that include positive correlation (Approach C) as well as negative correlation (Approach A) (see Fig. 2). As UNFCCC (2008) demanded that reductions in emissions or increases in removals are not overestimated, the application of the RME at the end of the assessment period is seen as a prerequisite for an operational REDD+ MRV system. Only the lower bound of the error interval of the estimated carbon stock (i.e the upper bound of the error interval of the emissions) at the end of the assessment period qualifies for accounting.

Figure 2 visualizes the approaches for the incorporation of uncertainties of the estimated emissions for the reference and the assessment period. Approach A (a–d) (Fig. 2, left) conservatively takes into account the uncertainties of the reference as well as the assessment period, representing a negative correlation of the estimates. Approach B (b–d) (Fig. 2, center) takes into account the mean value of the emissions in the reference period and the upper bound of the error interval for the emissions in the assessment period. This represents a medium correlation of the estimates. Approach C

Fig. 2. The three approaches analyzed in this study. Approach A (a–d) conservatively considers the uncertainties in both periods. Approach B (b–d) only takes into account the uncertainties at the end of the assessment period. Approach C (c–d) is oriented on the conservative estimate of the emissions in the reference period (upper bound of the error interval).

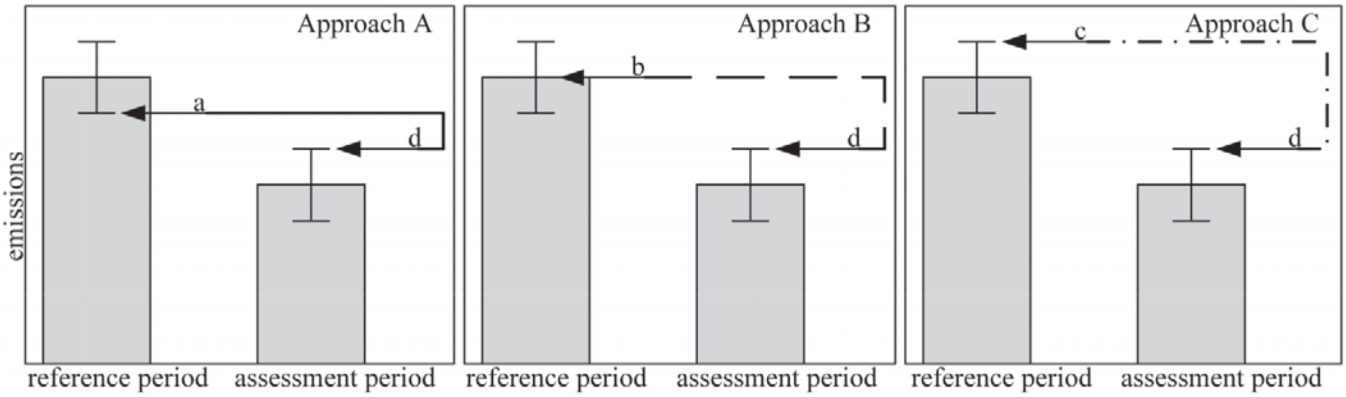


Table 3. Carbon stock change per hectare for the reference and the assessment period in total values ($Mg{\cdot}ha^{-1}$) and in percentage for the three selected sizes of the area of degradation (A_{deg}) for each country as well as the proportional reduction of the carbon stock change between the periods in percent (the values for the reference period represent the values for the baseline).

			Reference period (ΔC_{BL})		Assessment period		
	Country	A_{deg} (1000 ha)	$Mg{\cdot}ha^{-1}$	%	$Mg{\cdot}ha^{-1}$	%	Emission reduction (%)*
Area of degradation ($A_{deg} = 0.1A$)	Brunei	39.7	–46.9	–23.9	–16.8	–11.2	–64.2
	Cambodia	1154.6	–5.4	–11.5	–4.1	–9.7	–24.7
	Pakistan	211.6	–25.2	–19.3	–9.3	–8.9	–62.9
Area of degradation ($A_{deg} = 0.2A$)	Brunei	79.4	–23.5	–12.0	–8.4	–4.9	–64.2
	Cambodia	2309.2	–2.7	–5.7	–2.0	–4.6	–24.7
	Pakistan	423.2	–12.6	–9.6	–4.7	–4.0	–62.9
Area of degradation ($A_{deg} = 0.5A$)	Brunei	198.5	–9.4	–4.8	–3.4	–1.8	–64.2
	Cambodia	5773.0	–1.1	–2.3	–0.8	–1.8	–24.7
	Pakistan	1058.0	–5.0	–3.9	–1.9	–1.5	–62.9

*From the reference to the assessment period.

(c–d) (Fig. 2, right) focuses on the conservative estimate for the emissions at the end of the reference period, i.e., rather over- than underestimating the emissions, representing a positive correlation of the estimates.

To evaluate the efforts towards the reduction of emissions, the estimated emissions of the assessment period need to be set off against a reference level derived from historic rates of emissions during a reference period. Most of the previous studies consider the rates of deforestation only (e.g., Plugge et al. 2011). As we concentrate on the carbon stock changes due to degradation (ΔC_{deg}), we construct a baseline for those areas where degradation takes place (A_{deg}).

Table 3 presents the partition of the total change of carbon stock due to the process of forest degradation, ΔC_{deg}, as well as the proportional reduction of the carbon stock change between the periods for the selected countries. A change of ΔC_{deg} within a period as well as proportional reductions of total emissions from the reference to the assessment period do not allow for conclusions on the size of the degradation area, A_{deg}. With A_{deg} and the proportion of total carbon stock change that occurs on A_{deg}, ΔC_{deg}, the per hectare change of carbon stocks can be calculated. For a given ΔC_{deg}, the per hectare carbon stock change decreases logically consistent with increasing size of A_{deg} (see Table 3). To analyze the influence of the size of A_{deg} on the reporting of a specific country, we have introduced three different area fractions (p) where degradation is assumed to take place. A specific baseline (ΔC_{BL}) for each of the three selected sizes of A_{deg} can be deduced by utilizing the per hectare values for carbon stock changes in the reference period. Table 3 also shows that the proportional reduction of the carbon stock change between the periods (Table 3, last column) is independent of the size of A_{deg}.

The emissions in the assessment period are set off against the baseline to evaluate if a desired emission reduction has been met. There are various options that have been discussed recently on how to set up a baseline or reference scenario (Meridian Institute 2011). To facilitate the understanding of the current study, we assume a business as usual baseline. Furthermore, we assume that, while the uncertainty of the estimate at the end of the reference period is known, the baseline has been constructed without using the RME, i.e., using an anticipated error-free "true mean".

