Climate change mitigation through forest management, afforestation and avoided deforestation – analysis of accounting approaches

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I Susan J. Ortloff certify that the English of the cumulative dissertation "Climate change mitigation through forest management, afforestation and avoided deforestation – analysis of accounting approaches" written by Margret Köthke from the Thünen Institute of International Forestry and Forest Economics (TI-WF) has been reviewed and is correct."

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    - Prof. Dr. F.H. Schweingruber, *Trees and Wood in Dendrochronology*, Springer-Verlag .
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    - 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.
    - Daniel Plugge, *Capabilities and deficiencies of terrestrial forest inventory systems in the assessment of forest degradation in the scope of REDD+,* Dissertation Summary, University of Hamburg, Institute for World Forestry.
    - Thomas Baldauf , *Monitoring reduced emissions from deforestation and forest degradation (REDD+): capabilities of high-resolution active remote sensing*, Dissertation, University of Hamburg, Institute for World Forestry.

Susan J. Ortloff ______________________ December 28, 2013

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Summary

The United Nations acknowledged the important role of forest ecosystems in the context of climate change by addressing the source and sink functions of forests in the United Nations Framework Convention on Climate Change (UNFCCC). The aim of including climate change objectives within the UNFCCC was, on the one hand, to reduce current and expected emissions from forest ecosystems, mainly due to deforestation and forest degradation and, on the other hand, to incentivise the conservation and enhancement of existing forest carbon stock, e.g., through forest conservation, sustainable forest management, afforestation and reforestation. The reporting and accounting of carbon emissions and removals from the so-called land use, land-use change and forestry sector (LULUCF) was included in a binding policy framework under the Kyoto Protocol for industrialised countries. Detailed rules for reporting and accounting were implemented, which have undergone amendments since the first commitment period.

For developing countries the adoption and implementation of a corresponding system is still in progress. The so-called REDD+ system ('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') is currently in preparation under the UNFCCC. This system aims to incentivise developing countries to implement forest-based climate change mitigation options, with a results-based financing by industrialised countries. The design of a detailed financing, monitoring, reporting and accounting framework is currently being worked out, which for developing countries is loaded with additional difficulties, given the lack of capacity and experience, insufficient data availability and weak monitoring systems.

To guarantee global climate effectiveness, the entire forest-based climate change mitigation approach under the UNFCCC needs to be consistent. This means avoiding gaps, which could produce leakage, and insuring incentives are effective and properly aligned. These self-evident requirements are, however, not self-evidently inherent to a politicised system of such dimension and complexity. This thematic context of 'global climate change and the role of forest ecosystems' and of the 'political agreements to fight climate change' in industrialised and developing countries is introduced in the first part of the comprehensive summary of this cumulative dissertation. The underlying object of carbon accounting in the forest-related LULUCF sector are the natural and human-induced 'forest dynamics of carbon uptake and release through forest growth, forest management and forest cover change', which are summarised in the second Chapter. The details of 'the political design for accounting of carbon uptake and release by forests' are explained in the third part of the thematic context. Here the similarities and differences between the existing and envisaged accounting approaches between different land-use categories and mitigation activities and between industrialised and developing countries are addressed. Special attention is given to the implied incentive effect of different accounting options and the role of reference levels.

The design and implications of different accounting approaches for the mitigation activities of forest management, afforestation and avoided deforestation are analysed by three scientific articles presented in the second part of the comprehensive summary. The first article analyses the incentive effect of different sub-national carbon accounting approaches for afforestations and forest management in industrialised countries by analysing the interactions of different carbon and timber prices and interest rates. The results show that additional carbon crediting, passed down directly to the forest owner, increases the optimal rotation period when carbon prices outperform timber prices. When harvests are immediately charged with debits (without including the harvested wood products' intrinsic carbon stock), harvesting becomes uneconomic at a given price level.

The second article addresses the land-use change activity of deforestation by analysing national patterns of forest cover development on a global scale. For globally consistent accounting of land-use changes a quantifiably comparable forest cover development among the countries would facilitate a standardised approach for the accounting of land-use changes. The study, therefore, analyses recent data from developing countries and historic data from industrialised countries in a multi-national regression model. Regularities in the influence of certain drivers of deforestation on the forest cover decline could be detected and empirically quantified for 140 countries. The resulting global deforestation curve was included as a method for determining reference levels for a potential future REDD+ mechanism proposed in the third article. The third study applies national data of deforesting developing countries for the prediction of a business as usual forest cover development for REDD+ reference levels. The application of this uniform global deforestation curve for a REDD+ reference level approach provides the advantage of the consideration of individual national circumstances standardised by a uniform methodology. The three articles are each summarised briefly, stating the personal contribution, and their results are discussed in the thematic context described in the first part of the comprehensive summary.

In the final conclusions the relevance of the results of the three articles for the overall thematic context is described. The results show which major implications politically designed carbon accounting rules have on the incentive effect, and thereby on the effectiveness of climate change mitigation options. The accounting approaches have to be carefully designed and matched with each other to avoid false incentives or incentive gaps. The results also show that on the operational level competing interests may outweigh the incentives. Furthermore, the feasibility of consistent carbon accounting is discussed and the connections and similarities of the different existing approaches are depicted. The transferability of the different accounting approaches, between the various activities addressed and between industrialised and developing countries, but also the empirical quantification of a comparable forest cover development between different countries, encourages the implementation of consistent carbon accounting. Stepwise approaches are, however, needed to overcome existing data and capacity gaps. The complete versions of the three individual articles are included in the Appendix, as well as a list of further publications.

Abbreviations

AAU	– Assigned Amount Unit
ARD	– afforestation, reforestation, deforestation
BAU	– business as usual
C	– carbon
CDM	– Clean Development Mechanism
COP	– Conference of the Parties to the UNFCCC
CP	– commitment period
EU	– European Union
FAO	– Food and Agriculture Organization of the United Nations
FMRL	– forest management reference level
IPCC	– Intergovernmental Panel on Climate Change
JI	– Joint Implementation
KP	– Kyoto Protocol
LULUCF	– land use, land-use change and forestry
MAI	– mean annual increment
REDD+	– 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
REL	– reference emission level
RL	– reference level
SBSTA	– Subsidiary Body for Scientific and Technological Advice
UNDP	– United Nations Development Programme
UNEP	– United Nations Environment Programme
UNFCCC	– United Nations Framework Convention on Climate Change

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Part I: Thematic context

1. Introduction

1.1. Global climate change and the role of forest ecosystems

Climate change is observed in an increase in average global air and ocean temperatures, reduced snow and ice cover, sea level rise and extreme weather events, and is feared to have unforeseeable consequences for life on Earth (IPCC, 2007b). In 2007 the 4^{th} Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reported an average rise in global temperature since the late 1800s of 0.74 degrees Celsius and projected a further increase in the future. The temperature rise is attributed to higher levels of the greenhouse gas (GHG) concentration in the atmosphere since the industrial revolution (IPCC, 2007a).

Terrestrial ecosystems play a major role in the global carbon (C) cycle. Especially forest ecosystems are a significant global carbon stock (638 Gt C in 2005, with 44 % in biomass, 6 % in deadwood and 50 % in soils [top 30 cm] and litter) and have a major impact on the gross terrestrial carbon uptake through biomass growth (annual removal from the atmosphere estimated to be about 2.6 Gt C in the 1990s) (FAO, 2006, Ch. 2, p. 34-35; IPCC, 2007b).

Humans influence ecosystems through management and through land use conversions. They thereby affect the carbon stocks of ecosystem pools and the fluxes between ecosystems and the atmosphere. Major influence on global greenhouse gas emissions by sources and removals by sinks in the 1990s are attributed to tropical deforestation and forest re-growth in the boreal and temperate zones (IPCC, 2007a). Approximately 13 million hectares were deforested annually in the period 1990–2010 (FAO, 2010), resulting in about 1.58 Gt C emissions per year (IPCC, 2007a).

Terrestrial ecosystems provide several climate change mitigation options, especially from forest-related activities through both the increase of removals (carbon uptake from the atmosphere) and the reduction of emissions (IPCC, 2007a). The halt of deforestation is expected to have the largest and most immediate carbon stock impact in the short term according to the IPCC (IPCC, 2007a). Moreover, mitigation options related to land use, land-use changes and forestry (LULUCF) are expected to be most cost effective (Stern, 2006).

Forest-based mitigation options are the reduction of emissions from deforestation and forest degradation, the enhancement of the sequestration rate by new forests and in existing forests, the increase of the harvested wood products pool, the use of wood fuels as fossil fuel substitutes and the use of wood products as energy-intensive material substitutes (IPCC, 2007a).

1.2. Political agreements to fight climate change

The United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992 at the Rio Earth Summit and entered into force in 1994. It is an international treaty aimed at encouraging common action in the fight against human-induced climate change (UN, 1992). The ultimate objective of the Convention is to stabilize the greenhouse gas concentration in the atmosphere. To this end “dangerous anthropogenic interferences with the climate system” should be prevented (UN, 1992, Art.2). A maximum level of global temperature increase of below 2 degrees Celsius from pre-industrial levels was agreed to by the Parties to the Convention (decided in 2010 at the 15^{th} Conference of the Parties to the UNFCCC (COP15) in Copenhagen). A need for a worldwide reduction of anthropogenic greenhouse gas emissions was recognised. This covers “all relevant sources, sinks and reservoirs of greenhouse gases”, including emissions and removals from terrestrial ecosystems (termed the ‘land use, land-use change and forestry’ sector, LULUCF) (UN, 1992, Art. 4).

The Convention was operationalised by the Kyoto Protocol to the Convention (KP), which sets legally binding targets for emission reduction for industrialised countries (UN, 1998). The Kyoto Protocol was adopted in 1997 at the COP3, but only went into force in 2005 when all requirements for ratification were fulfilled, i.e., the ratification of at least 55 parties to the UNFCCC, incorporating parties included in Annex I with together at least 55 percent of the total CO_2 emissions for 1990 of the Annex I parties (UN, 1998, § 25). The rules for the implementation of the Kyoto Protocol were set in the 2001 Marrakesh Accords (at the COP7, UNFCCC, 2002).

The scope and commitment (signature and ratification) of international treaties is subject to national sovereignty. Currently there are 195 Parties to the Convention of which 192 are also Parties to the Kyoto Protocol (UNFCCC, 1992/2013), among them the European Union (EU). The United States of America signed the Kyoto Protocol, but did not ratify it and therefore has no legally binding emission reduction target. Canada withdrew from the Kyoto Protocol in 2011 (UNFCCC, 1992/2013).

The Convention and Kyoto Protocol follow the system of “common but differentiated responsibilities” (UN, 1992), focusing on action and financing by industrialised countries. Hence, different commitments and rules apply for industrialised and developing countries (termed Annex I and Non-Annex I parties to the UNFCCC respectively) (see UNFCCC, 1992/2013, for definition and party lists).

Rules for industrialised countries (Annex I parties)

Annex I parties to the UNFCCC are mainly industrialised countries (UNFCCC, 2011f). These countries are required to submit annual greenhouse gas inventories to the UNFCCC secretariat according to the guidelines of the IPCC (1997) and report regularly on policies and measures taken to reduce emissions in the national communications.

Legally binding emission reduction targets were agreed upon by Annex I parties listed in Annex B to the Kyoto Protocol (UN, 1998, Annex B). In the first commitment period (1st CP) of the Kyoto Protocol 2008-2012 37[1] Annex I countries and the EU have committed themselves to a reduction target of -5 % emissions compared to the base year of 1990 (UN, 1998, Art.3). Germany agreed to a national target of -21 % of emissions against 1990 (which was agreed in the burden sharing agreement within the EU). A continuation of the Kyoto Protocol by a second commitment period (2nd CP) was prepared at the COP17 in Durban in 2011 (UNFCCC, 2012b). The respective amendments to the Kyoto Protocol with reduction targets for the 2nd CP 2013-2020 were adopted at the COP18 in Doha in 2012, and will enter into force after acceptance by at least three fourths of the Parties to the Kyoto Protocol (IISD, 2012; UNFCCC, 2013b, Dec. 1/CMP.8).

The Kyoto Protocol's emission reduction commitments were made on the national level (except for the EU). Each Annex I party is assigned an individual amount of emission allowances to emit greenhouse gases in the commitment period. The assigned amount of emission allowances is calculated by subtracting the parties' national reduction targets from the parties' emissions in the base year. One Assigned Amount Unit (AAU) is equal to 1 metric tonne of CO_2-equivalent. Not to exceed the assigned amount of emission allowances, emission reduction must be conducted mainly by domestic action. Additionally, further cost effective options for emission reduction are created through three flexible market-based mechanisms of the Kyoto Protocol: Emissions trading, Clean Development Mechanism (CDM) and Joint Implementation (JI).

The idea of emissions trading is that AAUs can be traded (sold or bought) on the "carbon market" between the countries and emission reduction takes place where it is most cost effective. National or regional level emissions trading schemes are possible (UN, 1998, Art. 17). Today the European Union's Emissions Trading System (EU ETS) is the largest operating trading scheme.

Emission reduction projects in other countries can be conducted through the flexible market mechanisms of CDM and JI. By the flexible market mechanisms certain types of "credits" can be generated which can be used to meet the national emission reduction targets. Under the CDM

[1] Four countries joined in later and one withdrew.

Annex I parties can generate credits (called Certified Emission Reductions, CERs) through emission reduction projects in Non-Annex I parties (UN, 1998, Art. 12). Under the JI mechanism Annex I parties can generate credits (called Emission Reduction Units, ERUs) in other Annex I parties (UN, 1998, Art. 6). Under CDM and JI the forest-related activities of afforestation (A) on lands that have not been forests before and reforestation (R) by replanting of forests on former forest land are eligible.

The LULUCF sector was defined for the accounting of emissions from terrestrial ecosystems in Annex I parties. LULUCF emission accounting is completely different from the accounting of fossil fuel emissions, which are occurring in the other sectors. Not only emissions occur from the LULUCF sector, e.g., by management and land-use changes, but also carbon is removed from the atmosphere through biomass growth (further details will be given in Chapter 2). Additionally, the biospheric carbon exchange is reversible (i.e., once sequestered carbon can be emitted later) and activities often have long-term effects. In contrast, emissions from fossil fuels have an immediate and irreversible effect. Permanent fluxes of growth and decay take place in terrestrial ecosystems which are out of human control and are potentiated by greater natural disturbances (like forest fires). Because of those uncertainties, special rules were introduced for the accounting of emissions and removals from this sector (discussed in Höhne et al., 2007; Kirschbaum and Cowie, 2004).

Base year emissions and removals from the LULUCF sector are not included in the emission reduction target, but they can offset the assigned amount of emission allowances ex-post to a certain extent. Through LULUCF activities credits called Removal Units (RMUs) can be generated. Their accounting however is limited ("capped").

Forests (included in the LULUCF sector) are regulated by Kyoto Protocol Article 3.3 and 3.4. Annex I parties must report annually on LULUCF activities and resulting emissions and removals in the commitment period according to the Good Practice Guidance on LULUCF (IPCC, 2003). Those reports are needed for accounting of eligible emissions and removals under the Kyoto Protocol.

Under Kyoto Protocol Art. 3.3 the accounting of emissions and removals from afforestation, reforestation and deforestation (ARD) is mandatory. Net changes in emissions and removals from those land-use changes since 1990 can offset part of the assigned emission allowances.

The accounting of emissions and removals from forest management (FM) on existing forest land within the commitment period is regulated by Kyoto Protocol Art. 3.4. In the 1st CP countries voluntarily elected for accounting of this activity, in the 2nd CP it will become mandatory.

While the complete net emissions from forest management can offset the assigned emission allowances, the accounting of net removals is limited. Net removals from forest management can offset net emissions occurring from Kyoto Protocol Art. 3.3 activities (ARD) up to 9 Mt C. Beyond this, further net removals occurring from Art. 3.4 activities can offset the emission allowances up to a fixed country-specific cap (UNFCCC, 2006b, Appendix to Dec. 16/CMP1). The eligible amount of credits is thereby limited to 15 % of net removals from forest management or 3 % of the base year emissions, whichever is lower (for Germany this resulted in a cap of 1.24 Mt C/ year in the 1st CP). Further details on the LULUCF accounting rules will be given in Chapter 3.

The LULUCF accounting rules from the 1st CP have been widely criticised because of their complexity, insufficiency of the incentives given (caused by the restrictive cap) and lack of guarantee for the required additionality of the efforts taken (Ellison et al., 2011; Ellison et al., 2013; Grassi et al., 2012). Therefore new accounting rules for the 2nd CP were adopted at the COP17 in Durban in 2011 (Grassi, 2012; UNFCCC, 2012b, Dec. 2/CMP.7). The main changes are that forest management accounting will become mandatory in the 2nd CP and will be compared to a country-specific forest management reference level (FMRL). Instead of the fixed cap on credits from forest management, a cap of 3.5 % of base year emissions will be put on credits. Additionally, harvested wood products (HWP) will be included in the accounting as an additional carbon pool (see Grassi, 2012; UNFCCC, 2011c, Dec. 2/CMP6; 2012b).

All these commitments and incentives are effective on the national level only. Each state is responsible for all emissions and removals occurring from the forest sector in its country. The state therefore carries the load of debits and takes the benefit of credits. On a sub-national level the forest enterprises and forest owners were neither fined nor benefited from the international commitments, which provide no direct incentives on the sub-national level. However, it is up to each state to implement domestic incentive measures to influence the development of emissions and removals from the national forest sector. The same holds for a possible distribution of benefits on the sub-national level in the case of net removals (credits) for the state. Different options for the countries are given to manage domestic actions by the implementation of policy instruments for distribution of benefits or for incentivising forest-based mitigation actions, e.g., by performance oriented subsidies (Elsasser, 2008; Elsasser and Dieter, 2006). Economic incentives for forest-based mitigation actions might increase the carbon sequestration service influenced by the forest owners, which in turn will be credited for the state at the national level. The incentive effect of potential sub-national mitigation instruments is analysed and discussed in the first article of this cumulative dissertation (see Part II).

In Germany such a distribution of benefits to the forest owners or incentives for increased carbon sequestration was not implemented in the 1st CP. In 2013 a fund for forests and climate ("Waldklimafonds") was introduced with an initial financial volume of 34 Mio. € until 2019 (BMELV and BMU, 2013a). It is envisaged to also support adaptation and mitigation measures from the forest. Appropriate projects can be funded upon application (BMELV and BMU, 2013b). However, no comprehensive benefit-sharing or setting of incentives for forest-related mitigation activities is given.

Rules for developing countries (Non-Annex I parties)

The Non-Annex I parties to the UNFCCC are mostly developing countries. Currently these include 154 countries, which signed the Convention and therefore have a reporting requirement on adaptation and mitigation measures taken (although less frequently than Annex I parties) but they have no legally binding emission reduction targets under the Kyoto Protocol.