The three approaches render the enhancement of the equations presented above necessary to address uncertainties. Realistic error intervals in forest inventories range from 1% to 10% (Scott and Köhl 1994). We selected error levels $\varepsilon \in \{0.00, 0.01, 0.02, 0.05, 0.10\}$ including the idealistic situation of achieving an estimate without any error. The specific assumptions of including ε in the three approaches (see Fig. 2) are taken into account when calculating the respective $C_{deg,\,t_1}$ at the end of the reference period. The reportable emissions during the assessment period, $\Delta C_{\text{deg},\, t_1-t_2}$, are given on the basis of eq. 3 with $C_{\text{deg},\, t_1}$ including ε_{t_1} according to the assumptions and eq. 7 with $C_{\text{deg},\, t_2}$ including ε_{t_2} as the RME at the end of the assessment period, i.e.,

$$[8] \quad \text{Approach A}: \Delta C_{\text{deg},\, t_1-t_2} = C_{\text{deg},\, t_1}(1+\varepsilon_{t_1}) - C_{\text{deg},\, t_2}(1-\varepsilon_{t_2})$$

$$[9] \quad \text{Approach B}: \Delta C_{\text{deg},\, t_1-t_2} = C_{\text{deg},\, t_1} - C_{\text{deg},\, t_2}(1-\varepsilon_{t_2})$$

$$[10] \quad \text{Approach C}: \Delta C_{\text{deg},\, t_1-t_2} = C_{\text{deg},\, t_1}(1-\varepsilon_{t_1}) - C_{\text{deg},\, t_2}(1-\varepsilon_{t_2})$$

Positive values for $\Delta C_{\text{deg},\, t_1-t_2}$ denote emissions from forest degradation, while negative values indicate an increase in the carbon stock. The findings are strictly related to forest land remaining forest land during the assessment period and do not include emissions from deforestation on other areas.

For evaluating REDD+ efforts, the emission reduction needs to be validated. Therefore, a country is obliged to prove that emissions from deforestation and forest degradation are lower in the assessment period than they were in the reference period. When concentrating on degradation only, the emission reductions are the difference between the emissions during the assessment period, $\Delta C_{\text{deg},\, t_1-t_2}$, as observed on degradation areas and the anticipated emissions according to the baseline, ΔC_{BL}. For detailed information on the applied approach towards estimating emission reductions, please see Köhl et al. (2009). An example of a complete calculation of accountable emission reductions can be found in Appendix A.

Results

The results are presented in two parts. First, we present the influence of uncertainties for both periods on accountable emission reductions for the three different approaches under the precondition of an area of degradation (A_{deg}) of 10% of the total forest area (A). Second, we describe the influence of different extents of A_{deg} on the accountable emission reductions for each of the three approaches.

Influence of uncertainties on accountable emission reductions

This study focuses on the effect of different ways of handling the uncertainties at two points in time (Fig. 2) on the accountable emission reductions from forest degradation. While all three approaches use the RME at the end of the assessment period, they differ in the options of selecting the level of errors at the end of the reference period, thus simulating different trends in the correlation of the uncertainty of the estimates. Approach A reflects the lower bound of the errors of the emissions, Approach C considers the upper bound, while Approach B refers to the point estimate at the end of the reference period and neglects any associated errors. It is widely accepted that errors observed in forest surveys at successive occasions are correlated and do differ substantially in time (Köhl et al. 2006; Grassi et al. 2008; Waggoner 2009). However, the situation becomes different when the variation of the sampling population changes in time, which is likely to happen under degradation activities. In addition, survey protocols can change over time and lead either to an improved reliability of estimates due to newly introduced sophisticated technologies or to increased uncertainties when survey activities have to be reduced due to constraints in budgets and capacities. Therefore, we allowed for both an improvement and a worsening of the associated errors by applying error levels $\varepsilon \in \{0.00, 0.01, 0.02, 0.05, 0.10\}$ at each occasion. We thereby show examples for extreme positive or extreme negative correlation to analyze the effects of these correlations and the need to consider these in a REDD+ MRV system.

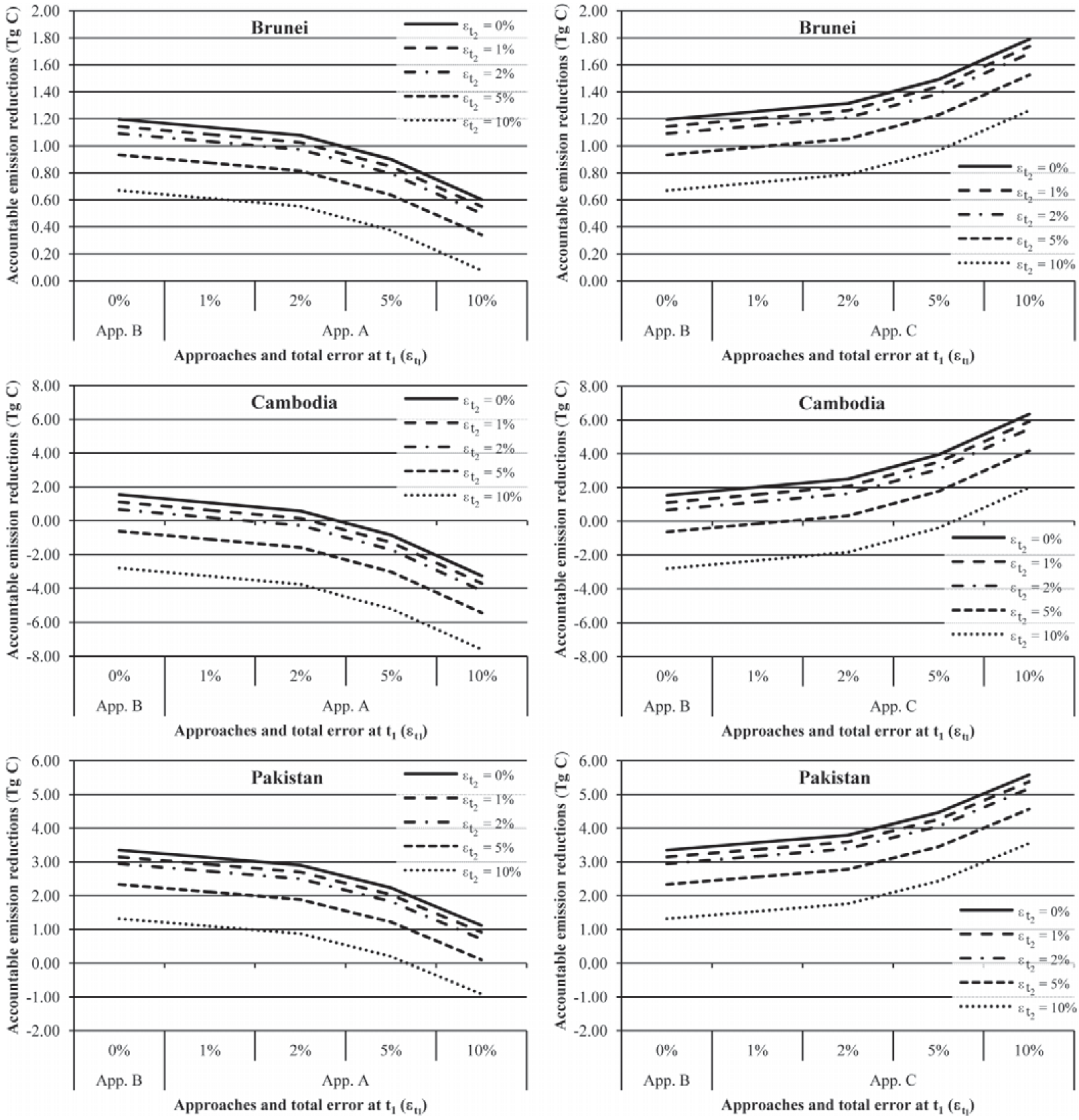
For all three selected countries, the amount of accountable emission reductions in teragrams of carbon is presented in Fig. 3. For this part of the study, we use a fixed size for the degradation area, A_{deg}, which is set to 10% of the total forest area, A. Two different graphs for each of the selected countries are shown. Approach A is displayed on the left graph and Approach C on the right graph. Approach B is shown as a reference on each of the two graphs, as it assumes error-free estimates at time t_1, $\varepsilon_{t_1} = 0\%$.

In Fig. 3, the influence of the total error on the amount of accountable emission reductions is depicted for each of the three approaches. On the x-axis, the total error at time 1 (ε_{t_1}, end of the reference period) is given, ranging from 0% to 10%. Each line represents the influence of a specific total error at time 2 (ε_{t_2}, end of the assessment period) on the accountable emission reductions. Positive values of teragrams of carbon show the amount of reportable emission reductions and negative values imply that no emission reductions can be reported. With $\varepsilon_{t_1} = 0\%$ and $\varepsilon_{t_2} = 0\%$ in Approach B, the point estimate for emission reductions without any error is shown. This point estimate is a reference for the effect of the total error in all other error scenarios.

For Approach B, the inclusion of the total error at the end of the assessment period (ε_{t_2}) leads to decreasing accountable emission reductions. The more the total error increases the larger is the negative impact on the emission reductions. Brunei and Pakistan would be in a position to report a reduction of their emissions from forest degradation for all error scenarios ($\varepsilon_{t_2} = 0\% - 10\%$) at the end of the assessment period. The situation is different for Cambodia, where the emissions at t_2 would need to be assessed with $\varepsilon_{t_2} < 5\%$ to gain benefits from reducing emissions from forest degradation.

For Approach A, the resulting accountable emission reductions are diminishing for each of the three countries with increasing uncertainties at the end of the reference and the assessment period. Any improvement in the uncertainty of the estimate from t_1 to t_2 (i.e., $\varepsilon_{t_1} > \varepsilon_{t_2}$) leads to a higher amount of accountable emission reductions than achievable with a maintained value for the uncertainties (i.e., $\varepsilon_{t_1} = \varepsilon_{t_2}$). Logically, a poorer performance regarding the uncertainties of the estimates at t_2 decreases the reportable value. Brunei would be in a position to report a successful reduction of its emissions even in the most unfavorable scenario of a total error of 10% for the estimates at the end of both periods. The results for Pakistan are no longer unambiguous. Except for the case of $\varepsilon_{t_1} = 10\%$ and $\varepsilon_{t_2} = 10\%$, all error situations allow for reporting emission reductions. However, the higher the error levels the closer the emission reductions are to

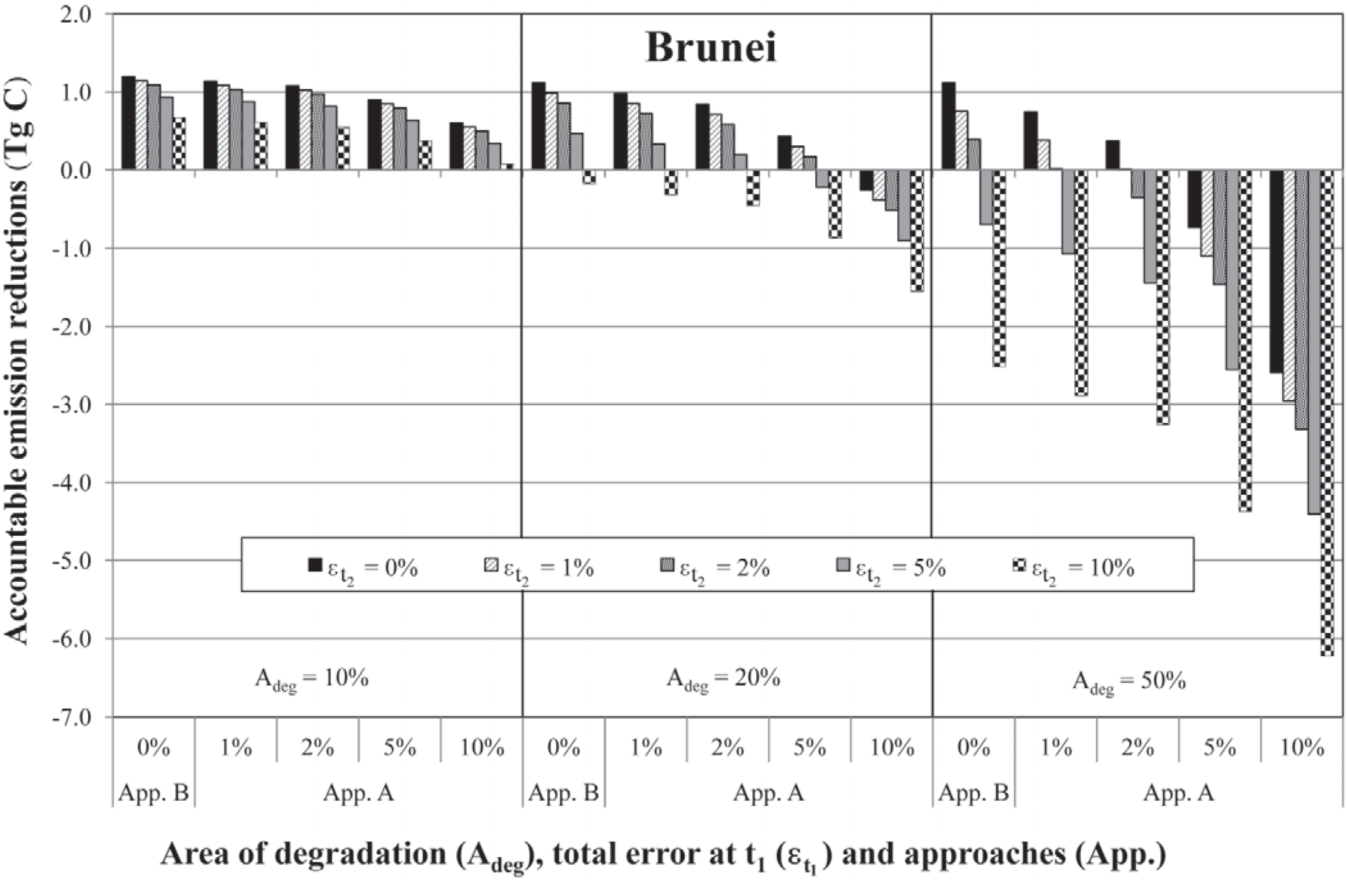
Fig. 3. Accountable emission reductions for each of the three countries for Approaches (App.) A and B (left panels) and Approaches B and C (right panels). The *x*-axis shows the total error for the estimates at the end of the reference period (ε_{t_1}) as well as the approaches; the graphs depict the different scenarios for the total error at the end of the assessment period (ε_{t_2}). Positive values of Tg C show the amount of reportable emission reductions; negative values imply that no emission reduction can be reported.