Part of the 'common but differentiated responsibility' is the support of developing countries by industrialised countries. The latter agreed by signing the Convention and Kyoto Protocol in the provision of additional financial support for climate change activities in developing countries. Part of this is done by the CDM, which is assigned to the emission accounting of Annex I parties (though this is not relevant for the climate impact). CDM is, furthermore, only project based and does not cover the national carbon balance of the developing countries.

The COP11 in Montreal in 2005 introduced an interim compensation mechanism for reducing emissions from deforestation in developing countries (first called 'RED') in the UNFCCC (UNFCCC, 2005). Initially this mechanism focused on the avoidance of deforestation, and has been broadly discussed and extended since its introduction. It, however, has not yet come to a binding agreement (see discussion on the evolution of the REDD+ mechanism by Pistorius, 2012). The COP15 in Copenhagen in 2009 extended the original RED discourse to the currently termed 'REDD+' mechanism. REDD+ is the acronym 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" (UNFCCC, 2008, 2010).
The purpose of REDD+ is to create a financing and incentivising mechanism for developing countries that facilitates their voluntary commitment to forest-related emission reduction in their countries. REDD+ maintains that action taken by developing countries toward reducing emissions from defined forest-related activities should be financed by industrialised countries. To guarantee environmental effectiveness and avoid international leakage, it will be necessary to have as many developing countries as possible committed to participating in the mechanism (Angelsen, 2008).

Activities that will be eligible by the REDD+ mechanism are:
(a) Reducing emissions from deforestation;
(b) Reducing emissions from forest degradation;
(c) Conservation of forest carbon stocks;
(d) Sustainable management of forests;
(e) Enhancement of forest carbon stocks (UNFCCC, 2011a, III.70).

Still on the ongoing REDD+ agenda of the climate negotiations and related working groups (SBSTA - Subsidiary Body for Scientific and Technological Advice) are issues regarding financing, measurement, reporting and verification (MRV), national forest monitoring systems (NFMS), safeguards and reference emission levels/reference revels (RELs/RLs) (UNFCCC, 2007, 2009, 2011e, 2013c). However, in the context of REDD+ these issues are still evolving. At the latest COP19 in Warsaw in 2013 methodological and technical guidelines for REDD+ were adopted (IISD, 2013). Small-scale pilot projects and supportive initiatives for capacity building already began making developing countries “ready for REDD” (e.g., the UN-REDD programme of the FAO, UNDP and UNEP and the Forest Carbon Partnership Facility of the World Bank) (see Angelsen et al., 2009, Part 5).

The planned support and crediting of the REDD+ activities requires the definition of benchmark emissions and activities and of the eligible activities and removals beyond. Therefore, so-called reference emission levels/reference revels (RELs/RLs) were introduced to benchmark the “allowed” emissions from the forest sector. The aim is to be able to compare emissions that occur in a commitment period to those pre-determined benchmark emissions. Thus, the countries’ performances in reducing emissions in comparison to business as usual (BAU) behaviour (defined by the RELs/RLs) can be quantified and credited (Angelsen et al., 2011a, 2011b; UNFCCC, 2012a, Dec. 12/CP.17).
In the UNFCCC terminology the expression of “reference emission level and reference revel (REL/RL)” is used in conjunction, however, the definition and application are still inexplicit. RELs shall benchmark the gross emission development from the source activities a) and b) (i.e., deforestation and degradation). RLs shall benchmark the net emissions from all five REDD+ activities (including the activities c), d) and e)) (UNFCCC, 2011d). Subsequently, the term reference level will be used for any potential benchmark.

The aim of reference levels is twofold, namely to benchmark BAU emissions and to benchmark the emission reductions eligible for crediting. In the political and scientific context, the definition of national business as usual reference levels (BAU RLs) remains under discussion. They should show the development of emissions in the commitment period without incentives by a REDD+ mechanism and without additional action taken to reduce emissions. While this BAU benchmark shall differentiate the BAU emissions and any development (increase or decline of emissions) in a commitment period relative to the benchmark, it is not automatically equal to a benchmark for crediting. The accounting rules for crediting eligible emission reductions could differ from a mere BAU reference level and, e.g., be determined by an additional crediting reference level. From a scientific point of view it is important to distinguish which purpose a reference level is following, although this is not explicitly differentiated in the UNFCCC documents. A crediting reference level (or the adjustment of a BAU reference level for crediting) is a matter of political negotiation. For example, it is politically decided that the reduction of emissions shall be credited by the REDD+ mechanism, but the increase of emissions shall not be debited. Such a decision for crediting is independent from a BAU RL. To guarantee global additionality of the overall emission reductions, however, a crediting reference level should be equal or below a BAU reference level (Angelsen et al., 2011b; UNFCCC, 2009).

The international REDD+ mechanism is not yet in force and only rough guidelines have been agreed for reference level setting (Angelsen et al., 2012, Ch. 16; UNFCCC, 2012a, Dec. 12/CP.17). In 2007 it was decided at the COP13 that emission reduction under REDD+ shall be assessed by the consideration of historic emissions and national circumstances (UNFCCC, 2008, Dec.2/CP.13). The developing countries are invited to voluntarily submit reference levels for their countries. If they do so, they must transparently provide information on data and definitions applied. They may also adjust their reference levels for national circumstances and report which and how they were considered. Submitted data and reference levels shall undergo a technical assessment afterwards (UNFCCC, 2012a, Dec. 12/CP.17). Furthermore, it is determined that REDD+ should become binding on the national level, also interim sub-national and stepwise approaches are possible. So far the local-level pilot projects applied sub-national reference levels comparable to project-level baselines under CDM. For an international REDD+ mechanism in the long term, however, national reference levels are needed (UNFCCC, 2011e, 9.-11.). Several proposals for reference level methodologies have been made by governments, scientists and politicians in the past years but none of them had been implemented so far (see Köthke et al., 2013; submitted, for discussion on reference level proposals). A reference level approach for REDD+, which takes into account national circumstances uniformly is proposed and discussed in the third article of this cumulative dissertation. The approach, thereby, refers to an empirical basis, which has been analysed in the second article (see Part II). Further information on the need for reference levels and the difficulties in setting them are given in Chapter 3.

2. Forest dynamics: carbon uptake and release through forest growth, forest management and forest cover change

Forests play an important role in the global carbon cycle through natural and human-induced forest dynamics, initially taking place independent of any political accounting. To cover all emissions and removals from the forest sector in carbon accounting and to incentivise forest-related mitigation activities, the knowledge of forest dynamics is essential. The forest dynamics relevant for the carbon cycle will be briefly summarised in the following Chapter.

2.1. Biomass growth and decay

Trees (as all photoautotrophic organisms) carry the ability of carbon assimilation from atmospheric CO_2 through photosynthesis. Thereby above and below ground organic biomass (carbohydrates) is synthesised (net primary production) (Bresinsky et al., 2008; Kramer et al., 1988). The sequestered carbon is stored in the biomass until decay or combustion. Decay occurs for instance in the periodic life cycle of leaves or as a consequence of natural mortality of branches or entire trees, due to competition, ageing or calamities. Different decay rates apply for different tree compartments which are also determined by the species, stand and site conditions. Part of the carbon released from the decaying biomass is transferred to the soil carbon pool, while part is released back into the atmosphere (Köhl et al., 2008; Malhi et al., 1999).

In an untouched forest ecosystem, trees of all ages are represented and the growth and decay processes within the forest are balanced. As older trees die, new trees receive enough light to grow. Therefore the carbon stock of the unmanaged forest is almost constant. An equal balance is given between re-growth and harvest in a managed continuous forest. The speed of tree growth and the maximum potential for carbon sequestration are reliant on the tree species, site characteristics (e.g., soil, water, climate conditions), stand composition (e.g., species composition and density) and management.

The balanced carbon stocks of unmanaged forests differ from the dynamics found in managed even-aged forests. In managed even-aged forest stands the rotation cycles of forest growth and harvesting repeat. The growth function of an even-aged forest stand over the stand's age is schematically displayed in Figure 1. The total increment (*yield*) shows the gross biomass increment over a stand age and is, therefore, linked to the gross carbon uptake. It is not equal to the remaining carbon stock of the standing forest because dead or harvested trees have not been distinguished in this accumulated figure. The current annual increment (*CAI*) shows the annual biomass growth which is dependent on the age of the forest stand. The increment increases in the younger stands and slows down in the older stands. The speed of increase and time of climax differ for species and sites as mentioned above. The mean annual increment (*MAI*) is the annual increment divided by the stand age. The time of maximum MAI is also called the biological optimum rotation age, or maximum sustainable yield in terms of volume, which is the time of maximum sustainable carbon uptake as well. Harvesting and replanting forest stands exactly at the time of the maximum MAI would result in the highest biomass production in the long term (Gadow, 2003).

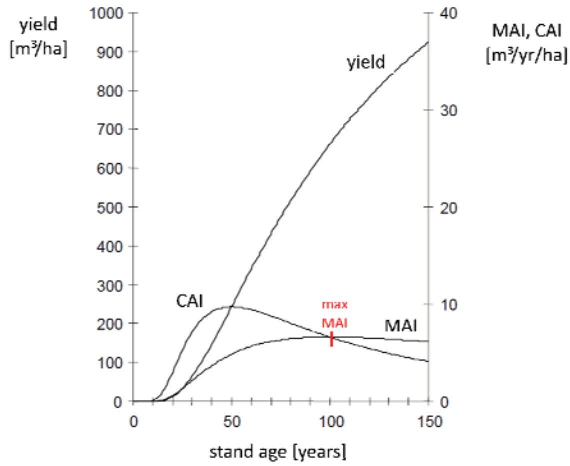

Figure 1: Total forest increment (yield), current annual increment (CAI) and mean annual increment (MAI) over the stand age of the forest (adopted and modified from Gadow, 2003, p. 156).

2.2. Forest management and carbon stock changes in the standing forest

Forest management for timber production usually applies different rotation periods than the time of maximum MAI, because timber qualities and related prices are not only mass oriented. Shorter rotation periods are often applied because the increment in value competes with the interest on current stand and land value. When the rotation periods are shorter than the time of maximum MAI, the full potential of maximum sustainable yield on the forest site is not fully tapped. In reverse, keeping the carbon stock of the standing forest longer than the time of maximum MAI, e.g., by not harvesting the stand at all or by applying long rotation periods, will also lead to reduced increment of tree biomass on the site. Left unharvested the carbon will remain stored in the biomass of the standing forest (balanced by re-growth and natural mortality), but the sink function (additional carbon uptake) will be saturated in the long term. Natural mortality and slow increment will reach an equilibrium stage in an untouched forest, although discussion on time and level of saturation is controversial (see IPCC, 2000; Köhl et al., 2009; Nabuurs et al., 2013). The average carbon stock of the standing forest, however, is higher in an untouched forest compared to a stand with regular forest management interventions (thinning and harvesting). See Figure 2 for schematic comparison of carbon stock levels in managed forests with different rotation periods and in an unmanaged forest.

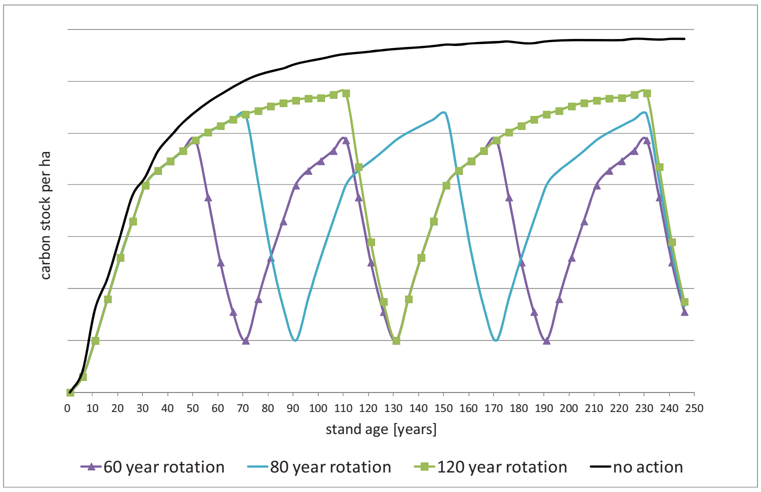

Figure 2: Carbon stock in the standing forest per ha with different rotation periods and without management (schematic illustration).

While in a forest on one single forest parcel the carbon stock onsite will increase and decrease periodically (see Figure 2), on a larger scale with multiple forest stands, the pattern averages out. This balance is idealised by the model of a fully regulated normal forest ("Normalwaldmodel") which is run under regular harvesting operations (Speidel, 1967). In a fully regulated normal forest even-aged forest stands are distributed to evenly sized parcels and each vintage is represented on one parcel of the model's forest area. The number of stands equals the rotation age. Each year one parcel reaches maturity, is harvested and replanted again. Thereby within the normal forest, the average carbon stock remains constant each year, along with the annual increment and the annual harvest volume.

Although this idealised model will not be found as such in practice, it can be used to demonstrate the principle of sustainable forest management and carbon cycles. A constant carbon stock in the standing forest is given and combined with a permanent increment and regular harvest volume.

The carbon cycle will be influenced by management changes such as altered rotation periods, thinning practices or tree species composition (Köhl et al., 2010). Different management practices influence quantities of dead wood and harvesting residues as well as soil carbon, but they are not discussed here in further detail (see Köhl et al., 2009).

The equally distributed vintages described for the normal forest are usually not present on a larger scale. For instance, in Germany the age class distribution over the whole forest area is uneven due to large-scale afforestations after the Second World War (Oehmichen et al., 2011). This means that even without any change in forest area and forest management practices, the carbon stock of the standing German forest will decrease (and be a source of carbon) and increase (be a carbon sink) over time depending on the respective weight of older or younger stands (Krug et al., 2009). However, a long-term average carbon stock is also given for uneven-aged forest areas when the time frame considered is long enough.

In addition to management interventions, the carbon stock of the standing forest is influenced by climate changes and natural events which might lead to increased or decreased increment as well as to sudden and large-scale forest losses.
Sustainable forest management as described above, however, shall not be confused with forest degradation, which cannot be considered a management practice in an intact forest ecosystem. Rehabilitation measures are needed to increase the carbon stock on degraded forest land.

2.3. Forest management, harvested wood products and substitution

Forest management affects the carbon stock of the standing forest (as described above) and additionally produces harvest volume. The carbon sequestered in the living biomass remains stored in the harvested wood until it decays or combusts and thus extends the carbon cycle beyond the standing forest. The carbon stock of harvested wood is not a sink per se, but is a stock which keeps carbon from being emitted to the atmosphere. The increase or decrease of this stock, however, is a sink or a source, comparable to the carbon stock changes of the standing forest. The time of carbon storage in the harvested wood products depends on the various products' lifetimes (Rüter, 2011). Residues from harvest operations and wood production naturally decay or combust and thereby release the stored carbon back into the atmosphere earlier than most wood products.

Additionally, the use of wood products can potentially substitute other more energy intensive materials. The effect of material substitution depends on the single materials and quantities substituted. A substitution factor compares the greenhouse gas potential over the lifecycle from two products in units of tons of carbon. The factor states the saved greenhouse gases occurring by the substitution of the two products in relation to the amount of biogenic carbon in the wood (measured in t C/ t C). A cubic meter of wood contains about 250 kg C (920 kg CO_2-equivalents). For wood products an average material substitution factor of 2.1 t C/ t C is applied in the literature (Rüter, 2011; Sathre and O'Connor, 2010).

Harvested wood can also be combusted directly after harvest or at the end of the lifetime of the wood products. The combustion of wood can substitute fossil energy when wood is used instead of a fossil energy carrier. For example, for the substitution of fuel oil a substitution factor of 0.67 t C/ t C applies. Depending on the energy carrier and efficiency, the energy substitution factor of wood varies

between 0.5 and 1.0 t C/ t C (Rüter, 2011).
The climate relevant substitution effect of wood usage, e.g., for a country, depends on the envisaged material and energy use in comparison to a reference (e.g., the current usage) (Rüter, 2011).

2.4. Land-use change

The forest-based influence on the carbon cycle does not only result from carbon stock changes on existing and remaining forest lands and the resulting use of wood, but also from land-use changes. Land-use changes largely affect carbon stocks above and below ground (IPCC, 2000). In the case of forests, relevant land-use changes are afforestations of other land uses to forests and deforestations to other land uses than forests. In the case of deforestation, the carbon stock of the living biomass is removed from the area and will either decay, combust or be stored in the wood products, as described previously. No tree re-growth will take place on that area, but a different vegetation type with biomass growth could possibly follow, e.g., crop land. The intervention of deforestation and conversion to a new land-use type also affects soil carbon (IPCC, 2000). The impact differs among different ecological regions, and especially tropical soils are sensitive to interventions due to fast turnover rates of soil organic matter (see Dion, 2010). The overall influence on the carbon cycle relies on both the land-use type and management before and after the land-use change, and on the procedures that are performed to carry out the land conversion (see IPCC, 2000).

In most industrialised countries forest area is increasing, because the areas of afforestation and reforestation exceed the areas of deforestation (FAO, 2010). For example, in Germany deforestation, e.g., for settlement development purposes must be compensated by afforestations on other sites (BWaldG, 1975, § 9 and Länder forest law). Over past centuries most industrialised countries have deforested huge parts of their initial forest areas, mainly driven by population growth and the need for agricultural and settlement areas. This trend of deforestation, however, has slowed down in accordance with economic and technological development and reverted into an increase in forest area (Rudel et al., 2005). This time-related trend from forest area decrease to increase is described as the forest transition development (Mather, 1992) (see Figure 3). It has been observed, e.g., in various European countries, the United States of America, Canada and Japan (see Köthke et al., 2013, for a review of Forest Transition studies).

In most developing countries net deforestation can be observed (FAO, 2010; IPCC, 2007a). According to the forest transition hypothesis, these developing countries are still in the phase of forest cover decline because relevant deforestation drivers (population growth, poverty, technological inefficiency) are still dominant in those countries and agricultural expansion replaces forest areas (see Grainger, 1995; Mather and Needle, 1998; Mather et al., 1998). Some developing countries, however, like China, India and El Salvador show already signs of forest cover increase (FAO, 2010; Mather, 2007).

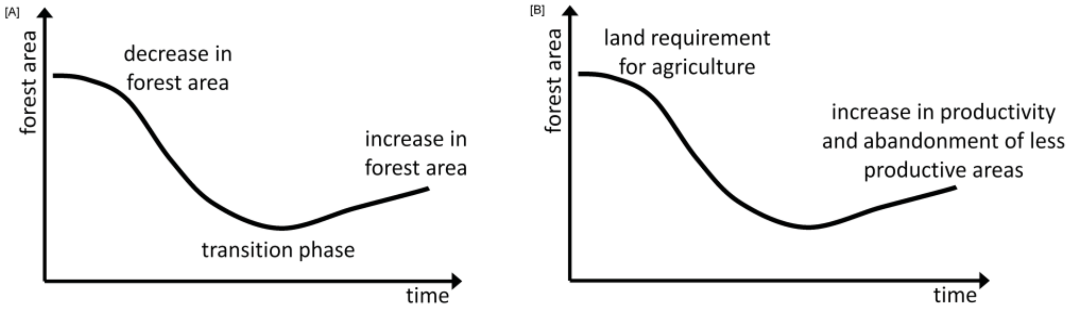

Figure 3: Forest cover development according to the forest transition hypothesis (from Köthke et al., 2013, p. 24, adapted from Grainger (1995) and Mather (1992)).

According to Kissinger et al. (2012) the main direct driver of deforestation is agricultural expansion, followed by mining, infrastructure and urban expansion. These direct drivers are influenced by underlying demographic, social, economic, political, cultural and technological processes and the physio-geographic situation.

3. The political design for accounting of carbon uptake and release by forests

No full carbon accounting is given in the LULUCF/forest sector. The forest dynamics relevant for the carbon cycle (described in Chapter 2) are rather captured by politically designed rules for accounting certain emissions and removals of greenhouse gases resulting from the forest sector. For the accounting eligible activities, considered carbon pools and case-by-case accounting approaches such as net-net or gross-net accounting, or the application and design of caps or reference levels are politically defined (the accounting approaches are further presented in the following Chapter). The accounting approach not only determines the advantageousness of the system for each country (whether and how much credits or debits a country can generate) but consequentially it affects the advantageousness of certain actions. Thereby the rules for accounting form the direction and extent of incentives to conduct certain activities.

Furthermore, no consistent carbon accounting exists for Annex I and Non-Annex I parties (see Dutschke and Pistorius, 2008). The reasons for this are manifold. For consistent carbon accounting a worldwide standardised system would need to be implemented and controlled, which is difficult especially in developing countries. Comprehensive monitoring systems and the measurement, reporting and verification of the carbon accounting are complex actions and are difficult to implement (Angelsen et al., 2009, Ch. 7; Plugge and Köhl, 2012; Romijn et al., 2012). Capacity, knowledge and financing are needed, which need to be gathered, built and distributed. This at least takes time; hence learning by doing was conducted by the implementation of emission accounting so far. This can be seen by amendments to the rules which have been made between the commitment periods (e.g., the change of LULUCF-forestry rules between the 1st and 2nd CP, see Chapter 1), and by several approaches which have a stepwise implementation character. For example, the IPCC's Good Practice Guidance for LULUCF presents a choice of different methods for emission reporting ranging from simplified default approaches to detailed approaches which require precise measurement and reporting of country-specific data (different "tiers" of reporting can be applied).

Due to the large coverage of the cross-sectoral emission accounting, emissions and removals are allocated to different sectors and pools. The allocation is, however, not unequivocal. The system boundaries for a full carbon accounting system would need to be defined without gaps and overlaps.

In addition, only anthropogenic impacts on the climate system are being addressed by the Convention. This means that only human-induced emissions and removals shall be accounted for under the Kyoto Protocol. Hence, several mitigation actions require that only additional efforts to reduce emissions/increase removals supplementary to business as usual (BAU) are accounted for (e.g., forest management, CDM and JI under Kyoto Protocol Art. 3.4, 6., 12. and REDD+ reference levels (Angelsen et al., 2011b; Streck, 2010). The separation of human-induced from non-human-induced impacts and initiators is, however, not always self-explanatory and needs to be defined.

3.1. The scope of accounting – land-use categories, mitigation activities and carbon pools

'Forest land' is one out of 6 **land categories** differentiated in the LULUCF reporting system: forest land, cropland, grassland, wetland, settlement and other land (IPCC, 2003). The land categories are sub-divided in managed and unmanaged lands. Emissions and removals from unmanaged forest land are however not considered an anthropogenic source or sink, and are therefore not included in the national inventory estimates (IPCC, 2003, Ch. 3.2).

Direct human-induced forest-related LULUCF **activities** under the Kyoto Protocol are land-use change activities since 1990: afforestation (A), reforestation (R) and deforestation (D), together called ARD (KP Art. 3.3) and the activity of forest management (FM) (KP Art. 3.4) (UNFCCC, 2006b, Dec. 16/CMP.1). Although the Kyoto Protocol directly addresses the activities rather than the land areas for accounting, the activities are assigned to **land-use categories** for reporting. Doing so shall avoid double accounting or gaps of relevant areas. Forest management takes place on the land-use category 'forest land remaining as forest land', afforestation and reforestation belong to 'another land-use category converted to forest land' and deforestation is allocated to the category 'forest land converted to another land-use' (IPCC, 2003, Ch. 3.2). See Table 1 for an overview.

All emissions and removals occurring from the forest-related LULUCF activities have to be reported for 5 carbon pools (IPCC, 2003, Ch. 3.1.3), which are 1) living biomass above ground, 2) living biomass below ground, 3) dead organic matter, dead wood, 4) dead organic matter, litter and 5) soil organic matter. For the reporting of those carbon pools different options (tiers) are given (IPCC, 2003).

Harvested wood products (HWP) will become an additional mandatory carbon pool for the 2nd CP. In the 1st CP the default assumption was applied, that all carbon is oxidised in the removal year (instantaneous oxidation) (IPCC, 2003). Thus harvests were put on a level with emissions, which is a conservative assumption. In the case of an increasing carbon stock in the harvested wood products pool in the 1st CP a country can voluntarily include this in the national inventory report (NIR). Stock changes in the harvested wood products pool have not been accounted for meeting the emission reduction targets in the 1st CP. For the accounting in the 2nd CP different accounting options can be chosen, which are the default assumption, accounting on the basis of the IPCC's first order decay function with default half-lifes (2 years for paper, 25 years for wood panels, 35 years for sawn wood) or by country-specific data on half-lifes (Grassi, 2012; UNFCCC, 2012b).

Without considering the harvested wood products pool and by ignoring the fossil fuel substitution (which is implicitly accounted for in the energy sector), the forest-related accounting rules in the 1st CP incentivise the maintenance and enhancement of the carbon stock in the forest only. The use of wood products (see Chapter 2) is not incentivised (Ellison et al., 2011; Suadicani, 2010; UNECE and FAO, 2008).

For **REDD+** different definitions of mitigation activities from the forest sector apply which are not consistent with the LULUCF accounting under the Kyoto Protocol, although they can be assigned to the IPCC's LULUCF categories (see Table 1).

Table 1: Scope of carbon accounting in the forest sector.

<table>
<tr><th>land-use categories related to forest land
(IPCC, 2003, 3.2)</th><th>direct human-induced LULUCF activities
(UNFCCC, 2006b, Dec. 16/CMP.1)</th><th colspan="3">accounted activities under the Kyoto Protocol for Annex I countries</th><th>accountable under a future REDD+ mechanism
(UNFCCC, 2011a, Dec. 1/CP.16, III.70.)</th></tr>
<tr><td rowspan="2">another land-use category converted to forest land</td><td>Afforestation (A)</td><td rowspan="3">KP Art. 3.3,
1st and 2nd CP:
ARD since 1990
mandatory gross-net</td><td rowspan="2">KP Art. 12:
in Non-Annex I countries under CDM</td><td rowspan="2">KP Art. 6:
in other Annex I countries under JI</td><td rowspan="2">removals from:
(e) Enhancement of forest carbon stocks (if not covered by CDM)</td></tr>
<tr><td>Reforestation (R)</td></tr>
<tr><td>forest land converted to another land-use</td><td>Deforestation (D)</td><td></td><td></td><td rowspan="2">removals from:
(a) Reducing emissions from deforestation
(b) Reducing emissions from forest degradation
c) Conservation of forest carbon stocks
(d) Sustainable management of forests
(e) Enhancement of forest carbon stocks</td></tr>
<tr><td>forest land remaining as forest land</td><td>Forest management (FM)</td><td>KP Art. 3.4,
1st CP:
voluntary gross-net,
fixed Cap,

2nd CP:
mandatory net-net,
3.5 % Cap</td><td></td><td></td></tr>
</table>

All of the 5 REDD+ activities (see Chapter 1, UNFCCC, 2011a, Dec. 1/CP.16, III.70) take place on forest land (comparable to the LULUCF land-use category 'forest land remaining as forest land'). Deforestation as such is a land-use change activity, but in the REDD+ context the 'reduction of emissions from deforestation' is addressed. Reduced or avoided deforestation, however, also takes place on existing forest land. This wording was chosen, because emissions from deforestation are not addressed under REDD+. None of the REDD+ activities address the occurrence of increased emissions because REDD+ is not an instrument for applying fines (imposing debits) but for incentivising (giving credits). The REDD+ activities a) and b) (reducing emissions from deforestation and degradation) do address the avoidance/reduction of emissions and also the formulation of the activities c) to e) (conservation of carbon stocks, sustainable forest management and enhancement of carbon stocks) is directed towards the stock- and sink-function of the forest. The cases of, e.g., increased emissions from deforestation or net emissions from forest management, are not mentioned. Unlike the Kyoto Protocol which addresses both aspects (sinks and sources) for the LULUCF activities. Therefore the activities for REDD+ and LULUCF were not treated as equivalent in the accounting system, although the activities carried out and the resulting mitigation effect might be the same (see Table 1).

Unclear is the definition of the REDD+ activity 'enhancement of forest carbon stocks', which might be interpreted either as the enhancement of carbon stocks in existing forests (e.g., by forest restoration or improvement) (e.g., by Dutschke and Pistorius, 2008) or also as afforestation/reforestation (and therefore would be a land-use change activity) (e.g., by Angelsen et al., 2011a). Afforestation and reforestation in developing countries are, however, so far regulated under CDM. When REDD+ comes into force, the scope of both mechanisms needs to be clearly defined (and separated) or both mechanisms need to be merged to avoid double accounting (see Angelsen, 2009).

The extension of the REDD+ mechanism from deforestation to degradation and finally to the three "plus-activities" was decided to avoid perverse incentives by creating a system with gaps.

For example, by accounting for deforestation only without degradation, it would be possible to increase the exploitation and degradation of the forests, while generating credits for avoided deforestation. The same could happen by considering only parts of the land area, e.g., by implementing sub-national approaches only. Thereby a leakage through shifting of deforestation to other areas might occur without any punishment. This leakage will also be likely on the international level, if not all (relevant) countries participate in a commitment (Angelsen et al., 2011b; Santilli et al., 2005).

Therefore environmental integrity through full carbon accounting requires the inclusion of all countries, sectors, areas, carbon pools and activities to cover all emissions and removals.

3.2. Accounting for additional human-induced emissions and removals – the need for a reference

Within the "scope" (land-use category, activity, carbon pool) considered a difference still remains between the real emissions and removals and the accounted emissions and removals for a party. This means the real emissions and removals reflect the climate relevance, which is independent from the location of occurrence (see Chapter 2). The accounted emissions and removals reflect which and how much emissions and removals can be accounted for meeting part of the emission reduction target of a party (can be converted in credits, offset to AAUs).

Under the requirement of additionality, the accounting of activities which are additional to business as usual (BAU) emissions and removals from human-induced activities shall be guaranteed (Angelsen et al., 2011b; Streck, 2010). To define additional human-induced emissions different accounting options for LULUCF activities have been created under the Kyoto Protocol:

- **Gross-net** accounting is the accounting of the absolute emissions and removals in a commitment period. This means that the total net emissions occurring in a commitment period are considered as direct human-induced and were fully assigned to the party. The reference is zero emissions.
- **Net-net** accounting is the accounting of the relative emissions and removals, calculated by the comparison of the net emissions in a commitment period to a benchmark. The benchmark sets the not accounted emissions. The benchmark can be expressed by BAU emissions from a reference year (e.g., base year emissions), or from a reference period (e.g., by defining a reference level). Only the deviation from the benchmark is assigned to the party.

The additional option of **"factoring out"** seeks to exclude non-anthropogenic effects from accounting. The UNFCCC (2006b, Dec. 16/CMP.1, §1h) especially demands the exclusion (factoring out) of removals from the accounting, which result from indirect nitrogen deposition, elevated CO_2 concentration above their pre-industrial level or from dynamic effects of age structure resulting from activities before the reference year. Factoring out might, for instance, be conducted by setting a cap or a discount factor on the eligible credits/debits or by applying a reference level which already considers non-anthropogenic effects.

Although factoring out is technically heading in both directions (sinks and sources), it is implemented mainly for capping credits from sinks. Thereby the gaining of "free" credits without taking any efforts (also called "hot air") shall be avoided (see Canadell et al., 2007).

The consideration of **"force majeure"** (introduced for the 2nd CP) is one special case of excluding/factoring out emissions from sources from the accounting which are not human-induced.

Those emissions which are beyond the control of the concerned Party are mainly caused by extraordinary occurrences (such as natural disturbances) (UNFCCC, 2011c).

The LULUCF accounting approach generally is net-net accounting, except of the forest-related activities in the 1st CP. Land-use change activities (ARD) (according to KP Art. 3.3) since 1990 are accounted in gross-net. This means all net emissions occurring from land-use changes since 1990 are fined with debits, as they are supposed to be directly human-induced. I.e., the Annex I parties are made responsible for all emissions from land-use changes. Forest management (according to KP Art. 3.4) since 1990 was also accounted in gross-net accounting in the 1st CP. The so-called ‘stock change approach’ which measures the carbon stock change between two forest inventories, or the ‘gain-loss approach’ which measures the difference from all gains and losses within the considered period could be applied for reporting (IPCC, 2003). Uncertainties and also non-anthropogenic effects were factored out by the fixed cap which was placed on credits from forest management.

Due to the difficulty of setting a cap at the right scale and due to the “lost” incentive in the 1st CP because of the strict cap on credits (see Chapter 1), forest management shall be accounted in the 2nd CP in net-net accounting (see discussion by Ellison et al., 2013, on the "incentive gap"). Therefore, a forest management reference level (FMRL) is introduced for the 2nd CP to set the benchmark for BAU emissions on forest land remaining as forest land. Each country must submit a FMRL to the UNFCCC for the 2nd CP (UNFCCC, 2011c). The FMRL submissions were based on either national projections or large-scale models. For example, for several EU member states model projections by the Joint Research Center (JRC) of the EU were applied (Böttcher et al., 2012; Groen et al., 2013). A projected BAU FMRL shall already include BAU forest management practices as well as natural conditions such as effects of the age class structure. It is also possible to include “force majeure” in this BAU FMRL (UNFCCC, 2011c). The consideration of both non-anthropogenic induced effects since 1990 as well as a differentiation of BAU to additional measures is, therefore, improved by the new approach. Further uncertain non-anthropogenic induced effects will still be factored out by a cap of 3.5 % of base year emissions on credits. This cap, however, is less strict than the cap from the 1st CP and, therefore, incentives for increasing removals from forest management are greater for most countries in the 2nd CP (Ellison et al., 2013; Grassi, 2012).

The main difference between land-use change accounting for developing and industrialised countries is the accounting approach, which assigns different responsibility and incentives for the occurring emissions. Land-use changes (ARD) under the Kyoto Protocol LULUCF rules are always measured in gross-net accounting, i.e., any net deforestation and resulting net emissions are accounted as debits for the industrialised country. Under a REDD+ scheme, deforestation will be accounted in net-net with a reference level, i.e., net deforestation and resulting emissions are “allowed” (not debited) up to the respective reference level. Therefore, the developing country is not made responsible for the mere fact that emissions occur due to net deforestation, but is honoured for additional action taken to reduce these emissions/deforestation rates. Human-induced deforestation will not be taken as the measuring unit here (like in the LULUCF context).

Deforestation accounting under REDD+ is, therefore, comparable to forest management accounting with a FMRL in the 2^{nd} CP (both net-net). Both need a forward-looking reference level for defining the benchmark of BAU development. A comparable accounting approach is conducted for CDM afforestation/reforestation projects as well, which also apply a reference level (called baseline here). A CDM baseline “reasonably represents the anthropogenic emissions by sources of greenhouse gases that would occur in the absence of the proposed project activity” (UNFCCC, 2006a, Dec. 3/CMP.1, Annex §44).

In contrast to the rules for FMRL and CDM baselines which are already defined and applied, a methodology for REDD+ reference levels and the consideration of national circumstances still needs to be negotiated. For setting REDD+ reference levels experiences from the earlier implemented approaches could be considered, but also the different circumstances for the targeted Non-Annex I parties have to be taken into account. For the participating countries under REDD+ no binding emission reduction targets exist and the voluntary participation of each Non-Annex I party will probably be influenced by the advantageousness of the approach for its own country. Additionally, external financing will be provided for REDD+. A two-sided approach with credits for emission reduction and debits for increased emissions is therefore not realistic. As mentioned before, the REDD+ activities are also only formulated in the “positive” way (addressing reduced emissions or increased removals) and only “positive incentives” (i.e., credits) will be implemented.

The extent of credible emission reduction, however, is a matter of political negotiation and may be negotiated individually for each country, e.g., by a crediting reference level (see Chapter 1). The benchmark for crediting might, thereby, differ from a BAU reference level (see Figure 4) and additional limits on the accounted emissions and removals might be set for factoring out any ineligible effects. However, this is a matter of political negotiations.

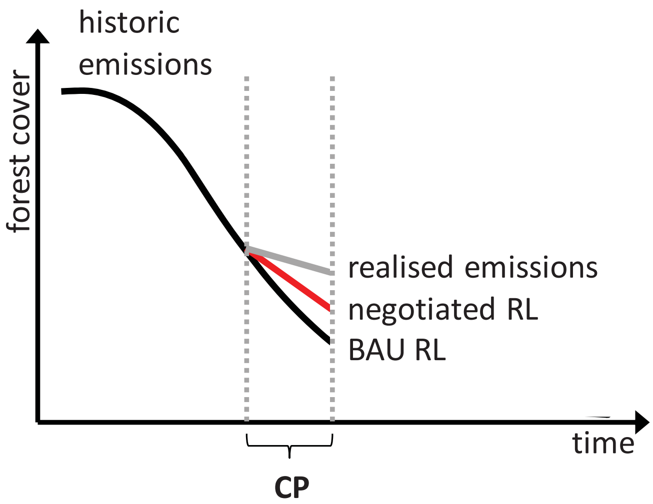

Figure 4: Options for reference level setting (schematic illustration).

Difficulties for setting reference levels

Scepticism also surrounds the net-net accounting approach with BAU reference levels, e.g., Kirschbaum and Cowie (2004) fear the creation of perverse incentives. They describe the risk that high BAU emissions would allow high future emissions in a net-net accounting approach and that no need for any emission reduction might be given. The difficulty in BAU reference level setting is the problem of defining the BAU development. A scientific quantification of this is hardly possible; therefore a negotiated definition needs to be applied. For REDD+ reference levels the UNFCCC/SBSTA requires the inclusion of historical deforestation as well as national circumstances (UNFCCC, 2008; 2010, Dec. 4/CP.15).