zero. For Cambodia, a successful reduction of emissions can only be reported when the value for ε_{t_1} is 1% and the value for ε_{t_2} is close to 2% or vice versa.

The results for Approach C (Fig. 3) are unambiguous for all three countries. In general, a high initial error (ε_{t_1}) would be rewarded by this option of including the uncertainties of the estimates at t_1 into the estimated accountable emission reductions at t_2. Furthermore, it can be stated that the lower the uncertainties at t_2 the higher is the amount of accountable emission reductions. For all three countries, the worst scenario of ε_{t_1} and ε_{t_2} of 10% would lead to larger accountable emission reductions than under the assumption of error-free assessments ($\varepsilon_{t_1} = 0\%$ and $\varepsilon_{t_2} = 0\%$). While Brunei and Pakistan would directly be able to report successful emission reductions, Cambodia would be in this position for all values of ε_{t_1} whenever ε_{t_2} is equal to or smaller than 2%. It becomes

Fig. 4. Accountable emission reductions for Brunei for Approaches A and B and different areas of degradation (A_{deg} = 10%, 20%, and 50%). The *x*-axis shows ε_{t_1} of the estimates, with an Approach B ε_{t_1} of 0% and an Approach A ε_{t_1} of 1%–10%. The graphs depict the resulting accountable emission reductions for the different error levels at t_2 (ε_{t_2}). Positive values of Tg C show accountable emission reductions; negative values imply that no emission reduction can be reported.



obvious that Approach C is likely to create an incentive for estimating emissions at t_1 with a high total error. As this is no option for a reliable and acceptable REDD+ MRV system, we do not consider Approach C in the following.

Influence of the area of degradation on accountable emission reductions

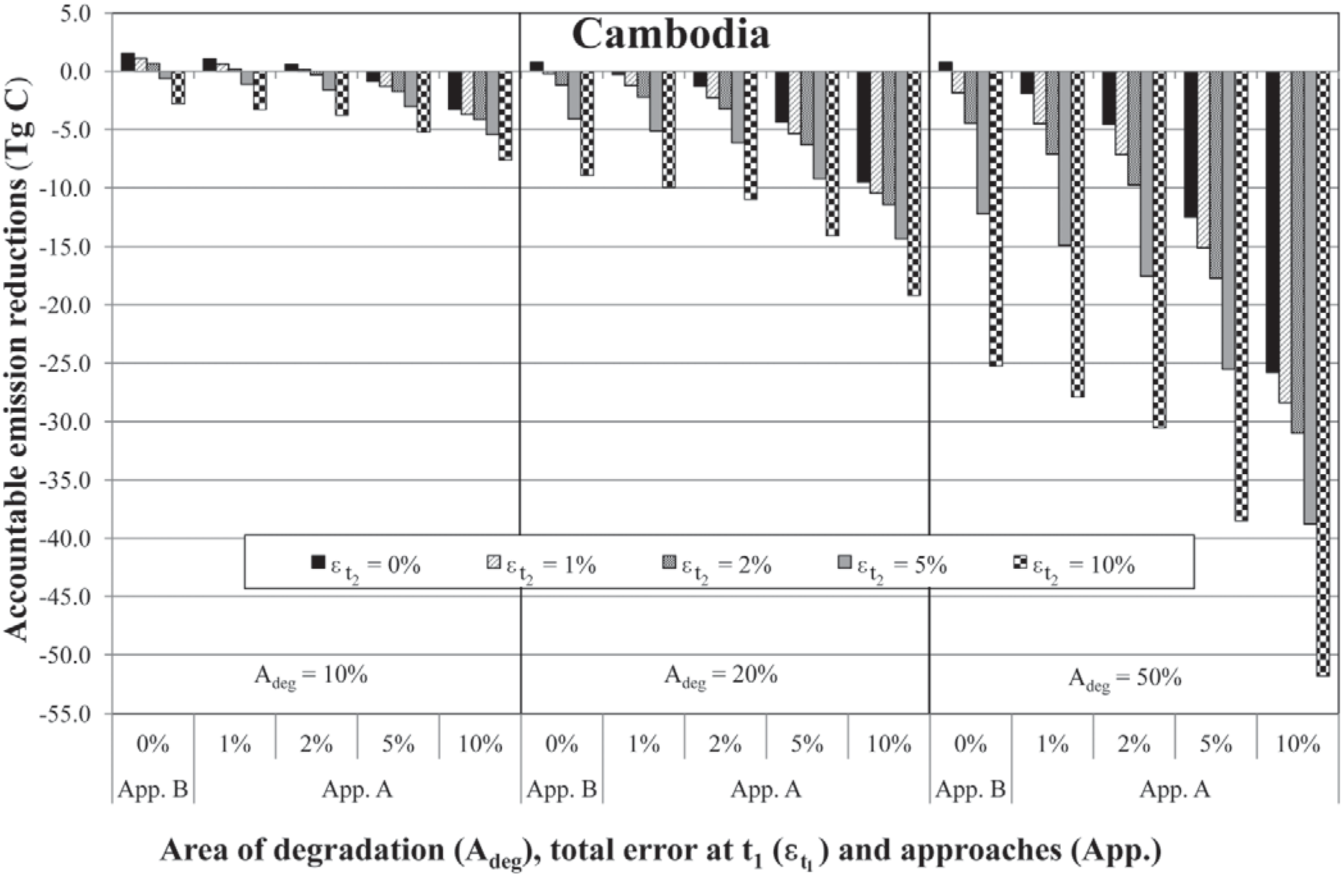
To study the impact of the different sizes of areas of degradation (A_{deg}) and uncertainties in estimated emission reductions on these areas, three different A_{deg}, ranging from 10% to 50% of the total forest area ($A_{deg} = \{0.1A, 0.2A, 0.5A\}$), were combined with error levels (ε) between 0% and 10%.

On the basis of the FRA data, the amount of the total emissions from degradation are calculated. When A_{deg} increases, the proportional emissions (i.e., the per hectare emissions) decrease. Or, put in another way, as the total carbon stock on A_{deg} increases with increasing A_{deg}, the effect of the total error associated with the estimation of the carbon stock and carbon stock changes increases, too. This effect has substantial consequences for the estimated accountable emission reductions. Figure 4 presents the interrelations for the example of Brunei. The left part of Fig. 4 presents the situation for an A_{deg} of 0.1A and serves as a reference for comparisons with Fig. 3. Approach B neglects any error associated with the t_1 estimates, while Approach A accounts for errors at both points in time (t_1, t_2).

Figure 4 shows the effect of three different sizes of A_{deg}. Brunei is in a situation to report successful reductions of its emissions from degradation for all simulated error combinations of Approaches A and B given an A_{deg} of 10% (Fig. 4, left). For an A_{deg} of 20% (Fig. 4, center), no accountable emission reductions can be achieved whenever ε_{t_1} or ε_{t_2} is 10%. If for Approach A, ε_{t_1} is 5%, benefits from the reduction of emissions from forest degradation can be gained only for ε_{t_2} being smaller than 5%. The situation intensifies when degradation is assumed to happen on an A_{deg} of 50% (Fig. 4, right). No emission reductions can be reported for Approaches A and B as soon as ε_{t_1} or ε_{t_2} exceeds 5%. Under Approach A, the total error of estimates needs to be 1% at one occasion and 2% at the other to qualify for emission reductions.

Cambodia is an example for a country showing a large forest area with a low carbon per hectare values and a low forest degradation rate that only slightly changes from the reference to the assessment period. Such a country is strongly affected by an increasing A_{deg} (Fig. 5). With an A_{deg} of 10%, Approach B would provide accountable emission reductions from forest degradation if ε_{t_2} is close to 2%. A similar situation holds for Approach A; ε_{t_1} has to be 2% or less and ε_{t_2} needs to be close to 0% to allow for reporting successful emission reductions (Fig. 5, left). For an A_{deg} of 20% or more, only an error-free assessment at one time and estimates with 1% error at the other time qualify for reporting emission

Fig. 5. Accountable emission reductions for Cambodia for Approaches A and B and different areas of degradation (A_{deg} = 10%, 20%, and 50%). The *x*-axis shows ε_{t_1} of the estimates, with an Approach B ε_{t_1} of 0% and an Approach A ε_{t_1} of 1%–10%. The graphs depict the resulting accountable emission reductions for the different error levels at t_2 (ε_{t_2}). Positive values of Tg C show accountable emission reductions; negative values imply that no emission reduction can be reported.



reductions (Fig. 5, center). In the worst-case scenario of this simulation with an A_{deg} of 50% and ε_{t_1} and ε_{t_2} of 10%, a country like Cambodia would need to report emissions from forest degradation more than 30 times larger than the emission reductions without any error (1.5 to –51.1 Tg C).

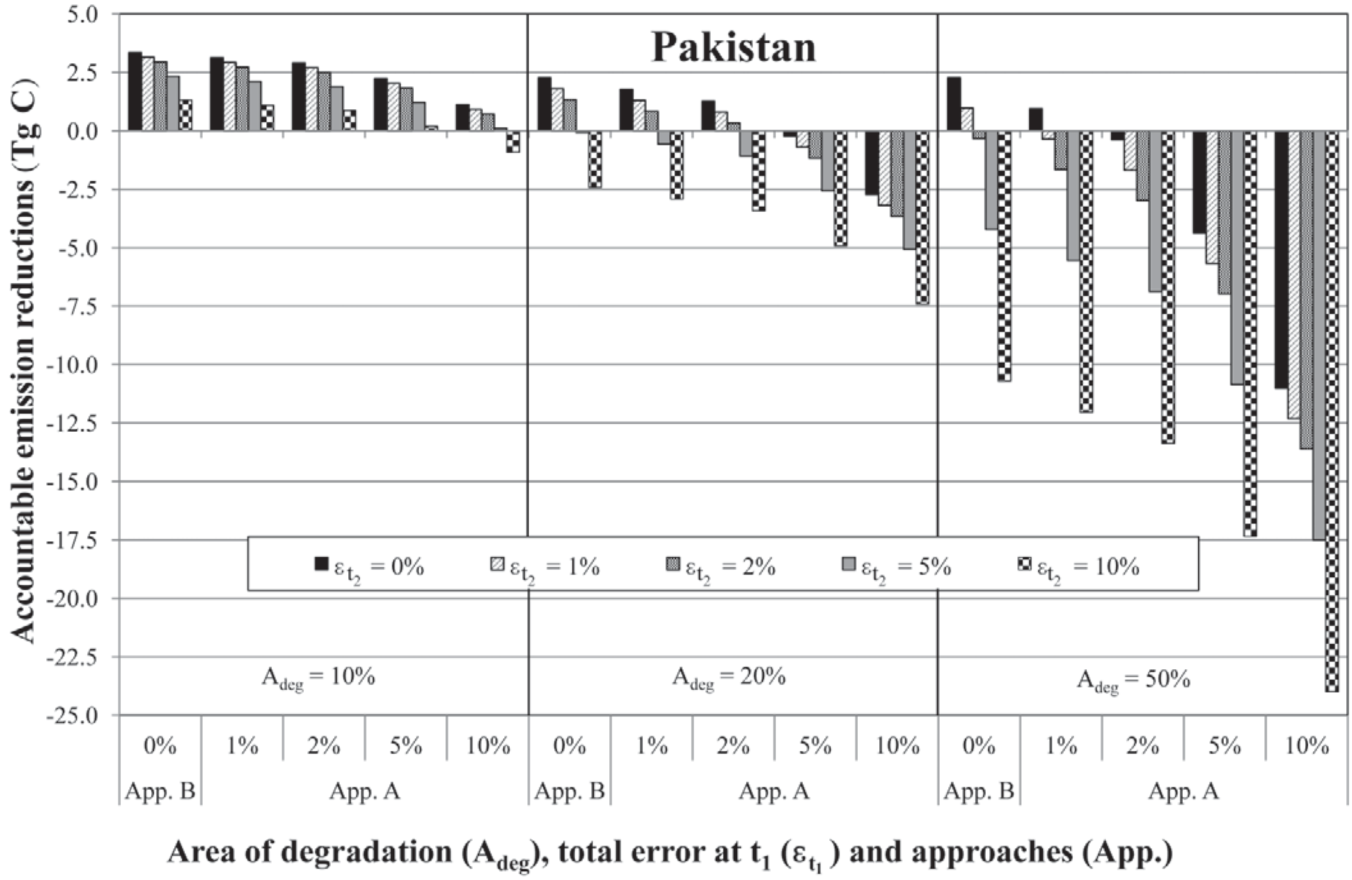
Pakistan is able to gain benefits for an A_{deg} of 10% (Fig. 6, left) for all error combinations except for the worst-case scenario of ε_{t_1} and ε_{t_2} being 10%. For an A_{deg} of 20% (Fig. 6, center), an error of 10% either at t_1 or t_2 prevents the reporting of an emission reduction. If ε_{t_1} is 5% and ε_{t_2} exceeds 1%, no emission reductions can be reported. For nearly all constellations of ε_{t_1} and ε_{t_2}, no successful emission reduction can be reported when A_{deg} is 50%. Only in the cases of small errors at both occasions can a positive value for accountable emission reductions be achieved.