To define a BAU reference level, a prediction of BAU emissions is required. As the complex procedure conducted for the submission and review of Annex I parties' FMRLs showed, this is not easy and becomes even more complicated in developing countries, where less data is available (UNFCCC, 2011b).

The idea of simply defining the extrapolation of historical deforestation as a future BAU development for a REDD+ BAU reference level came up early in the political process (called simple historical reference level) (Santilli et al., 2005). However, putting historical behaviour on a level with future targets, would advantage historically high emitters and vice versa disadvantage historically low emitters. This leads back to the requirement for the consideration of national circumstances in reference level setting (see Angelsen, 2008, Ch. 6; Angelsen et al., 2011b; Köthke et al., 2013; UNFCCC, 2008, 2012a). Thereby development opportunities for the single countries shall not be hindered by setting strict reference levels. Adjustments of historical extrapolations were discussed among others for BAU reference levels. But comparable to the difficulties in setting a cap level for factoring out or for considering force majeure, the extent of such an adjustment could not be determined uniformly. Each country is asked to propose an individual adjustment for national circumstances (UNFCCC, 2012a, Dec. 12/CP.17)

According to the forest transition hypothesis (see Chapter 2), the BAU forest area development can be described to be on a deforestation path, where deforestation slows down and finally transits into a trend of increased forest area. The prediction of a forest transition development as proposed by Angelsen (2008, Ch. 6) might, therefore, be seen as BAU development including both historical development and national circumstances. The inclusion of the forest transition stage as an adjustment for national circumstances in reference levels has, however, not been applied further, due to the lack of empirical evidence (Angelsen et al., 2011a, Box 1).

Several reference level approaches and discussions focus on the description of the forest area development, although the development of emissions is the addressed subject by the UNFCCC. An approach related to forest area can be seen as a first step, but is difficult to determine. Area-related reference levels are addressed in the first REDD+ activity which is related to deforestation only. The subsequently required translation of forest area into emissions is possible, even though it depends on different forest types, densities, management regimes, etc. (see Chapter 2). The determination of the greenhouse gas impacts of the other 4 REDD+ activities requires even more complicated inventories and measurement, reporting and verification systems, where data on the global scale is not yet available (Angelsen et al., 2009, Ch. 7; Hardcastle and Baird, 2008; Plugge et al., 2013; Romijn et al., 2012). Developing countries are, therefore, asked to build up and improve national inventories and reporting systems (IISD, 2013).

Part II: Integration of the single articles into the thematic context

This cumulative dissertation analyses the design and implications of different key elements of accounting approaches for the climate change mitigation activities of forest management, afforestation and avoided deforestation. Thereby policy options within the political framework for forest-based mitigation in industrialised and developing countries (described in Part I) and different levels of consideration (sub-national, national, global) were examined and published in three individual studies.

Within the LULUCF context, accounting of mitigation options from the forest sector are regulated on the international and national level, while so far in most countries no incentives or benefit-sharing on the sub-national level have been implemented (see Chapter 1). This gap has been analysed in the first article (Köthke and Dieter, 2010, Chapter 4). The study analyses sub-national policy instruments for carbon crediting on the enterprise level and assesses the incentive effects on forest management. The study is based on the example of forest growth conditions in Germany (Annex I party) and is applied to the activities of afforestation/reforestation (other land converted to forest land) and forest management on existing forest land. Different accounting approaches for carbon crediting with different treatments of harvests and carbon stored in harvested wood products were calculated. The effects on forest management decisions (optimal rotations) under the additional carbon crediting options in competition to timber production were analysed. The study demonstrates that the incentive effects are reliant on the design of the accounting approaches and benchmarks.

For a targeted, consistent carbon accounting between industrialised and developing countries conformed accounting approaches were needed which consider the different national circumstances. Thereby the question arises whether a consistent or at least comparable forest development between industrialised and developing countries could be taken as a basis. Patterns of the global forest cover development were analysed in the second article (Köthke et al., 2013, Chapter 5). The study investigates whether the observed regularities of forest cover development in industrialised countries (Annex I parties), known as forest transition development (see Chapter 2), could be transferred to developing countries (Non-Annex I parties). For Non-Annex I parties a uniform deforestation pattern could be empirically quantified, which also proved to be statistically identical for Annex I countries. Thus, a consistent development of forest cover decline could be confirmed.

The application of the detected uniform global deforestation curve for determining REDD+ BAU reference levels was analysed in the third article (Köthke et al., submitted, Chapter 6). As REDD+

reference level setting has not been implemented so far (see Chapter 1 and 3), the article proposes a reference level approach and applies it to 86 Non-Annex I countries. National circumstances were considered in the proposed approach, based on a uniform methodology. BAU forest cover predictions by the proposed reference level were made in a hypothetical future REDD+ commitment period and were compared to observed data. The implications of applying such a uniform deforestation curve for reference level setting were discussed and set in relation to other elements of the UNFCCC mechanisms concerning mitigation activities from the forest. The proposed consistent approach provides the advantage of the required consideration of individual national circumstances standardised by a uniform methodology.

In the following Chapters each of the three scientific articles is summarised briefly and its contribution and integration into the thematic context, described in Part I, is discussed. The applied method and results of the single studies are described in detail in the original articles, which are included in Appendix I. The connection of the three articles and their contribution to the progress of science within the thematic context are described in the final conclusions in Chapter 7.

4. First article: Köthke, M., Dieter, M. (2010): “Effects of carbon sequestration rewards on forest management – An empirical application of adjusted Faustmann-Formulae”

The first article was written by Margret Köthke and Matthias Dieter and published in 2010 in the reviewed journal Forest Policy and Economics. The basic concept of the article was developed by M. Dieter in collaboration with M. Köthke. M. Köthke conducted the data collection, calculations and writing of the main parts of the text. M. Dieter contributed to the discussion and conclusions.

4.1. Summary

The article examines which incentive effects different economic instruments to reward the carbon sequestration service of the forest have on forest management activities. Therefore, different carbon crediting approaches were defined and different carbon prices, timber prices and interest rates were applied. The optimum time for harvests (optimum rotation period) is calculated by maximising the land expectation values under different price influences. The differences of the optimum rotation periods with and without carbon crediting were assessed.

The study was applied to the growth conditions of spruce forests in Germany, considering even-aged stands in a clear cutting regime with different thinning operations. The calculations were conducted for single forest stands and for forest enterprises. The single stands scenarios represent afforestations on bare land, which were managed under infinite rotations after initial planting. The forest enterprises represent a composition of existing forest stands of different vintages, which were composed as fully regulated normal forest enterprises (see Chapter 2).

For both, single forest stands and whole forest enterprises, three different carbon crediting approaches were defined. The crediting approaches all reward the carbon uptake through gross tree biomass increment with carbon credits. They differ in their approaches for debiting carbon emissions. In the first crediting approach, the removal of timber from the standing forest (through final harvesting, thinning or mortality) is debited immediately at the time of timber removal. In the second crediting approach, timber removal is not debited at all and only the gross carbon uptake is rewarded. In the third crediting approach, carbon emissions are debited at the end of the lifetime of the harvested wood. The mean lifetime of the harvested wood varies in the calculations between zero and 500 years. The difference between new planted (afforested) forest stands and existing forests is that in the first case all carbon uptake by forest increment is additional to the reference (which is bare land) and in the latter case only an increased carbon uptake compared to the business as usual (BAU) carbon uptake is additional and therefore accountable. In the latter case the BAU reference is the standing forest stock and the increment of the forest enterprise under a BAU forest management regime, applying the economical optimum rotation period without carbon credits. Only the additional carbon stock of the standing forest and the additional carbon increment are credited. The same holds for reduced carbon stocks, reduced increments and increased harvests compared to the reference, which were debited respectively.

The carbon prices varied between 0 and 100 € per tonne of CO_2, the timber prices, which were subject to diameter, varied from 50 to 400 % from the initial price scenario and the interest rates varied between 0.1 % to 10 %. Regeneration costs and harvesting costs were fixed.
The calculations are based on adjusted Faustmann-Hartman-Models, applying land expectation values adjusted for the carbon values of the respective crediting approaches.

The findings show that the influence of carbon crediting tends to extend the optimum rotation period in all considered cases with increasing carbon prices, but with different intensity. Certainly the relation of carbon prices to timber prices is relevant for the intensity of the effects. The optimum rotation period calculated with land expectation values for timber is usually earlier than the time of maximum mean annual increment (MAI) (see Chapter 2). Crediting total carbon increment of the forest stand (as in the second crediting approach) will extend the optimum rotation period towards the time of maximum MAI. Rotations at the time of maximum MAI maximise the carbon uptake by the forest stand. Debiting emissions further extends the optimum rotation period (beyond the time of maximum MAI), depending on the time of debiting. The earlier the debits are charged (depending on the mean lifetimes of the harvested wood products in the third crediting approach), the longer the optimum rotation period. The strictest assumption of immediate debiting at the time of timber removal is applied in the first crediting approach. Here the longest rotation periods are optimal, and if carbon prices are high enough, harvesting becomes no longer profitable.
Similar effects were found for the forest enterprise scenarios, but the influences of the carbon prices on the extension of the optimum rotation periods are much stronger. Although the increment within the enterprises decrease if the rotation periods extend the maximum MAI, the carbon stocks of the standing forests are higher in enterprises with longer rotation periods. The additional carbon stock in the standing forest, thereby, outweighs the decreased increment. The optimum rotation periods, therefore, rapidly increase once the carbon price outperforms the timber price.

Furthermore, the findings show that high interest rates tend to decrease the optimum rotation period of a forest stand managed for timber production, but also tend to extend the optimum rotation period if this delays a debit payment. Therefore, interest rates have a varied influence on the interrelation of carbon and timber prices, while different thinning regimes only show little impact on the optimum rotation period.

4.2. Discussion in the thematic context

The analysis of different carbon crediting approaches for afforestation and forest management activities in Germany is an example for industrialised (Annex I) countries. The analysis considers a hypothetical carbon accounting and rewarding on the sub-national level, as the carbon accounting from afforestation and forest management activities in industrialised countries is conducted only on the national level (according to Kyoto Protocol Art. 3.3 and 3.4, see Chapter 1). Under the current accounting system of the Kyoto Protocol, forest owners are not incentivised to adapt forest management practices for carbon benefits. The hypothetical domestic rewarding system presented in the article, directly passes credits/debits to forest owners and, thereby, demonstrates which incentive effect a direct carbon accounting of the forests carbon sequestration service would have on forest management.

The study clearly shows that different accounting approaches, especially different treatments of timber removals and definitions of benchmarks, have different incentive effects on forest management.

In the analysis the considered case of afforestation activities on bare land is comparable to the LULUCF land-use category 'other land converted to forest land'. The reference case is zero emissions and removals, i.e., gross-net accounting is applied. The considered case of existing forest enterprises is comparable to the land-use category 'forest land remaining forest land' and the activity of forest management. The reference case is the BAU forest management defined by economic optimal rotation periods for timber production, i.e., net-net accounting is applied.

Although the hypothetical domestic crediting approaches are independent from any national carbon accounting, comparisons may be drawn to the Kyoto Protocol rules on the national level. The first crediting approach applied in the article is comparable to the accounting approach applied in the 1st CP of the Kyoto Protocol. Timber removals are treated under the assumption of instantaneous oxidation and only carbon stock changes are accounted for. The incentive effect of this approach clearly favours an increased carbon stock in the standing forest before increased annual increments and harvest volume. The envisaged accounting in the 2nd CP is comparable to the third crediting approach presented in the article. Here the carbon pool in harvested wood products is also accounted for and the incentive effect results in a more balanced management between increased carbon stocks in the standing forest and a regular harvest volume. The 2nd CP plans forest management accounting to be compared to a projected forest management reference level (FMRL) (see Chapter 3). This has been applied in the forest enterprise scenarios described in the article by defining a BAU forest management reference. Decreased or increased carbon uptake relative to the reference has been accounted as an additional emission or removal. Dependent on the BAU definition (management practice in the past) credits or debits could be generated by a change in the management practice.

The calculations conducted in the article do not consider any commitment period, as the analysis is based on static comparisons of different management scenarios. The effects of most changes in forest management practices, however, take longer than five years to show.

5. Second article: Köthke, M., Leischner, B., Elsasser, P. (2013): "Uniform global deforestation patterns – An empirical analysis"

The second article of the cumulative dissertation was written by Margret Köthke, Bettina Leischner and Peter Elsasser and was published in 2013 in the reviewed journal Forest Policy and Economics. The basic concept of the article was developed by B. Leischner. The theoretical development of the study was developed by M. Köthke in collaboration with B. Leischner and P. Elsasser. The data collection was conducted by B. Leischner and M. Köthke and the calculation was conducted by M. Köthke in collaboration with B. Leischner. The main parts of the text were written by M. Köthke.

5.1.Summary

The article assesses whether the global forest cover development shows regularities on the national level which could be empirically tested and quantified among the countries of the world. The theoretical background for this assumption is deduced from the forest transition hypothesis first described by Mather (1992), which implies that changes in a region's forest area follow a determinable pattern of decline and later increase over time (see Chapter 2). The resulting forest transition curve was observed in several industrialised countries and argued to be driven primarily by population growth and the resulting demand for agricultural areas and settlements and followed by technological development (see Köthke et al., 2013, for literature review and references).

The motivation for the analysis on the existence of uniform patterns of forest cover development was driven by the need for country-specific REDD+ reference levels which predict the business as usual forest area development of developing countries by a uniform methodology. The article, therefore, analyses the phases of forest cover decline of 140 countries and empirically tests whether a uniform pattern could be quantified. A cross-section analysis was applied in a multi-national regression model. As potential drivers of deforestation several physio-geographic, demographic and further socio-economic variables were tested.

A globally uniform pattern of forest cover decline could be detected on the national scale for 140 countries and a global s-shaped deforestation curve was quantified. The findings showed a significant influence of population density, cereal area yield, land suitability and the proportion of potential forest vegetation area on forest cover decline. The regression model was first parameterised with recent data from developing countries (N=111) and later tested for differences with historical data from developed countries. No statistically significant differences occurred between developing and developed countries' development of forest cover decline. By the global deforestation curve and the application of national data, national BAU forest cover development can be predicted for five years in the future.

The empirical evidence that a uniform deforestation pattern exists provides the necessary justification for any further discussion of its inclusion in REDD+ reference levels.

5.2. Discussion in the thematic context

The study assesses globally uniform patterns of forest cover decline. It considers both developing (Non-Annex I) and industrialised (Annex I) countries, but only in their phases of net forest cover decline. This is currently the case in most developing countries and has been observed in industrialised countries in the past (before the industrial revolution) (see Chapter 2).
Therefore, the analysis conducted is applicable to considerations on the REDD+ activity of deforestation in developing countries, but not for the whole forest-related land-use change activities addressed under LULUCF in industrialised countries. For application of the uniform forest cover pattern to countries with net forest cover increase (today mainly industrialised countries), the whole forest transition curve (including the phase of forest area increase) would need to be quantified (see Chapter 2). This has not yet been considered in the prevailing analysis, but the findings on similarities in the global development of forest cover decline provide an impulse for further discussions on a consistent carbon accounting system among developing and industrialised countries.

The prevailing uniform deforestation curve, however, provides a justification for the implementation of a uniform methodology for the setting of REDD+ reference levels among developing countries. The deforestation curve can be applied for predictions of BAU forest cover development on national level and might therefore be applied for BAU reference level predictions related to the REDD+ deforestation activity in developing countries. Such an application would fulfil the required consideration of national circumstances and of net-net accounting (comparison to reference levels) (see Chapter 3 and article 3).

The analysis has been conducted on forest area changes, rather than carbon stock changes, which however might be translated into carbon emissions from deforestation by applying area-related carbon values (e.g., the country-specific IPCC default values) (see Chapter 3). It does not include any changes related to forest stock changes on existing forest land, which would be captured by the REDD+ activities of degradation, sustainable forest management, conservation and enhancement of carbon stocks on existing forest land, and in industrialised countries by forest management activities.

6. Third article: Köthke, M., Leischner, B., Elsasser, P. (submitted): "National REDD+ reference levels deduced from the global deforestation curve"

The third article of the cumulative dissertation was written by Margret Köthke, Bettina Leischner and Peter Elsasser and was submitted to the reviewed journal Forest Policy and Economics in September 2013. The basic concept of the article was created by M. Köthke and P. Elsasser in collaboration B. Leischner. The data collection was conducted by M. Köthke and B. Leischner. The calculation was conducted by M. Köthke and the main parts of the text were written by M. Köthke in collaboration with P. Elsasser.

6.1.Summary

The article proposes a method for REDD+ BAU reference level determination developed further from the detected globally uniform deforestation curve published in the second article of this cumulative dissertation (Köthke et al., 2013, see Chapter 5). The study applies the global deforestation curve for the prediction of BAU forest cover development in a hypothetical commitment period for 86 developing countries. Country-specific data of the 86 REDD+ target countries which are still in their deforestation phase according to recent FAO data (FAO, 2010) was applied for calculation of forest cover development five years later. The hypothetical commitment period was defined to be 2005 to 2010, which provides the option of comparison of the reference level prediction with observed FAO data in this period.

Based on the underlying country-specific data for most countries, an ongoing forest cover decline in the period 2005 to 2010 was predicted by the deforestation curve. In the comparison with observed data, 53 countries have deforested more area than predicted and 33 countries have deforested less area than predicted.

The proposed methodology considers national circumstances rather than past performances and is based on the mean global development of forest cover. Countries' deviations from this mean global development were accounted for in the BAU reference levels, but country-specific conditions resulting from population density, cereal area yield, land suitability and the proportion of potential forest vegetation area are subtracted from this deviance. By applying the BAU reference level as the allowed deforestation development, the individual countries would be made responsible for the remaining deviance only. This deviance from the BAU reference level does not necessarily need to result in a predetermined allocation of credits or debits, as a BAU reference level might be different from a crediting reference level (see Chapter 3). The BAU reference level predicted in this article can, however, form the basis for negotiations on crediting reference levels, which is further discussed in the article.

6.2. Discussion in the thematic context

The article proposes an accounting approach for a potential future REDD+ mechanism for forest-based mitigation options in developing countries (Non-Annex I). The accounting for the REDD+ land-use change activity of deforestation (see Chapter 1) is considered in this case, which is supposed to be accounted relative to a reference level. Such a net-net accounting approach is envisaged for REDD+ to distinguish business as usual development from additional actions (see Chapter 3). For the reference level determination under REDD+ proposed in this article, as a first step the BAU development needs to be defined, which can provide the basis for further political negotiations on accounting approaches for crediting (such as crediting reference levels).

As the REDD+ mechanism is not yet in force and the design of reference levels is not yet decided, the study proposes a possible methodology for BAU reference level determination. The methodology is applicable for the deforestation activity of countries which are still in their net deforestation phase; such as most developing countries are today (see Chapter 2). Carbon stock changes on existing forest areas, such as degradation and the other 'plus-activities' are not covered but could be included as described above.

The proposed BAU reference level is determined by the comparison of the forest cover extent at two points in time (namely at the beginning and at the end of a commitment period). This is comparable to a stock change approach, although only forest areas are compared rather than carbon stocks. The net-net accounting approach can be applied for the comparison of the reference level development to the real performance within the commitment period. Predictions of five years are possible by the deforestation curve, and recalculations can be conducted after each period. National data is necessary for the calculations, as historic forest cover and further national circumstances were considered (see Chapter 5). The BAU development of each country according to the proposed BAU reference level approach is the mean global development of forest cover decline according to the forest transition hypothesis. By the consideration of national circumstances, the country's stage on the forest cover decline curve and the extent of deforestation are determined.

7. Conclusion of the cumulative dissertation

7.1. Implications of politically designed carbon accounting approaches

Carbon accounting in the LULUCF sector is designed with very complicated rules in the carbon accounting system. A special framework of Good Practice Guidance on LULUCF by the IPCC (2003) is effective for the LULUCF sector, while the IPCC Guidelines for National Greenhouse Gas Inventories (1997) are valid for all other sectors.

Different accounting approaches apply for different forest-related activities, which are further differentiated for industrialised and developing countries (see Chapter 3). Beyond this, amendments have been made to the rules between the commitment periods and the design of all aspects is not yet finalised.

The design of the accounting approaches, however, influences the incentive effects for emission reduction related to each activity and, therefore, influences the activities conducted. For example, Krug et al. (2009) assess the implications of different accounting approaches (gross-net, net-net with different base years, caps and discount factors) for the forest management activity in Germany and conclude that the incentive effects for the reduction of greenhouse gases depend on the accounting approach. Ellison et al. (2011) and (2013) claim that a huge incentive gap is created by the prevailing LULUCF accounting approaches for industrialised countries, that inconsistencies within the system exist and that the options for political negotiations on accounting rules lead to a “cherry-picking” mentality, in turn undermining possible incentive effects for emission reduction. The first article of this cumulative dissertation (Köthke and Dieter, 2010) assesses a different level of carbon accounting in industrialised countries, namely the direct sub-national incentive systems. This is the level where the incentive effect directly becomes effective, e.g., on the enterprise level, by domestic forest management and forest conversion actions. The findings on the sub-national level are comparable to the results of the above-mentioned authors, but are directly linked to competing interests for timber production and price influences. The authors conclude that different accounting approaches for afforestation and forest management activities on the sub-national level have a major influence on the incentive effect. Especially the application and design of reference levels (benchmarks for accounting) influences whether credits/debits are generated for additional action only or whether they are generated also for BAU activities (called ‘hot air’). Similarly, the different treatment of harvested wood products in accounting positively effects either the enhancement of the standing forests or the use of timber. The incentive effect, however, only comes into play if carbon prices are able to compete against timber prices. The authors demonstrate the potential direct economic effect of different accounting approaches on the operational level.

Comparable implications of the design of accounting approaches on the incentive effect in developing countries have been observed in the case of reference level design for REDD+. Perverse incentives such as leakage effects and 'hot air' are possible by the "false" determination of reference levels (Angelsen, 2008; Angelsen et al., 2011b). Several authors comparing different approaches for REDD+ reference level setting agree that the design of the reference level approach is crucial for the implications, namely the amount of credits generated for the individual countries and, therefore, the incentive effect for further action needed to reduce emissions. For example, Leischner and Elsasser (2010) assess the implications of four REDD+ reference level accounting approaches discussed in the political context (Compensated Reduction, Compensated Conservation, Incentive Accounting and Corridor Approach) on 84 countries and conclude that the different approaches provide a different favourability for the different countries (depending on their national circumstances) and that huge windfall effects can be generated. Griscom et al. (2009) calculate the implications of seven REDD+ reference level approaches and find significant differences in their implications. The overall implication is that each country possible of negotiating a reference level approach would favour the approach that maximises the amount of credits for this country ("cherry picking"). In the third article of this cumulative dissertation Köthke et al. (submitted) propose a new approach for reference level determination, which for the first time applies a globally uniform deforestation curve according to the forest transition hypothesis. This approach basically treats all countries equally (i.e., a uniform methodology is applied) but in addition considers national circumstances. Thus, new aspects for the political negotiations on reference level approaches are provided. The proposed consideration of the countries' stages on the forest transition curve in REDD+ reference level setting has been requested before (e.g., Angelsen, 2008; UNFCCC, 2009), but as of yet it could not be quantitatively applied and, therefore, was not followed up. The necessary empirical quantification of the deforestation curve has been conducted in the second article of this cumulative dissertation (Köthke et al., 2013).

In the light of the diverse incentives induced by the design of the several accounting approaches, it is most important that the overall global climate effectiveness is considered. The incentive effect for a single activity must be considered in relation to all other activities incentivised, which leads to the objective of a full and consistent carbon accounting.

7.2. Feasibility of a consistent carbon accounting

Consistent carbon accounting in the forest sector is neither a given among different countries nor among different activities (see Chapter 3). A consistent carbon accounting calls for comparability among national conditions, monitoring systems and measurement, reporting and verification capabilities and global accounting approaches. Currently, none of these requirements are in place.

National conditions differ substantially among the countries of the world with regard to land-use changes and forest management, but also concerning the underlying causes such as physio-geographic conditions, demographic and socioeconomic factors. These differences are even greater between industrialised and developing countries. According to the forest transition hypothesis (described in Chapter 1) there are, however, regularities in forest area development which can be observed in several countries, even though they are stretched and shifted in time. A globally uniform development of forest cover decline on national level has been empirically quantified by the second article of this cumulative dissertation (Köthke et al., 2013) which proved to be valid for industrialised as well as developing countries. Such quantification makes it technically possible to model forest cover decline. Furthermore, the quantification of the global forest cover development provides the first step for further discussions on global accounting approaches related to land-use change accounting. The described deforestation curve by Köthke et al. (2013), though, only considers the phase of forest cover decline according to the forest transition hypothesis and further analyses on the phases of forest transition and forest cover increase need to be conducted before the whole land-use change activities are covered.

Any further conclusions on area-related carbon stock changes, however, cannot be drawn from the findings. This deficit is also linked to the **problem of inconsistent measurement, reporting and verification capabilities** among the different countries, which are weak in developing countries where experience is lacking and capacities need to be developed (Angelsen et al., 2009, Ch. 7; Plugge et al., 2013; Plugge and Köhl, 2012). Once these problems are overcome, national data on carbon stocks and carbon stock changes could be applied on much finer scales for carbon reporting and accounting. Such an improvement of national data bases is still in progress in industrialised countries as well, but is not yet foreseeable on global scale in a comparable accuracy. Therefore, approaches for stepwise improvement of data accuracy will be implemented in developing countries as well (UNFCCC, 2012a, Dec. 12/CP.17; 2013a, 2013c). Besides these technical and capacity problems, rules for a consistent carbon accounting in the forest sector should be envisaged among industrialised and developing countries, not at least because emerging nations currently still classified as Non-Annex I countries will become Annex I countries in the future (Dutschke and Pistorius, 2008). **Globally consistent accounting approaches** are needed for the comparability of emission reductions conducted in the different countries to assess the global climate effectiveness. The global climate effectiveness cannot be guaranteed as long as gaps occur in the accounting system, which bear the risk of leakages. Thus, the different role of industrialised and developing countries must be respected, which is politically defined by the 'common but differentiated responsibilities'. The emission reduction of developing countries is subject to an external result-based financing from industrialised countries. This, however, is a matter of differentiated crediting/debiting decisions among industrialised and developing countries and might be independent from a uniform reporting and accounting procedure.

The projection and submission of FMRLs for industrialised countries in the 2nd CP could be an example for developing countries as well. The projections of BAU FMRLs are based on submissions by the individual industrialised countries calculated with national data (where available) and model projections. The national submissions undergo a standardised review process. A comparable FMRL for REDD+ would cover all carbon fluxes from the four activities of degradation, sustainable forest management, conservation and enhancement of forest carbon stocks. For REDD+ a combined benchmark of carbon stock changes on forest land and by land-use changes (including deforestation) is intended (REL/RL, see Chapter 1). National submissions on RELs/RLs by developing countries on a voluntary basis are already requested by the UNFCCC and technical assessments are envisaged (UNFCCC, 2012a, Dec. 12/CP.17). But as the full implementation is dependent on reliable measurement, reporting and verification systems, the interim requirements will be less strict for developing countries.

Comparable BAU reference levels have already been implemented in developing countries for CDM afforestation and reforestation activities but only on a small-scale project level. Yet, due to the complicated rules the afforestation and reforestation CDM projects have rarely been implemented in practice (Dutschke and Pistorius, 2008). The considerations conducted in the first article of this cumulative dissertation (Köthke and Dieter, 2010) on different sub-national accounting approaches also hold in developing countries on the project level, however, the price structures and interest rates in developing countries differ and, therefore, the incentive effect might shift. However, comparable considerations on the incentive effect of envisaged carbon accounting approaches in competition to other interests are needed in developing countries as well.

To overcome the lack of time needed to build capabilities for measurement, reporting and verification in developing countries, less complex reporting and accounting approaches are needed at least as stepwise approaches (Angelsen et al., 2012, Ch. 16). Different ‘tiers’ for reporting, with increasing demand on accuracy and national data input are envisaged, which has been proven to be operational for Annex I countries as well (see Chapter 3). The developing countries have the opportunity to adjust their reference levels (which are based on national data) for national circumstances. They have to argue and make transparent the choice of national circumstances considered and the way and extent of reference level adjustment. This implies case-by-case solutions and reference levels and requires a transparent and comparable technical assessment. The accounting approach for REDD+ reference levels proposed in the third article (Köthke et al., submitted) is a solution where only little national data is needed (for the underlying national circumstances, including the historic forest cover), which might be attractive at least as an interim solution. The proposed method further provides a consistent approach for the adjustment for national circumstances for all countries instead of case-by-case solutions, which would increase comparability and an equitable treatment.

Generally, a consistent carbon accounting in the forest sector should be envisaged in the long term, which does not include the harmonisation of the crediting and debiting approaches among industrialised and developing countries in the light of ‘common but differentiated responsibilities’.

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Appendix I: Scientific articles

Köthke, M., Dieter, M., 2010. Effects of carbon sequestration rewards on forest management – An empirical application of adjusted Faustmann-Formulae. Forest Policy and Economics 12 (8), pp. 589-597.

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Effects of carbon sequestration rewards on forest management—An empirical application of adjusted Faustmann Formulae

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ABSTRACT

This paper assesses the effects that different economic instruments to reward carbon sequestration services might have on forest management, especially on the optimal rotation period. Three different carbon crediting schemes are considered, which are based on different accounting rules. The schemes are different with respect to the question whether and how to account for carbon emissions.

The forest valuation method used for calculation is based on the land expectation value (LEV), which was adjusted for the value of carbon sequestration services. Changes in the LEV and optimal rotation are expected to be induced by the amount and interactions of carbon and timber prices, harvesting and regeneration costs, and interest rates. The optimal economic rotation period is calculated for single stands as well as for whole forest enterprises (fully regulated "normal" forests). Crediting the carbon sequestration of single stands—starting from the time of regeneration—is comparable to rewarding afforestation projects. When crediting forest enterprises with existing timber and carbon stocks, additional carbon sequestration compared to a reference is rewarded.

The findings reveal that, depending on the carbon price level, the optimal rotation period is increased in all considered crediting schemes, but with different intensity. If wood removals have to be accounted as carbon emissions this has the most significant effect on the optimal rotation period for forest stands and enterprises. In this case the increase of the optimal rotation period by rising carbon prices is boosted additionally by rising interest rates. Different thinning regimes, however, have only little impact on the time of maximum LEV under carbon crediting schemes.

1. Introduction

Quantitative targets for reducing CO_2 emissions have been agreed upon among the contracting parties of the Kyoto Protocol for the first commitment period. The Kyoto Protocol already integrates rules for the inclusion of forest sinks and sources (UNFCCC, 1998, Art. 3.3 and 3.4). Generally carbon credits will be generated by the participating states if the carbon balance of the national forests is positive compared to a reference, and debits will be generated if the balance is negative. However the details for carbon accounting methods and implementation are open for revision for the period after 2012. Forest owners have no direct rights to profit-sharing from the forest carbon credits of the state, and they are also not authorized to participate in the European Union Emission Trading System (EU-ETS). As a consequence, they have no incentive to increase the carbon sequestration of their forests. By setting appropriate incentives, each state may try to influence the sequestration by the forests within its national borders, and therefore influence the national carbon balance. The implementation of domestic policy instruments and incentives—which is addressed case by this study—is independent from the accounting on the national level.

This study investigates how different economic incentives aiming at increased carbon sequestration in forests can influence the economic advantageousness of different forest management regimes, in particular rotation regimes. Domestic policy instruments may for example aim at increasing the carbon and wood stock in the forests, or at increasing annual increment and thus, the carbon sequestration rate, optionally in combination with the use of long living wood products. If forest owners take such incentives into account, they will have to reassess various management decisions, e.g. whether to lengthen or shorten the rotation period, whether to change the tree species composition and whether to maintain forest management at all. Depending on different management practices and goals, rational forest owners will calculate the implicit sequestration value—which results from the political incentive—in competition with timber values and all expected costs.

For this study the forest valuation method of maximum land expectation value (LEV) based on the Faustmann Formula is chosen as

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the basis for calculation. The optimal rotation period is identified by static comparisons of different rotation regimes. Differences between unstocked land and existing timber stocks are considered by regarding single stands as well as “normal” forest enterprises. The mutual influences of carbon and timber prices, harvesting and regeneration costs and interest rates are analyzed as well as different thinning practices and intensities, including a no thinning option.

2. Materials and methods

2.1. Literature review

To our knowledge, the first approach of allocating value to the standing forest and opposing it to the value of harvested timber can be ascribed to Hartman (1976) who adjusted the Faustmann Formula with the value of recreational and other services of a forest. Later studies concretized this idea by including the value of carbon sequestration, focusing on the optimization of the harvesting decision or the related costs (see review of cost studies by Richards and Stokes, 2004). The question of optimal rotation was analyzed by some studies disregarding thinning and mortality (Creedy and Wurzbacher, 2001; Gong and Kriström, 1999; Olschewski and Benítez, 2010), which allows for continuously differentiable analyses, but implies a simplification. Further simplification is made by using standardized growth functions as yield data, whereas this study uses data generated with detailed growth and management models based on site specific data for Germany. It is valuated with regard to dimensional assortments and their corresponding pricing instead of averaged prices. Comparable to this, Maclaren et al. (2008) assessed the impacts of carbon crediting on forest management under the current New Zealand Emission Trading Scheme; however these authors did not take harvested wood products into account.

The problem was also analyzed using dynamic and linear programming approaches (e.g. Daigneault et al., 2010; Hoen and Solberg, 1994; McCarney et al., 2008; Newell and Stavins, 2000; Spring et al., 2005) also including additional values besides carbon sequestration or risks.

In this study different approaches of carbon crediting are compared and the carbon storage in harvested wood is considered as well. Comparable assessments group harvested wood on a quantity basis into either “immediate emitters” or “everlasting carbon stores” but do not include different lifespans of wood products (see e.g. Cacho et al., 2003; Creedy and Wurzbacher, 2001; Romero et al., 1998; Stainback and Alavalapati, 2002; van Kooten et al., 1995). The approach in this paper shows the whole range for including harvested wood, related to the lifespan of wood products ranging from zero years to nearly infinity in correlation to the diameter of the removed timber. In the context of a carbon fee on fossil fuels in Scandinavia Solberg (1997) used a detailed approach of debiting the carbon emissions at the end of use plus decaying time of harvested wood for assessing the net value of carbon fixation in a forest stand. Comparable approaches are conducted in the context of temporary carbon credits from the Clean Development Mechanism (CDM) market (Guitart and Rodriguez, 2010; Olschewski and Benítez, 2010).

This study discusses the concern of additionality and appropriate reference levels by the examples of unstocked land and existing forests on enterprise level. The carbon sequestration of existing forests is conducted by some studies as well (e.g. Foley et al., 2009; Guitart and Rodriguez, 2010; Huang and Kronrad, 2001; Sohngen and Brown, 2008; Spring et al., 2005) but mostly the assessments are focused on the costs of externally given rotation ages and are based on single stands only. Plantinga and Birdsey (1994) assessed optimal rotations of existing forest stands, but did not consider the problem of existing carbon stocks and additionality as it is given regarding the enterprise level. One of the rare studies conducting the enterprise level is that of Knoke and Weber (2006), taking into account ecological, social and sustainability constraints, in particular risk aspects in a dynamic approach. However, the study is considering a planning period of only 30 years and therefore not reflecting the key characteristic of forest management: exceptionally long production periods. Also they are not allowing for the optimization of rotation periods which is the focus of our study, addressed by using the model of a “normal” forest enterprise as an example for existing forests with the LEV-analysis under different accounting schemes.

2.2. Database

The calculations are applied to one example of a virtual forest stand and one of a virtual forest enterprise. The yield tables for the stand are generated with the growth and management model SILVA 2.2 for an even-aged spruce stand in Bavaria, Germany. The forest enterprise is based on this yield data and built up as a fully regulated forest according to the model of a normal forest. A normal forest consists of evenly distributed forest stands concerning vintages and stocking. The stands are equally sized and the number of stands is equal to the rotation age *T*. The annual volume of increment equals the volume of harvests, thus the normal forest is in equilibrium (see e.g. Salo and Tahvonen, 2002; Speidel, 1967, pp. 109–110). The basic stand is managed according to a selective thinning regime, thinned at most every 5 years. Variations of the thinning regime are considered in an additional sensitivity analysis (see Section 3). Since the growth model does not produce values for the first 25 years, these data are extrapolated. In consequence of lacking data on growth, mortality and management of stands older than 170 years, the data is extrapolated up to a stand age of 250. To avoid an overestimation of the carbon sequestration of old stands, we assumed that the standing volume decreases after 170 years because of increased mortality, technically this was modeled as intensified thinning (see Figs. 1 and 2).

The carbon content is calculated by multiplying the volume of increment and removals (m^3 solid volume over bark/ha per year) by the mean carbon density of spruce wood (0.24 tC/m^3) (Wirth et al., 2004), with 1 tC≙3.67 t CO_2 (44 g/mol CO_2, 12 g/mol C). Our calculation is restricted to solid volume only, and does not include other tree biomass (roots and needles).