Discussion

The current study focuses on the influence of uncertainties as well as different sizes of areas where forest degradation activities take place and shows the respective implications on reportable emission reductions from forest degradation. Data of FAO's FRA 2010 for the years 1990, 2000, and 2010 were utilized under the assumption that measures other than REDD+ were applied to reduce forest degradation from the reference to the assessment period. The data of each year were treated as independent of the other years, as no information on the data collection was available. Three different approaches for the inclusion of uncertainties for the reference and the assessment period were studied for the example of three selected countries that substantially differ in forest areas as well as in carbon stocks. The approaches represent both positive and negative correlations of the uncertainties aligned to any MRV methodology. Positive correlations would be expected for a CFI system; however, even within CFI, negative correlations may occur due to disturbances in forests like, e.g., degradation activities (Köhl et al. 2006). While some of the examples might appear to be disproportionate to the real situation, it has to be kept in mind that no decision on how to include uncertainties at different points in time has been taken for REDD+ so far. We therefore show these extreme examples to raise awareness for the implications that different error constellations have on the reporting of a specific country.

The first objective was to analyze the influence of including the uncertainties at the end of the reference and the end of the assessment period on the reporting of a country. To avoid confounding with changing area sizes, the degradation area was fixed to 10% of the total forest area. We were able to show the pronounced impact of errors associated with the estimation of emissions on the potential to report emission reductions. This corresponds to findings from other studies (Grassi et al. 2008; Köhl et al. 2009; Plugge et al. 2012).

Fig. 6. Accountable emission reductions for Pakistan for Approaches A and B and different areas of degradation (A_{deg} = 10%, 20%, and 50%). The *x*-axis shows ε_{t_1} of the estimates, with an Approach B ε_{t_1} of 0% and an Approach A ε_{t_1} of 1%–10%. The graphs depict the resulting accountable emission reductions for the different error levels at t_2 (ε_{t_2}). Positive values of Tg C show accountable emission reductions; negative values imply that no emission reduction can be reported.



When the estimates at the end of the reference period are assumed to be associated with an error, either the upper or the lower bound of the error interval can be selected. Approach A utilizes the lower bound for emission estimates (i.e., showing a negative correlation) and confirmed the strong influence of uncertainties on accountable emission reductions. Countries with low degradation activities in the reference period and extensive forest areas like Cambodia (ΔC_{BL} = 5.4 Mg·ha^{-1}) would be excluded from reporting emission reductions. For countries with high degradation rates and smaller forest areas, such as Brunei and Pakistan, Approach A also has a strong influence on the potential to gain benefits from REDD+. The amount of accountable emission reductions vanishes with increasing total errors at both points in time. While for most error constellations, emission reductions can be reported, errors of 10% at both points in time would exclude Pakistan from gaining benefits from REDD+.

Approach B did not consider any error associated with the estimate at the end of the reference period ($\varepsilon_{t_1} = 0\%$). Increasing errors for estimates at the end of the assessment period, ε_{t_2}, reduce the potential to gain benefits from a REDD+ mechanism for this approach. These findings are confirmed by other studies focusing on deforestation (e.g., Köhl et al. 2009; Plugge et al. 2012). The influence of the total error of the estimates at the end of the assessment period may outweigh successful efforts towards reducing emissions from forest degradation. For countries with high forest cover and low historical emissions from forest degradation like Cambodia, the implemented MRV system would need to produce estimates with total errors well below 2% to render the gain of benefits from REDD+ possible. However, achieving a total error below 2% is not realistic for a national or large-scale forest inventory (Waggoner 2009).

In contrast with Approach A, Approach C utilizes the upper bound of the error interval for the emissions of the reference period. Under this assumption, it is likely to create an incentive for estimating the emissions in the reference period with a considerable total error. The higher the total error at the end of the reference period and the lower the total error at the end of the assessment period the more accountable emission reductions can be reported. In the worst-case scenario of $\varepsilon_{t_1} = 10\%$ and $\varepsilon_{t_2} = 10\%$, all of the selected countries would be able to gain more benefits from REDD+ than eligible due to their actual efforts towards reducing their emissions from forest degradation. Thus, it is not advisable to approve this approach as an alternative for a robust, reliable, and acceptable MRV system for REDD+.

The second objective of this study was to analyze the sensitivity of estimated emission reductions to different spatial extents of areas where degradation takes place. Therefore, the proportion of degradation areas was varied and set to

10%, 20%, and 50% of the total forest area. It is likely that deforestation takes place on areas that have been previously degraded. Nevertheless, to focus on the impacts of different area sizes where degradation takes place and the uncertainties aligned with the estimation of the emissions from these areas, we assigned the loss of carbon stock per hectare as given in the FRA data for both periods to these specific areas. Deforestation was consequently assigned to areas that are not subject to degradation activities. Thus, we could keep the complexity of the study on a manageable level by avoiding the introduction of too many variables. Approach C was excluded from this part of the study, as it does not qualify as a viable alternative for a REDD+ MRV system.

The results for all three selected countries show that a country's potential to prove the reduction of emissions from degradation depends on the size of the area where forest degradation activities occur (A_{deg}). Using the data of FRA 2010 on the carbon stock change per hectare, it becomes obvious that the larger the degradation areas are the more difficult it gets to verify emission reductions from reduced degradation activities. This is due to the fact that when treating the FRA data from 1990, 2000, and 2010 independently, the influence of the total errors, which are proportional to the carbon stock at the end of both periods, increases, too. Consequently, the effects of a conservative inclusion of the total error for Approaches A and B, as described above, increase with an increasing A_{deg}. This leads to a situation where countries that are successful in the reduction of their emissions from forest degradation from the reference to the assessment period like Brunei (emission reduction = 64.2%) and Pakistan (emission reduction = 62.9%) would be obliged to report less emission reductions for the same error scenarios when A_{deg} increases. This ends up to the point where no emission reductions can be reported at all (see also Appendix A for an exemplary calculation showing this effect). Countries with low degradation activities and less success in reducing their emissions from forest degradation like Cambodia (emission reduction = 24.9%) would be excluded from gaining benefits from REDD+ whenever A_{deg} exceeded values of 10% of the total forest area. For such countries, successfully participating in a REDD+ mechanism is limited by the need to implement a MRV system that reports estimates with very small total errors.