Timber prices as well as harvesting and regeneration costs are taken from the literature and market statistics (WBR, 2003, 2006; ZMP, 2005–2006) (see Table 1) and are structured in dimensional assortments. They are applied to the mean diameter of thinning wood and wood stock for each period combined with the assortment tables of Schöpfer and Dauber (1989) subject.

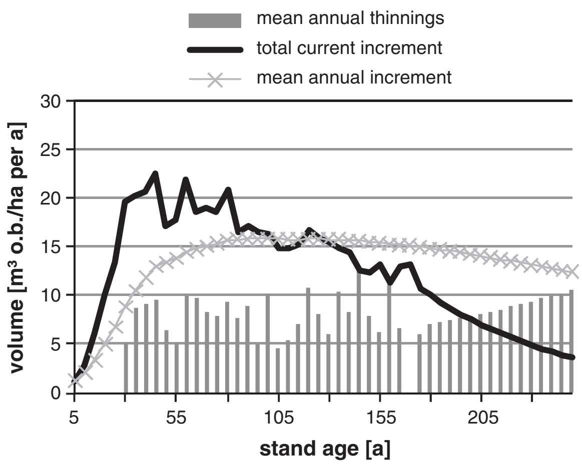

Fig. 1. Total current increment, mean annual thinning volume and mean annual increment of a spruce stand, selective thinning (growth and management data generated with Silva 2.2, extrapolated).

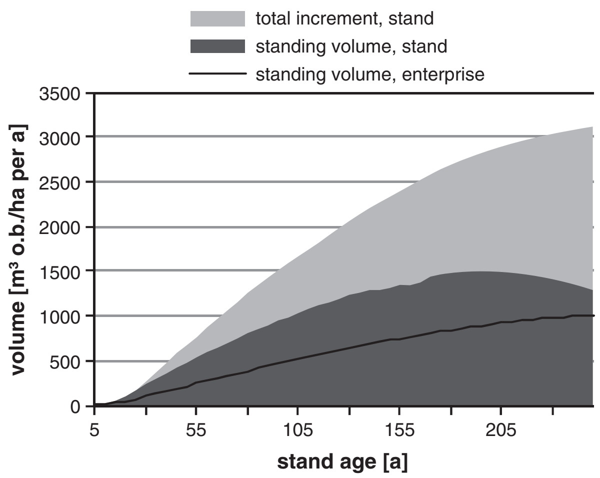

Fig. 2. Total increment and standing volume of a single stand and a normal forest enterprise (spruce, growth and management data generated with Silva 2.2, extrapolated).

As the future development of carbon prices is linked with uncertainties, we chose a carbon price variation from 0 to 100€/t CO_2. The carbon price in the basic variant is 34€/t CO_2, which is the modeled price for carbon trading in the EU in the year 2030 from the calculation of Kuik (2008). He modeled carbon prices with the model GTAP-E under different emission reduction scenarios and trading regions. The highest assumed carbon price (100€/t CO_2) can be considered as an upper limit, as it is the current penalty for excess emissions in the EU's ETS market (EU, 2003), and current prices in the EU-ETS as well as abatement costs in several studies are well below this limit (e.g. IEA, 2001; McKinsey and Company, 2007).

The interest rates are varied from 0.1 to 10%. Higher interest rates are not shown because they hardly apply for forestry in most Annex-I-countries. The interest rate in the basic variant is 2%.

Transaction costs coming along with the various policy instruments are not included in the calculations.

The lifespan of harvested wood is correlated to the use of the wood which may range from short-living fire wood to long-living wood products. The used factor *h* for the lifespan of harvested wood is therefore linked to the dimensional assortments. Hence thicker stem wood is assigned to be used for wood products with longer lifespan than thinning material. The options for defining the diameter-correlated lifespan are manifold, as timber use and wood processing are not constant. Therefore a series of values for *h* was calculated. The mean lifespan, from the time of harvest to the final combustion or decomposition, is varied from 0 to 500 years. In the basic variant harvested wood is assumed to have a mean lifespan of 30 years.

For assessing the influence of price relations and other factors, basic assumptions about prices and interest rates are varied in sensitivity analysis but are always constant within one simulation (see Table 1).

2.3. Valuation method

With the standard LEV analysis the optimal economic rotation is calculated by discounting all infinite revenues and costs to a reference year. Profit-maximizing forest management oriented on the rotation of the highest LEV is chosen as the reference case for determining the sequestration rate without carbon credits. The differentiation between forest stand and forest enterprise is chosen to analyze the case of afforestation on bare land (stand level) and the case of "existing forest land remaining forest land" (enterprise level). Without carbon crediting there is no difference between these two in the optimal rotation period of the highest LEV. But as soon as crediting schemes are established, stands and enterprises become different with respect to their reference level. While in the case of afforestation all increment is additional and therefore accountable, in the case of existing forests only changes from the reference economic optimum are accountable. Since in the normal forest enterprise current annual increment, annual removals and the annual financial flows are equivalent each year, differences only occur among enterprises with different rotation regimes. The comparison is static, as modeling a dynamical transition process from one status to another would require some additional assumptions, in particular about the length of the transition time. This would lead away of the core question asked here. The static comparison and the consideration of discontinuous events (like thinning operations) require a discrete calculation (see Deegen et al., 2000).

2.4. Carbon crediting schemes

The three different approaches to carbon crediting are all based on the assumption that carbon sequestration by forests is rewarded to the forest owners by the national states according to the individual design of economic incentive schemes. The three incentive schemes are activity related carbon crediting schemes for rewarding additional carbon sequestration. They differ in the way the duty to account for the carbon emissions resulting from harvesting or natural decomposition is allocated.

The first scheme (in short "Cert1") rewards forest increment by crediting each metric ton of carbon sequestered in the growing wood, and penalizes any kind of carbon release caused by wood removal; for instance by harvests, thinnings and natural mortality. Wood removals are treated as immediate carbon emissions in this scheme. For the existing forests (enterprise level) this means accounting for the changes in the carbon stock.

The second scheme ("Cert2") honors total increment, but does not discriminate the use of wood. In this scheme wood removals do not cause any debits for a forest owner, assuming that the carbon will be stored in long living wood products (inter alia using product cascades), or in the deadwood or it will replace fossil fuels. This scheme aims at increasing the mean increment rate; emissions from combustion or natural decomposition are not being accounted for.

The third scheme ("Cert3") lies in between the two aforementioned. A debit for carbon emissions has to be paid when the carbon is

Table 1
Basic data and economic variables.

	Basic variant assumptions	Source	Variations v
Interest rate	2%		v∈{0.1, 0.2, …10%}
Regeneration cost	1900€/ha	WBR, 2003	
Carbon price	34€/t CO_2	Kuik, 2008	v∈{0, 1, …100€/t CO_2}
Timber prices	20.00, …69.40€/m³ subject to diameter	ZMP, 2005-2006	v∈{50, 100, …400%}
Harvesting costs	13.77, …33.36€/m³ subject to diameter	WBR, 2006	
Mean lifespan of hwp	30 years		v∈{0, 1, …500 years} subject to diameter
Thinning regime	Selective thinning	SILVA 2.2	v∈{selective thinning, intensive crown thinning, no thinning (but final harvesting)}

emitted to the atmosphere. In Cert3 it is assumed that the debit will be paid through a carbon tax at the end of life of the wood products (which practically corresponds to when the wood is burned in most cases). As the carbon tax will have to be paid by wood consumers rather than wood sellers, it does not directly affect the forest owners, but it will indirectly affect the market price for wood.

2.4.1. Single forest stand

The optimal economic rotation age of the single forest stand is reached when the LEV reaches its maximum. The valuation is based on the Faustmann Formula, which calculates the net present value (NPV) of all revenues and costs related to wood production (NPV^w) (Eq. (1)). For the crediting schemes it is extended by the NPV of all revenues and costs related to carbon crediting (NPV^c) (Eq. (2)).

LEV (without carbon crediting):

$$LEV = NPV^w = \frac{Rh_T + \sum_{a=0}^{T}(Rs_a*(1+i)^{T-a}) - K*(1+i)^T}{(1+i)^T - 1} \rightarrow \max!, \quad (1)$$

with

LEV	land expectation value [€/ha]
NPV^w	net present value of all revenues and costs related to wood production [€/ha]
T	rotation age [years]
a	year of revenue or cost [years]
Rh	net revenues from final harvest / felling value (net of harvesting costs) [€/ha]
Rs	net revenues from silvicultural measures/ thinning (net of harvesting costs) [€/ha]
K	regeneration cost [€/ha]
i	interest rate.

LEV (with carbon crediting):

$$LEV = NPV^w + NPV^c = \frac{Rh_T + \sum_{a=0}^{T}\left(Rs_a*(1+i)^{T-a}\right) - K*(1-i)^T}{(1+i)^T - 1} + \frac{\sum_{a=0}^{T}\left(Rc_a*(1+i)^{T-a}\right)}{(1+i)^T - 1} \rightarrow \max!, \quad (2)$$

with

NPV^c	net present value of all revenues and costs related to carbon crediting [€/ha]
Rc	net revenues from carbon crediting [€/ha].

The NPV^c is added to the NPV^w when carbon sequestration is rewarded. As the net revenues from carbon crediting are defined by the crediting scheme, the specific equations of the NPV^c referring to the three carbon crediting schemes are presented subsequently (Eqs. (3)–(5)).

Cert1 :

$$NPV^{c1} = \frac{\sum_{a=0}^{T} ci_a*CP\ (1+i)^{T-a} - \sum_{a=0}^{T} ce_a*CP*(1+i)^{T-a}}{(1+i)^T - 1}, \quad (3)$$

with

CP	carbon price [€/t C]
ci	carbon content of total current increment [t C/ha per year]
ce	carbon content of annual wood removal (thinning, harvest or mortality) [t C/ha per year].

In the crediting scheme Cert1, carbon credits are generated annually for the net carbon increment of each year (credits for total current increment *ci* less debits for annual wood removal *ce*). At the time of final harvest, the debit is charged for the whole harvest volume free of interest (*a* equates *T*). Interest accrues for all revenues and expenses according to the interest rate *i* until the end of the rotation period. In our calculation, interest will be paid (charged) for credits (debits) to the same interest rate, and carbon prices remain the same for credits as for debits.

Cert2 :

$$NPV^{c2} = \frac{\sum_{a=0}^{T} ci_a*CP*(1+i)^{T-a}}{(1+i)^T - 1} \quad (4)$$

Compared to Cert1, the crediting scheme Cert2 is much simpler; only gross increment leads to payments (credits for total current increment) and no debits are charged.

Cert3 :

$$NPV^{c3} = \frac{\sum_{a=0}^{T} ci_a*CP*(1+i)^{T-a} - \sum_{a=0}^{T} ce_a*CP*(1+i)^{T-(a+h)}}{(1+i)^T - 1}, \quad (5)$$

with

h	lifespan of harvested wood (products) [years].

In contrast to Cert1 and 2, Cert3 is more complex, since the time of thinning and harvesting and the time of debit charge differ. Hence the debit cannot be subtracted immediately from the credit of the respective year (as in Cert1). The debit is delayed by *h* years (i.e. the time the carbon is stored in the harvested wood).

All three crediting schemes can be expressed by Eq. (5), with *h* defining the time of debit charge after wood removal. For Cert1 debits are charged at $h=0$, for Cert2 debits are never charged ($h=\infty$).

2.4.2. Forest enterprise

The calculation of the optimal economic rotation age for the normal forest enterprise is based on the land expectation value as well, regarding all revenues and costs of the forest stands within the forest enterprise (e.g. Speidel, 1967, p. 178) (Eq. (6)). For the static comparison of forest enterprises with different rotation periods, the enterprises are assumed to have a fixed total area, consisting of *T* forest stands, each having a size of 1/*T* times the area of the forest enterprise.

LEV (without carbon crediting):

$$LEV^w = \frac{1}{i}*\left(\frac{Rh_T + \sum_{a=1}^{T} Rs_a - K}{T} - \frac{i*\sum_{m=0}^{T-1} SEV_m}{T}\right) \rightarrow \max!, \quad (6)$$

with

SEV	stand expectation value [€/ha]
m	age of the immature stand [years].

The calculation includes the stand expectation value *SEV* of the immature forest stands as the opportunity cost of retaining the forest stock (see e.g. Speidel, 1967, p. 102), defined in Eq. (7).

$$SEV_m = \frac{Rh_T + \sum_{a=m}^{T} Rs_a*(1+i)^{T-a} - NPV^w*\left((1+i)^{T-m} - 1\right)}{(1+i)^{T-m}} \quad (7)$$

Eq. (7) includes the NPV^w for calculating the soil rent. NPV^w is described in Eq. (1), it is equal to the land expectation value without carbon credits for a single stand.

A forest enterprise managed according to the maximum land expectation value without carbon crediting serves as the reference (R) in the following calculations ($LEV^{w} \rightarrow \max = LEV^{w}{}_{TR}$). TR is the optimal economic rotation age (T) without carbon crediting. The carbon stock and sequestration rate of this reference case are used to quantify the additional carbon sequestration when carbon credits are considered (Eq. (8)). It will be determined whether a rotation regime differing from TR will become optimal when carbon credits are included.

LEV (with carbon crediting):

$$LEV = LEV^{w} + V^{add}$$

$$= \frac{1}{i} * \left(\frac{Rh_{TR+t} + \sum_{a=1}^{TR+t} Rs_a - K - i * \sum_{m=0}^{(TR-1)+t} SEV_m}{TR+t} + V^{add} \right) \rightarrow \max!, \quad (8)$$

with

V^{add} annual revenue from carbon crediting [€/ha per year]
t time of shift of TR [years].

The annual net revenues from crediting additional carbon sequestration (V^{add}) are added to the LEV of revenues and costs from wood production (LEV^{w}).

Additional carbon sequestration only happens when the rotation age is unequal to the reference rotation age TR. Thus, different rotation ages $TR+t$ are considered, and the results are compared to the reference forest enterprise. The regarded rotation regimes may be longer or shorter as compared to TR, as t may become negative as well.

V^{add} is defined differently for each crediting scheme and the specific equations are presented in Eqs. (9)–(11).

Cert1 :

$$V^{add1} = \left(\frac{\sum_{m=1}^{TR+t} cs_m}{TR+t} - \frac{\sum_{m=1}^{TR} cs_m}{TR} \right) * CP * i, \quad (9)$$

with

cs carbon content of standing volume [t C/ha per year].

The carbon content of the standing volume (cs) of the forest enterprise managed with a rotation period of $TR+t$ years is compared to the standing volume of the reference forest enterprise with a rotation age of TR years. If the carbon stock is higher than in the reference case, the difference is rewarded with a carbon credit. If the stock is lower than in the reference case, debits rather than credits are generated.

Because the standing volume in the normal forest enterprise is a static value, the credit is only paid once. The forest enterprise gains an annual interest from this one-time credit for the net carbon stock increase that is permanently maintained. Since in the normal forest the volume of annual increment and annual removals is equivalent, only the additional standing volume is considered here.

Cert2 :

$$V^{add2} = \left(\frac{\sum_{m=1}^{TR+t} cs_m}{TR+t} - \frac{\sum_{m=1}^{TR} cs_m}{TR} \right) * CP * i + \left(\frac{\sum_{m=1}^{TR+t} ci_m}{TR+t} - \frac{\sum_{m=1}^{TR} ci_m}{TR} \right) * CP \rightarrow \max! \quad (10)$$

Cert2 rewards the additional standing volume (cs) as before, and also the additional total current carbon increment (ci). For the latter the total current increment of the reference forest enterprise is substracted from the total current increment of the regarded forest enterprise. The annual surplus is rewarded with annual carbon credits. No debits are charged for annual wood removals.

If the stock or the increment of the regarded forest enterprise is lower compared to the reference case, debits are generated accordingly.

Cert3:

$$V^{add3} = \left(\frac{\sum_{m=1}^{TR+t} cs_m}{TR+t} - \frac{\sum_{m=1}^{TR} cs_m}{TR} \right) * CP * i + \left(\frac{\sum_{m=1}^{TR+t} ci_m}{TR+t} - \frac{\sum_{m=1}^{TR} ci_m}{TR} \right) * CP - \left(\frac{\sum_{m=1}^{TR+t} ce_m}{TR+t} - \frac{\sum_{m=1}^{TR} ce_m}{TR} \right) * CP * (1+i)^{-h} \rightarrow \max! \quad (11)$$

Cert 3 rewards additional stock and annual increment like in Cert 2. But the credits generated have to be paid back at the end of life of the wood products. If the end user will have to pay the debit, he will reduce the market price of wood correspondingly, so that the forest owner will have to bear the debit eventually.

Again, all the three crediting schemes for the enterprise can be expressed by Eq. (11) defining the time of debit charge h adequately. Equivalent to the crediting rules for the single forest stand, Cert1 results from Eq. (11) if $h = 0$, Cert2 results if $h = \infty$.

3. Results

The economically optimal management of a forest is oriented towards the rotation of the highest LEV. The LEV of the normal forest enterprise is equal to the LEV of a single forest stand (see Fig. 3). Rotation periods longer or shorter than that of the highest LEV are not profitable as long as other incentives are absent.

According to the concept of the LEV, the rotation period without carbon crediting reaches its economic optimum (TR) before the mean annual increment (MAI) has reached its maximum. With respect to the different reference levels, the rotation optimum of the stand and the enterprise differ, when carbon credits are considered (see Fig. 4). Fig. 3 shows the development of the LEV for the single stand under the three crediting schemes. Under the carbon crediting scheme Cert2, which supports total increment, the rotation period of the forest stand is increased for some years (compare Figs. 3 and 4). At stand level (comparable to afforestation of bare land) most carbon credits are generated at the time of strong increment. Accordingly the rotation period will be increased towards the year of maximum MAI, but not become infinite because interest gains have to be offset against decreasing gains from timber and carbon increment over time.

Cert1 has the same effect for increment credits, but the debit for harvest weakens the effect of the credits already in earlier years. Thus the optimum is delayed. Due to the fact that final harvesting not only offers the opportunity for new and high increment but also is "punished" by a debit on harvested carbon content in this scheme, there is no clear maximum of the land expectation value over time (see Fig. 3).

Cert3 was argued to be an approach somewhere between Cert1 (debit immediately at the time of harvesting and thinning, respectively), and Cert2 (no debit for carbon release). Correspondingly the LEV and the optimal rotation age of Cert3 lie between those of Cert1 and Cert2 (which can be seen in Figs. 3–5). Cert3 varies according to the mean lifespan for harvested wood h; to reduce the figures to a readable minimum, the presented graphs for Cert3 only display the results for $h = 30$ years. For all possible variations of h Cert3 is always bounded by Cert1 and 2. The closer h gets to zero, the more Cert3 converges to Cert1, the higher h gets, the closer Cert3 comes to Cert2. Since the graphs of Cert1 and Cert2 define the range of Cert3 for all following variations, Cert3 will no longer be shown in the presentations.

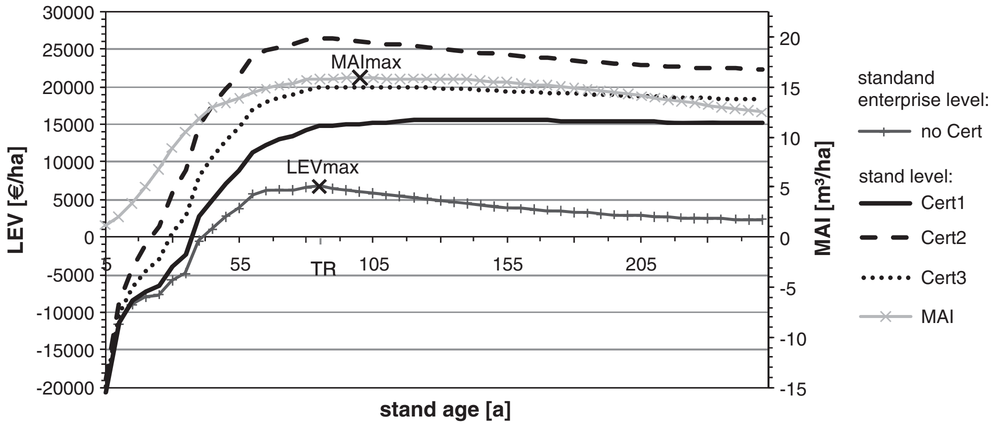

Fig. 3. Development and maximum of the land expectation value (LEV) and the mean annual increment (MAI) over time; and LEV for single stands under different carbon crediting schemes (spruce, selective thinning, carbon price 34€/t CO_2, interest rate 2%).

At the enterprise level, all values are related to the reference rotation age *TR* (see Fig. 3). Forest enterprises with rotation ages higher than *TR* can generate net carbon credits under all three crediting schemes in the presented example. Enterprises with shorter rotation periods will generate net debits in the example.

Carbon credits shift the maximum of the LEV clearly to rotation ages much higher than *TR* (see Fig. 4). This effect occurs due to higher standing volumes per hectare in enterprises with longer rotation periods (see Fig. 2), which is the strongest influencing value (in Cert1 it is the only influencing value). The carbon volume of the additional total current increment is much smaller than the carbon volume of the additional standing volume. Moreover, the total current increment per hectare is declining when the rotations exceed a certain period (equal to the time of maximum MAI at stand level). This countervails the effect of higher carbon stocks, which can be seen under Cert2 and Cert3 (see Figs. 4 and 5).

The sensitivity of the system was assessed by varying the economic parameters. When carbon prices increase, the sequestration value becomes more influential in relation to timber values. The effect of carbon prices on the optimal economic rotation period is shown in Fig. 4 at stand and at enterprise level. When carbon prices rise notably, the use of wood may become unprofitable in comparison with carbon storage, and the interest profit from carbon sequestration revenues may exceed potential timber revenues. For the existing forests long rotation regimes become profitable already when carbon prices are low.

Fig. 6 reveals the very strong influence of the carbon prices on the optimal rotation period at stand level, in particular for Cert1. Increasing carbon prices considerably increase the optimal rotation period under the Cert1 scheme. Moreover, Fig. 6 shows that there is hardly a difference between selective and intensive crown thinning, but compared to a "thinning regime" which refrains from any thinning, the latter notably reduces the optimal rotation period. The missing debits for wood removal from thinning are replaced by debits for mortality, but in contrast to the regimes with thinning, there are no revenues from thinning. (Note that the growth model predicts relatively high mortality rates of around 100–120% compared to thinning volume.) Hence an earlier final harvest is more economic. For Cert2, the described effects are much weaker.

The effect of carbon prices needs to be related to other prices and costs as they may be competing factors. Our calculations prove that a raise of the timber price level tends to shorten the optimal rotation period and is thus countervailing the effect of rising carbon prices. Without carbon credits the effect of decreasing optimal rotation periods is small; e.g. there is a five-year decrease in optimal rotation age (from 85 to 80 years) by a 30% timber price increase, but the two next 5-year reductions are reached only at rather unrealistic timber price increases of about 100% and 450% respectively.

Likewise, with the increase of interest rates, the optimal economic rotation period decreases, which has been shown in other studies as well (e.g. Möhring, 2001). This effect can be found as well for single

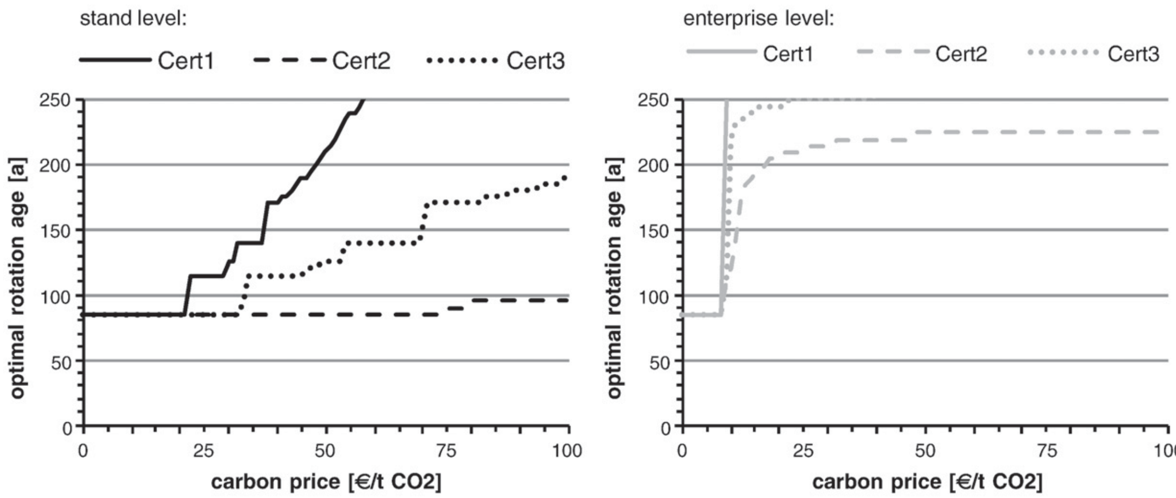

Fig. 4. The effect of carbon prices on the optimal rotation age at stand level (left) and enterprise level (right) (spruce, selective thinning, interest rate 2%).

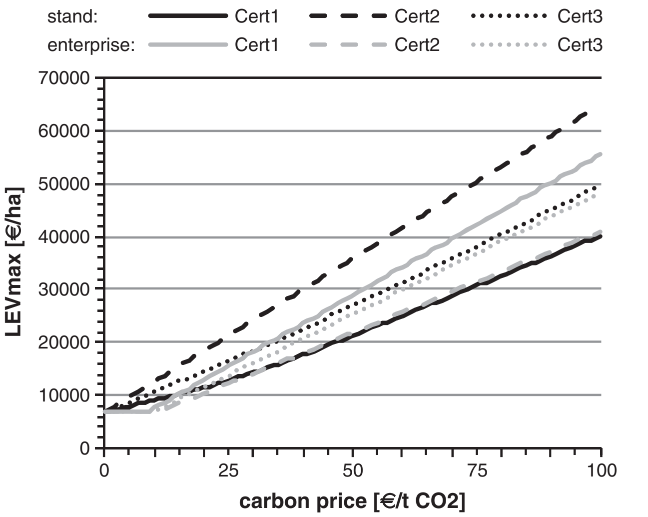

Fig. 5. The effect of carbon prices on the maximum land expectation value (LEVmax) (spruce, selective thinning, interest rate 2%).

stands under carbon credits, although the carbon crediting weakens the effect of rising interest rates (Fig. 7). Here differences exist between the carbon crediting schemes. Given the obligation to pay a debit when the timber is harvested, higher interest rates have only weaker effects on the optimal rotation period. This can be explained by the fact that the credits are earned in younger stand ages and are accumulating interest yield over time. Interest losses by postponing final harvest are offset to some extent by interest gains by postponing debit payment. In contrast to these findings, at enterprise level the interest rate is boosting the annual revenue from the interest profit of the one-time credit, and longer rotation regimes become more profitable at higher interest rates (see Fig. 7). The order of Cert1 causing longer optimal rotation periods than Cert3, followed by Cert2 with shortest optimal rotation periods, is still valid at different interest rates at both stand and enterprise level.

An analysis of the interrelation between interest rates, carbon prices and the optimal rotation period comes to interesting results. As expected from the results above, a decrease of the optimal rotation period with rising interest rates is visible at stand level (Fig. 8). However, for Cert1 this effect only occurs up to carbon prices of about 40€/t CO_2. With higher carbon prices, the rotation period is increasing more rapidly when interest rates increase. The surplus of carbon credits in Cert1 is gained by the interest yields of the increment-credits. This is caused by the time gap between wood increment and wood removal; the effect is boosted by increasing carbon prices and interest rates. Relating to the underlying timber prices and harvesting costs, carbon prices beyond 40€/t CO_2 obviously offset the revenues from final harvest. At enterprise level this effect is valid for all crediting schemes, but it already occurs at very low carbon prices (2—10€/t CO_2) (see Fig. 9).

4. Discussion and conclusion

Even though the future policy framework for accounting the carbon sequestration of forests is not yet set, the implications of feasible economic instruments on forest management can be assessed. To assess the influence of carbon sequestration reward schemes on forest management, this study compares the development of the forest value and optimal rotation period under different conceivable policy instruments. The design of the instruments is varied in order to capture different possible accounting and liability rules for carbon emissions from wood removal, and to scrutinize how sensitively forest values react to changes in carbon prices, timber prices, interest rates and thinning regimes.

The findings show the great impact instrument design can have on forest management. Rewards for carbon sequestration raise the land expectation value (LEV), which can be seen at all considered crediting schemes. Obviously the achievable returns per hectare increase with the carbon price. A shift of the LEV level needs not necessarily result in a change of the rotation period; first of all, it affects profitability. The rewarding of carbon sequestration services could be an opportunity to reach profitability for so far unprofitable forestry sites. This may as well cause a shift among the profitability relations between different tree species due to their different carbon densities, and therefore may lead to a change in favorable tree species composition.

Secondly, the defined and assessed carbon crediting schemes increase the optimal economic rotation period subject to the level of the carbon price. The intensity of this effect is influenced by the accounting rule for harvested wood and therefore different among the different crediting schemes. It is strongest when wood removal is handled as an immediate carbon release and immediately charged with emission-debits (Cert1). The later the debit is charged (i.e. at the end of lifespan of the harvested wood in Cert3 or never in Cert2), the smaller is the effect.

Since additionality is a key criterion of international climate policy, we distinguish two cases with rather different reference systems. The first case considers afforestation on bare land where all increment is additional and hence accountable. To some extent, this case methodologically serves as an intermediate step. Afforestation on bare land is not a major issue in most of the European countries.

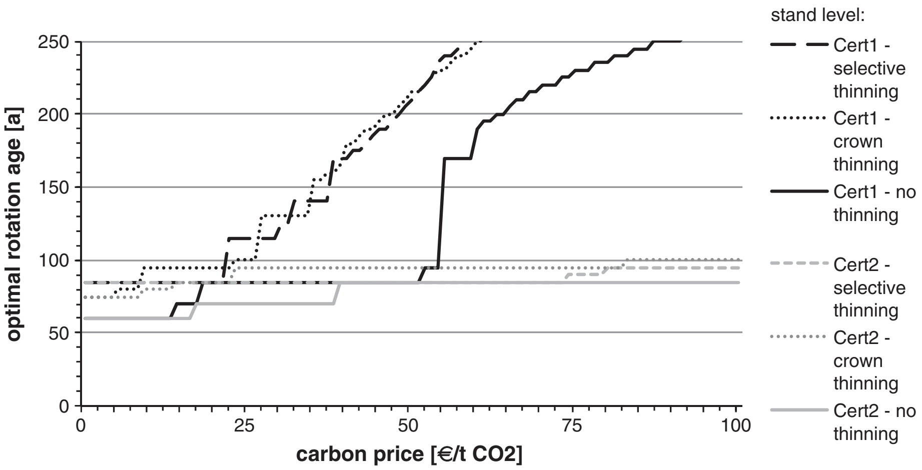

Fig. 6. The effect of carbon prices on the optimal rotation age under different thinning regimes at stand level (spruce, interest rate 2%).

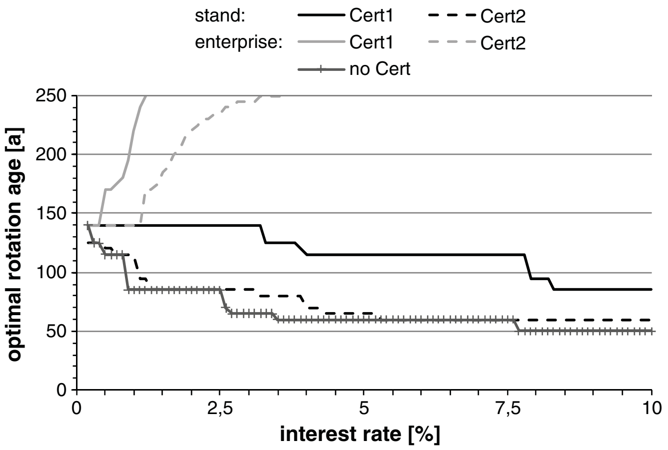

Fig. 7. The effect of the interest rate on the optimal rotation age at stand and enterprise level (spruce, selective thinning, carbon price 34€/t CO_2).

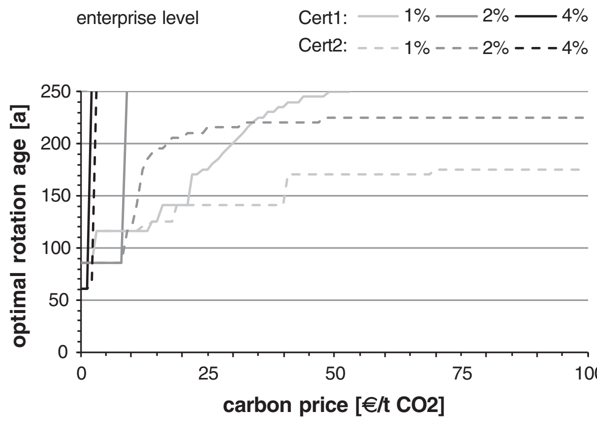

Fig. 9. The effect of carbon prices on the optimal rotation age at enterprise level for different interest rates (spruce, selective thinning).

However, the results show the basic interrelations between the different carbon crediting schemes and forest management. The second case of existing forests is deemed to be much more relevant for forestry in Annex-I-countries. The reference system in this case is the optimal economic forest management of forest enterprises in the absence of carbon crediting schemes. Only carbon sequestration exceeding this reference level is additional and hence accountable.

Under the defined reference assumptions all of the three crediting schemes prove to have much stronger effects on forest management for existing forest enterprises than for new forest stands. In particular the optimal rotation age can be expected to rise dramatically already at lower carbon prices. Even the carbon crediting scheme which is aimed at enhancing wood increment and fostering wood use by exempting it from any debit, neither at the time of removal nor at the end of lifespan, (Cert 2) results in a forest management regime with much longer rotation periods and lower harvesting volume than in the reference case. This result shows the relevance and potential impact of the reference system and emphasizes the need to analyze the interrelation between potential reference systems and potential policy instruments.

The study is comparing potential management regimes to the reference management regime, and is not considering the conversion from one regime to another. This is recommended for further assessments, as the arising expenditures of cost and time may counteract the described effects.

Different thinning regimes do not significantly influence the direction and intensity of the effect of the crediting schemes as they are not changing the development of the forest stands that much. Only for regimes without thinning the revenues from thinning are missing whereas the volume of mortality is debited (Cert1). Long rotations with high mortality rates are not profitable in this case.

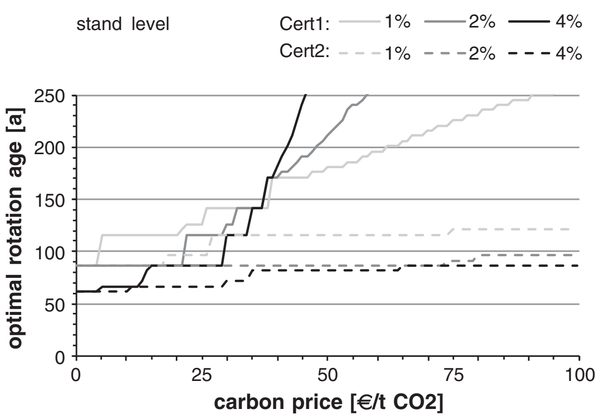

Fig. 8. The effect of carbon prices on the optimal rotation age at stand level for different interest rates (spruce, selective thinning).

The model results not only provide knowledge of the effects of carbon sequestration rewards on forest management, but also, rather as an ancillary effect, indications on how much timber price variations affect the optimal rotation period. Basically, the direction of reaction is in line with micro-economic theory: a rise in timber prices shortens the optimal rotation period and hence increases the supply of timber through the cutting of existing timber stock. However, the extent to which price changes induce rotation age changes is rather low. Even though this is the result only of one single model stand, it indicates a tendency to price inelastic supply, even for profit maximizing forest owners. This finding could be helpful in validating of one of the basic assumptions in timber market models.

Risks—caused by natural hazards or uncertainties of timber and carbon markets—are not taken into consideration in our study. Reliable data for risk analysis are rare as well as reliable data on growth, mortality and thinning volume of very old stands. The future market development and the forest owner's expectations about it as well as his risk aversion are unknown variables and would require further assumptions for conducting such assessments (see e.g. Knoke and Wurm, 2006; von Gadow, 2001). The inclusion of risk analysis in the calculations would have weakened the effects of increasing rotation periods, granted that the probability of risks increases with the stand age. Spring et al. (2005) comes to comparable results considering risks.

Moreover the calculations of this study have not considered transaction costs due to a lack of reliable empirical data (Dieter and Elsasser, 2004). This question is recommended for assessment in further studies. Transaction costs may reduce, or at least exceed, the revenues from carbon sequestration services, and therefore weaken the effect of the incentives provided by reward schemes based on carbon prices.