The current study shows several implications concerning the incorporation of uncertainties and the assessment of area sizes of $A_{deg,}$ which need to be considered when designing an MRV system for REDD+. First, the performance in reducing the emissions from forest degradation is decisive on whether a country is in a position to beneficially participate in REDD+ or not. This is confirmed by many other studies (Herold et al. 2008; Grassi et al. 2008; Köhl et al. 2009, Plugge et al. 2012). Second, even a good performance may be outweighed by the total error aligned to estimating the emissions in a conservative way as requested by the Intergovernmental Panel on Climate Change. This corresponds to studies that have been undertaken mainly on the topic of deforestation (Grassi et al. 2008; Köhl et al. 2009; Plugge et al. 2012). Third, the size of the area where forest degradation takes place has an even higher impact on the accountable emission reductions than the conservative estimation of these emissions. This is an important new topic that, to the knowledge of the authors, is not considered elsewhere so far.

It should be kept in mind that the estimation of the area where forest degradation takes place is also confounded by uncertainties. Furthermore, it can be argued that these uncertainties would increase with an increasing size of A_{deg}, especially given a fixed budget for the task of measuring, reporting, and verification. These uncertainties were not included in this study, but conservatively including these uncertainties would lead to the obligation of reporting the upper limit, i.e., a larger A_{deg}. This would consequently result in even lower values of accountable emission reductions. Following the principle of conservativeness as requested by the Intergovernmental Panel on Climate Change, these conservative estimates are a prerequisite for an operational, robust, and transparent MRV system for REDD+.

Conclusion

The presented study deals with one of the major issues for scientists and policy makers regarding the realization of a credible REDD+ mechanism: the setup of an operational, robust, and transparent MRV system. The results of this study lead to three principle conclusions for the implementation of such a MRV system for REDD+.

(1) Given the influence of uncertainties on the estimation of accountable emission reductions, scientists and policy makers that are recently involved in developing a MRV system for REDD+ should clearly define how uncertainties are to be included in national accounting rules. The different options of including uncertainties at two points in time have a pronounced effect on the amount of accountable emissions reductions and thus on the benefits that are achievable through REDD+. Regulations for error propagation between successive periods should be prepared and adopted before the operational launch of REDD+. Especially windfall profits as obtainable from one-sided application of error propagation rules (see Approach C in this study) are to be avoided.

(2) Forest degradation is an intrinsic part of REDD+. The study explicitly showed that the estimation of the area where degradation takes place has a strong influence on the accountable emission reductions. Therefore, measures should be agreed upon that yield a high accuracy for the assessment of degradation areas. The results of this study suggest that a country participating in REDD+ benefits from reporting a lower than actual area of degradation. Gaining false benefits from reducing emissions by underestimating areas subject to degradation can be avoided by applying suitable remote sensing techniques as well as terrestrial assessments.

(3) Forest degradation is a dynamic process that it is likely to take place in areas that are more prone to degradation or are already degraded. Likewise, it is widely acknowledged that areas that are already degraded stand to be completely deforested. In the long run, this results in a spatial shift of areas where forest degradation takes place. It is clear that a MRV system should focus on sampling on successive occasions according to the prerequisites of a CFI. However, a static MRV system would sooner or later lead to estimates with increasing uncertainties due to the fact that it would not be able to adapt to moving and changing spatial patterns of forest degradation. A dynamic system adjusts the sampling design in time and could incorporate the measures of sampling with partial replacement as introduced by Ware and Cunia (1965), Scott (1981), or Scott and Köhl (1994). In-

cluding the dynamics of forest degradation into an operational, robust, and transparent MRV system is therefore inevitable for the setup of a credible REDD+ mechanism.

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Appendix A

Calculation for the estimation of emission reductions on different A_{deg} for the example of Approach A for Brunei and

Table A1. Initial data according to FRA 2010 for Brunei.

Country	A_{t_0} (1000 ha)	A_{t_1} (1000 ha)	A_{t_2} (1000 ha)	C_{t_0} (Tg C)	C_{t_1} (Tg C)	C_{t_2} (Tg C)	C/ha_{t_0} (Mg·ha^{-1})	C/ha_{t_1} (Mg·ha^{-1})	C/ha_{t_2} (Mg·ha^{-1})
Brunei	413	397	380	81	76	72	196.1	191.4	189.5

error levels of 5% for both periods (Table A1). Equations A1–A8 directly correspond to eqs. 1–8 in the main text. Equations A1, A2, and A3 for the carbon stock on $A_{\text{deg},\,t_1}$:

$$[\text{A1}]\quad A_{\text{deg},\,t_1} = A_{t_1} \times p \text{ with } p \in \{0.1, 0.2, 0.5\}$$

$$[\text{A2}]\quad C_{\text{int},\,t_1} = A_{\text{int},\,t_1} \times C/\text{ha}_{t_0} = (A_{t_1} - A_{\text{deg},\,t_1}) \times C/\text{ha}_{t_0}$$

$$[\text{A3}]\quad C_{\text{deg},\,t_1} = C_{t_1} - C_{\text{int},\,t_1} = C_{t_1} - [(A_{t_1} - A_{\text{deg},\,t_1}) \times C/\text{ha}_{t_0}]$$

$$C_{\text{deg},\,t_1} = 76 \text{ Mt C} - \{[397\,000 \text{ ha} - (397\,000 \text{ ha} \times 0.1)] \times 196.1 \text{ t C/ha}\} = 5\,924\,213 \text{ t C}$$

$$C_{\text{deg},\,t_1} = 76 \text{ Mt C} - \{[397\,000 \text{ ha} - (397\,000 \text{ ha} \times 0.2)] \times 196.1 \text{ t C/ha}\} = 13\,710\,412 \text{ t C}$$

$$C_{\text{deg},\,t_1} = 76 \text{ Mt C} - \{[397\,000 \text{ ha} - (397\,000 \text{ ha} \times 0.5)] \times 196.1 \text{ t C/ha}\} = 37\,069\,007 \text{ t C}$$

The result from eq. A3, and eqs. A4, A5, A6, and A7 for the carbon stock on $A_{\text{deg},\,t_2}$:

$$[\text{A4}]\quad \Delta A_{t_1-t_2} = A_{t_1} - A_{t_2}$$

$$[\text{A5}]\quad \Delta C_{\text{def}} = \Delta A_{t_1-t_2} \times C/\text{ha}_{t_0} = [(A_{t_1} - A_{t_2}) \times C/\text{ha}_{t_0}]$$

$$[\text{A6}]\quad \Delta C_{\text{deg}} = \Delta C_{t_1-t_2} - \Delta C_{\text{def}} = \{(C_{t_1} - C_{t_2}) - [(A_{t_1} - A_{t_2}) \times C/ha_{t_0}]\}$$

$$[\text{A7}]\quad C_{\text{deg},\,t_2} = C_{\text{deg},\,t_1} - \Delta C_{\text{deg}} = C_{\text{deg},\,t_1} - \{(C_{t_1} - C_{t_2}) - [(A_{t_1} - A_{t_2}) \times C/\text{ha}_{t_0}]\}$$

$$C_{\text{deg},\,t_2} = 5\,924\,213 \text{ t C} - \{(76 \text{ Mt C} - 72 \text{ Mt C}) - [(397\,000 \text{ ha} - 380\,000 \text{ ha}) \times 196.1 \text{ t/ha}]\} = 5\,258\,354 \text{ t C}$$

$$C_{\text{deg},\,t_2} = 13\,710\,412 \text{ t C} - \{(76 \text{ Mt C} - 72 \text{ Mt C}) - [(397\,000 \text{ ha} - 380\,000 \text{ ha}) \times 196.1 \text{ t/ha}]\} = 12\,964\,820 \text{ t C}$$

$$C_{\text{deg},\,t_2} = 37\,069\,007 \text{ t C} - \{(76 \text{ Mt C} - 72 \text{ Mt C}) - [(397\,000 \text{ ha} - 380\,000 \text{ ha}) \times 196.1 \text{ t/ha}]\} = 36\,323\,415 \text{ t C}$$

Estimating the emissions from different A_{deg} on the example of Approach A and $\varepsilon_{t_1} = 5\%$ and $\varepsilon_{t_2} = 5\%$ to analyze the influence of the area size and the total error on the estimate:

$$[\text{A8}]\quad \text{Approach A}: \Delta C_{\text{deg},\,t_1-t_2} = C_{\text{deg},\,t_1}(1 + \varepsilon_{t_1}) - C_{\text{deg},\,t_2}(1 - \varepsilon_{t_2})$$

$$\Delta C_{\text{deg},\,t_1-t_2} = (5\,924\,213 \text{ t C} \times 1.05) - (5\,258\,354 \text{ t C} \times 0.95) = 1\,224\,998 \text{ t C}$$

$$\Delta C_{\text{deg},\,t_1-t_2} = (13\,710\,412 \text{ t C} \times 1.05) - (12\,964\,820 \text{ t C} \times 0.95) = 2\,079\,354 \text{ t C}$$

$$\Delta C_{\text{deg},\,t_1-t_2} = (37\,069\,007 \text{ t C} \times 1.05) - (36\,323\,415 \text{ t C} \times 0.95) = 4\,415\,213 \text{ t C}$$

Calculating the baseline ΔC_{BL} (adapted from Köhl et al. 2009):

$$\Delta C_{\text{BL}} = C_{\text{deg},\,t_0} - C_{\text{deg},\,t_1} = (A_{\text{deg},\,t_1} \times C/\text{ha}_{t_0}) - C_{\text{deg},\,t_1}$$

$$\Delta C_{\text{BL}} = [(397\,000 \text{ ha} \times 0.1) \times 196.1 \text{ t C/ha}] - 5\,924\,213 \text{ t C} = 1\,861\,985 \text{ t C}$$

$$\Delta C_{\text{BL}} = [(397\,000 \text{ ha} \times 0.2) \times 196.1 \text{ t C/ha}] - 13\,710\,412 \text{ t C} = 1\,861\,985 \text{ t C}$$

$$\Delta C_{\text{BL}} = [(397\,000 \text{ ha} \times 0.5) \times 196.1 \text{ t C/ha}] - 37\,069\,007 \text{ t C} = 1\,861\,985 \text{ t C}$$

Estimating the accountable emission reduction, ΔC_{REDD} (adapted from Köhl et al. 2009) (positive values signify emission reductions):

$$\Delta C_{\text{REDD}} = \Delta_{\text{BL}} - \Delta C_{\text{deg},\,t_1-t_2}$$

$$\Delta C_{\text{REDD}} = 1\,861\,985 \text{ t C} - 1\,224\,988 \text{ t C} = 636\,998 \text{ t C}$$

$$\Delta C_{\text{REDD}} = 1\,861\,985 \text{ t C} - 2\,079\,354 \text{ t C} = -217\,368 \text{ t C}$$

$$\Delta C_{\text{REDD}} = 1\,861\,985 \text{ t C} - 4\,415\,213 \text{ t C} = -2\,553\,228 \text{ t C}$$

Reference

Köhl, M., Baldauf, T., Plugge, D., and Krug, J. 2009. Reduced emissions from deforestation and forest degradation (REDD): a climate change mitigation strategy on a critical track. Carbon Balance Manage. **4**(10). doi:10.1186/1750-0680-4-10. PMID: 19909557.

Personal contribution:

The presented scientific articles that, together with the comprehensive summary, constitute this cumulative dissertation reflect a substantial part of my scientific research. They were selected under the premise that a high personal contribution is given. This is reflected formally by the lead-authorship for all presented articles. This includes the development of methodologies and statistical backgrounds for the articles, the writing and submission as well as the responsibility for the review process of each article and the physical conduction of terrestrial inventories for the first article. However, the contributions of the co-authors of the articles shall not be questioned.

Further research articles are listed in Annex II.

None of the scientific articles presented here have been or are currently part of another cumulative dissertation.

Annex II
List of further publications

Baldauf, T., Plugge, D., Rqibate, A., Köhl, M. 2009. Case studies on measuring and assessing forest degradation. Monitoring degradation in the scope of REDD. FAO, Rome. Forest Resources Assessment Working Paper, 162.

Baldauf, T., Plugge, D., Rqibate, A., Leischner, B., Dieter, M., Köhl, M. 2010. Development of a holistic methodology for implementing a REDD-Scheme at the example of Madagascar. Institute for World Forestry; Institute of Forest Based Sector Economics, Hamburg. Work Report.

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Kuntz, S., Poncet, F. von, Baldauf, T., Plugge, D., Kenter, B., Köhl, M., 2011. A multi-stage inventory scheme for REDD inventories in tropical countries. In: International Society for Photogrammetry and Remote Sensing (Ed.), Proceedings of 34th International Symposium for Remote Sensing of the Environment. The GEOSS Era: Towards Operational Environmental Monitoring.

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