The question of how carbon sequestration rewards affect forest management has been tackled using different adjusted Faustmann Formulae. Faustmann (1849) developed his formulae for the purpose of calculating the value of bare forest land and immature forest stands. However, his formulae also have been applied to determine the optimum rotation period. In this regard, Faustmann's work attained high economic appreciation (e.g. Samuelson, 1976, pp. 469, 472) and wide recognition, e.g. by the periodical international Faustmann symposia in his former home city, Darmstadt. Nonetheless the application of even adjusted Faustmann Formulae represents only a specific type of forest owner who is aiming at high profits and takes alternative capital investments into account. In reality, there are several types of forest owners, even extended by the increasing relevance of “externalities” of forests as, e.g., their contribution to biodiversity, climate protection or recreation (see e.g. Bormann, 2010). With regard to the question raised in this paper, different management goals are expected to also be reflected in different responses to carbon sequestration rewards. E.g. if the forest value is calculated by maximizing the net annual yield, without consideration of interest profits, the optimal rotation period may even be shortened, converging the time of maximum mean annual increment (Köthke and Dieter, 2010). Other forest owners aiming mainly for nature conservation are supposed to hardly adapt their forest management to sequestration rewards. Against this background, it should be kept in mind that the results are subject to the assumption of profit maximizing and that they are sensitive to the underlying methodological assumptions, e.g., constancy of timber prices, forest management costs and interest rate.

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Uniform global deforestation patterns — An empirical analysis

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ABSTRACT

The forest transition (FT) hypothesis implies that changes in a region's forest cover follow a determinable pattern of decline and later re-expansion over time, which is supposed to be similar across regions and countries. Such a uniform pattern – if empirically proven and quantified – might help in establishing REDD+ baselines (i.e., references against which reductions in the emissions from deforestation and forest degradation of developing countries could be measured, and subsequently be rewarded). REDD+ baselines are required to be based on a globally standardised method and also to consider country-specific circumstances. These requirements might be fulfilled by applying the concept of forest transition in a baseline setting.

With the objective of finding empirical evidence for a uniform global deforestation pattern, we specified a model of forest cover decline which is empirically testable at the global scale. Referring to the causal theory of the FT concept, we define variables which are globally testable with currently available data. By parameterisation of different model specifications, we first analyse deforestation patterns of developing countries, applying cross-section data from the most recent FAO Global Forest Resources Assessment 2010. Population density, cereal area yield, land suitability and the proportion of potential forest vegetation area are determined to significantly explain the variance of forest cover decline.

In a next step, we test the basic model by including modelled historical cross-section data of developed countries. The previously defined model was still found to be valid and no significant differences occurred between developing and developed countries.

Hence, a uniform pattern of forest cover decline could be detected on the national scale for 140 countries by an adjusted coefficient of determination of 0.788. The empirical evidence of a deforestation pattern provides the necessary justification for any further discussion of an inclusion in REDD+ baselines.

1. Introduction: REDD+ as the basic motivation for this study

Deforestation is a threat to biodiversity on Earth and a significant cause of anthropogenic greenhouse gas emissions. Reducing deforestation is a long-standing item on the political agenda of governments and non-governmental organisations. In the context of the United Nations' Framework Convention on Climate Change (UNFCCC), the development of incentives 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 (REDD+) currently have high priority (UNFCCC, 2008, 2009, 2010). For recent overviews, see, e.g., Miles and Kapos (2008), Skutsch and McCall (2010) or Streck (2010). One of the still unsolved problems with REDD+ is that of baseline determination, i.e., the development of a reference against which a country's reduction of emissions due to deforestation and forest degradation can be measured (cf. Griscom et al., 2009; Huettner et al., 2009; Leischner and Elsasser, 2010). Different basic possibilities exist for determining such a baseline: it could either refer to each country's previous ("historical") deforestation, or it could rely upon some general regularity of forest cover development (a third alternative would be avoided, i.e., negotiating reference emission levels individually for each country) (see Combes Motel et al., 2009). A mere reference to previous national deforestation rates might, however, hardly be acceptable for many countries, since this would privilege countries with previously high deforestation, and conversely inhibit development chances for other countries which have been canny with their forests so far. Moreover, a historical reference might be ambiguous and complicated to establish if previous deforestation was variable. Thus, several criteria have already been voiced in the international negotiations which are considered important for a REDD+ baseline: besides being reliable and applicable in any participating country, a baseline should go beyond mere "historical" deforestation rates and account for different national circumstances (e.g., UNFCCC, 2007).

The concept of forest transition (FT) might be a good starting point for developing a baseline method which meets such criteria. This concept suggests a general regularity of long-term changes in a country's forest cover, which is supposedly similar across regions and countries

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(Mather, 1992). According to the FT concept, a country initially runs through a period of decline in forest cover, followed by a transition phase and eventually, some re-expansion during the course of development (Grainger, 1995; Mather and Needle, 1998; Walker, 1993, and others, see Section 2.1 for detailed literature review) (see Fig. 1). Indeed such a pattern has been observed in various countries and regions. However, two major problems are still associated with the FT concept: First, from an epistemic point of view, the empirical content of the concept (and vice versa, its refutability) is still low to this date. The original concept – although it has been elaborated further by several authors – neither specifies the duration and intensity of any of the aforementioned development phases, nor does it give much substantial guidance on how to measure and model these phases (with respect to relevant variables, and the functional relations between them). In Section 2.1, the theory behind the FT concept and its problems are described in more detail and a review of its application and further elaboration in recent studies, as well as on alternative approaches of forest cover modelling, is given. Second, the empirical application of the FT concept implies data requirements which are almost impossible to satisfy, since the concept includes statements about phenomena which were not recorded at the times of their occurrence (for example, the first centuries of deforestation in many now developed countries). The data problem is addressed in Section 2.2.

Therefore, the objective in this study is to apply the current FT concept to define a forest cover model which can be used to test the supposed structural similarity of forest cover development across time and between countries on the global scale (see Section 3 for model specification). According to the scope and practical motivation of our study, it is not our main interest to further refine the causal theory of the FT concept or to identify and explain individual drivers of deforestation processes in different regions, but rather to test whether any global similarities of forest cover decline can be empirically demonstrated (see Section 4 for regression results). Empirical evidence for such a global deforestation pattern is the starting point and justification for any further political and technical discussions on a possible application and for further specification of a deforestation model. Section 5 describes how predictions of future forest cover development, under consideration of country-specific circumstances, can be made by the model. A discussion on the possible contribution of the findings and on the still existing gaps in the process of defining REDD+ baselines is included here. The paper ends with a final discussion (Section 6) about the methodology and the reliability of data and on recommendations for model improvement and further investigation.

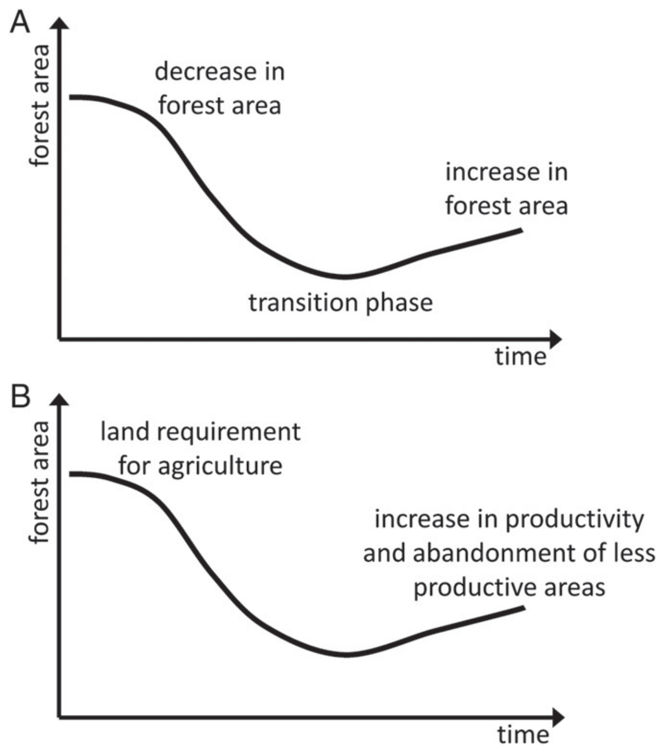

Fig. 1. The forest transition curve: shape [A] and rationale [B] (schematic diagrams, adapted from Grainger (1995) after Mather (1992).

2. Materials

2.1. The Forest Transition (FT) hypothesis as a theoretical background

The FT concept was initially a historical generalisation going back to the observation that a change from decreasing to expanding forest areas has taken place in many developed countries, a phenomenon which might similarly occur in developing countries in the future (Mather, 1992). Walker (1993) named the phenomenon “landscape turnaround”. The original argumentation generally acknowledged that a combination of many factors affects forest area development as underlying causes, but it emphasised the progressive adjustment of land-use to agricultural needs and possibilities as a single fundamental driver (Mather and Needle, 1998). According to this rationale, forests are initially reduced due to a society's need for farmland. Progress in agricultural productivity and knowledge will later allow some of the farmland which turns out to be only marginally productive to be abandoned, so that forests can recover (see Fig. 1). Other factors may delay this adjustment (such as growing demand for food due to population growth), or they may accelerate it (such as increasing factor productivity due to technological progress).

Starting from this core explanation at the macro-level, several authors have modified the framework of the FT concept. Rather than interpreting forest cover development as the result of one single process, Grainger (1995) distinguished deforestation and forest cover increase as two distinct phenomena which might be influenced by different mechanisms. He called the two phases “national land-use transition” and “forest replenishment” and specifically acknowledged timber demand as a driver of the latter. This distinction explicitly allows for a delay between the deforestation and the forest replenishment phase, rather than interpreting this transition as a single turning point. This two-phase division has been taken up and further refined by other authors like Barbier et al. (2010) and Palo (2000).

Empirical studies have revealed exemplary evidence of forest transitions in several industrialised countries including Denmark (Mather et al., 1998), France (Walker, 1993; Mather et al., 1999), Switzerland (Mather and Fairbairn, 2000), the USA (Walker, 1993; Houghton and Hackler, 2000), Scotland (Mather, 2004), Austria (Krausmann, 2006), Greece, Portugal, Spain, Italy, United Kingdom, Norway, Japan and Canada (Walker, 1993), and in some developing countries (Puerto Rico: Walker (1993); Grau et al. (2003); Rudel et al. (2000); Dominican Republic: Aide and Grau (2004); El Salvador: Hecht et al. (2006); Vietnam: Mather (2007); Meyfroidt and Lambin (2007); China and India: Mather (2007)), generally by exploring the course of deforestation over time. Altogether these case studies go deeper into the details of forest transitions in the respective countries; however, explanations often remain context-specific for the analysed cases, and cannot be generalised. Cross-national evidence for the alleged structural similarity of forest cover development across time and space does not emerge from these studies.

Cross-national analyses on forest cover development have been conducted in the past with reference to different theoretical backgrounds, mostly focussing on deforestation rates in developing tropical countries and the underlying drivers. Among the first of such cross-sectional regression analyses on deforestation in developing countries is the study by Allen and Barnes (1985). A general overview and meta analysis of forest development modelling studies can be found in Angelsen and Kaimowitz (1999), Brown and Pearce (1994) and Rudel et al. (2009a).

Simultaneously a second group of scientists conducted analysis on long term forest cover trends, starting in the 1980s, when Palo and his colleagues first theorised a cross-national forest cover model following a sigmoidal function (recorded, e.g., in Palo, 1987; Palo and Mery, 1990). This approach is pursued later in several empirical analyses and different model specifications (e.g., Palo and Lehto, 1996; Palo et al., 2000; Uusivuori et al., 2002) by the application of sub-national data from tropical countries before 1990. Different definitions for the dependent variable, among them forest cover (here defined as forest area divided by land or non-forest area) were tested in different functional forms. Population density and gross domestic product (GDP) per capita have been identified as the most influential drivers. The sigmoid forest cover model based on the aforementioned studies was further developed into the so called “forest area change model”, which was applied for corrections of the forest area estimates in the FAO Forest Resources Assessment (FRA) 1990 (described by Scotti, 2000). This model was supposed to define the relationship of non-forest cover and population density by analysing sub-national data (time series and cross-section) before 1990.

Kaplan et al. (2009) built their deforestation model for Europe on the S-shaped relationship between forest cover and population density as well, and applied this to time series data of single developed countries.

A different technique was used by Mahapatraa and Kant (2005), Rudel and Roper (1997) and Rudel et al. (2005) with the transformation of forest cover development into nominal categories and the application of logistic regressions. This approach solves problems of data scarcity which occur at global scale, but it incurs a loss of information which prohibits its application for our purpose, the establishment of REDD+ baselines.

A further approach in the field of forest development analysis is the hypothesis about the Environmental Kuznets Curve (EKC). Although this approach has neither been completely theorised, nor is it the background of our investigation, it should be mentioned here for completeness. The EKC suggests an inversely U-shaped relation between the degradation of an environmental resource and economic growth, and has often been applied in the context of deforestation rates, e.g., by Bhattarai and Hammig (2001), Culas (2007), Ehrhardt-Martinez et al. (2002), Koop and Tole (1999), Nguyen Van and Azomahou (2007) and Shandra (2007). The influence of GDP and further demographic, economic and social factors on the deforestation rates are analysed in these studies. Barbier (2004) and Barbier and Burgess (2001) applied the EKC approach but replaced deforestation rates with annual agricultural expansion rates to overcome data problems. The evidence concerning the existence of an EKC-like relationship, as well as the influence of per capita GDP, is mixed and often varies among world regions. We are not going to prove the EKC hypothesis.

Returning to the FT hypothesis, the problem of scale has to be considered. Forest transitions are discussed and observed at different scales including the sub-national, national, aggregated supranational or, finally, the aggregated world level (cf. studies by Pfaff and Walker, 2010; Walker, 2012). As our aim is politically motivated, we are searching for the existence of uniform forest changes at the national level, disregarding further aggregated or regional developments, which nevertheless might be of interest for subsequent investigations that go beyond our question (e.g., Meyfroidt and Lambin, 2009). Neither are sub-national forest transitions of interest in our study, because a potential national REDD+ baseline accounts for the aggregated forest area balance at the national level. Such investigations may, however, be of interest in the design of national policy strategies.

The very concept of FT has been subject to debate in recent years (Perz, 2007, 2008; Walker, 2008). Besides some fairly general criticisms (e.g., the application of “universalist” and “modernist” thinking), some practically relevant problems have been raised in this debate. A first point addresses definition issues: In addressing forest area only, the original FT hypothesis does not account for the differences between forests with regard to species composition, and the amount of carbon they store. This specifically applies to differences between natural and secondary forests, and is directly relevant if the hypothesis is applied to the REDD+ problem. In this context a focus on forest area only would prohibit the accounting for forest degradation or for the possibly different carbon contents of original and restored forest areas. Several approaches redefine forest area to, e.g., forest cover or annual deforestation (see studies mentioned above), but no consensus exists in this regard.

A second point addresses measurement problems: the FT concept neither offers much guidance for quantitatively specifying the rate and extent of forest decline and later recovery, nor does it help in forecasting the duration of any of the periods it describes.

Hence the original FT concept, as it has been elaborated up until now, still seems more useful for guiding qualitative and case-study oriented research about forest area development than for its quantitative global analysis.

2.2. Global forest cover development: data availability

Another major problem of applying the FT concept empirically at the global scale is that of data availability. Since in many parts of the world deforestation began long before satellite imagery and forest inventories were introduced, the question arises of from where the data for an empirical analysis should come.

2.2.1. Global Forest Resources Assessments by FAO

Currently the most comprehensive source of global forest cover data is the Global Forest Resources Assessment (FRA) which was compiled by the FAO. The most recent version dates from the year 2010 (FAO, 2010b); it also includes revised estimates for earlier assessments (1990, 2000 and 2005). FRA 2010 contains data for a total of 233 countries and territories. Country data covers about 90 variables, including total land area; the area covered by “forest” and “other wooded land” (both of which are further subdivided into five categories: primary, modified natural, and semi natural areas, productive plantations, and protective plantations), and their carbon content. “Forest” is defined quite broadly here and comprises closed as well as open forests (which may contain very different amounts of carbon).[1]

While the database is the central source for information about the current state and development of the world's forests, two kinds of problems have to be kept in mind when using FRA data for our purpose. First, the FRA time series goes back only to the year 1980, and even the precursory FAO production yearbook series which might be used as a supplementary (if less reliable and not fully comparable) data source has only been available since 1948. Second, although the underlying country reports have been guided by a common reporting framework, the basic data have been collected by the individual countries under national sovereignty, with different data acquisition methods and for different reference years. Data gaps, extrapolation needs and quality problems of individual country data reduce the reliability of this data set as a whole,

[1] Forest definition according to FRA 2010: land spanning more than 0.5 ha with trees that can grow higher than 5 meters and develop a canopy cover of more than 10%, including palms and bamboo.

as well as the comparability of data across countries and over time. The FRA data before 2000 is partly modelled to fill data gaps (cf. Barbier and Burgess, 1997; FAO, 2010b; Grainger, 2008; Rudel and Roper, 1997). Moreover, the definitions and methodologies of data compilation changed between the assessment years, leading to inconsistencies between the different reporting years. But data for the previous assessments have subsequently been revised in each new FRA report, leading to internally more consistent time trends. We therefore use forest area data from 2000 and 2010 for model parameterisation in our study, both taken from the latest FRA report 2010[2] (see Grainger, 2008, for detailed discussion on FRA data quality). We used the FAO's category *total forest area*, as this is more reliable and complete than any of the subcategories.

2.2.2. Historic land-use reconstructions

Modelled reconstructions of historic land-use seem to be the only source for global historic land-use data. Researchers in the Max Planck Institute for Meteorology (MPI) have recently synthesised "the first detailed reconstruction of global agricultural areas (cropland and pasture) and the resulting changes in land cover over the last millennium", consisting of a series of global 0.5-resolution grid maps in annual time steps, which cover the period from AD 800 to 1992 (Pongratz et al., 2007, 2008). This work is based on two earlier historical high-resolution data bases (the SAGE data base: Ramankutty and Foley (1999); and the HYDE2 data base: Klein Goldewijk (2001); for a comparison, see Klein Goldewijk and Ramankutty (2004)). Both earlier data bases incorporate sporadic observations of land cover changes since AD 1700 from remote sensing data and historical records in several countries.

None of these three data sources focuses explicitly on forest cover but rather on the historical development of global agricultural area. Agriculture is supposed to replace the original vegetation, which may consist of forests or other forms of (natural) vegetation. The resulting land-use maps are linked to a high-resolution map of potential natural vegetation. Hence, information about historic deforestation is implicitly contained as a by-product (i.e., the forest area remaining at a specific time can be read from the respective maps).

Alternative estimates of historic land-use (e.g. that of Kaplan et al. (2009), which focuses on forest itself) do not cover the whole world and are therefore not suitable for the purposes of our study.

3. Methodological approach

3.1. Variable and data specification

As mentioned earlier, any effort to empirically test the FT concept in a regression analysis faces the two problems: lack of specificity in the current formulation of the FT concept, and the problem of data availability.

The specificity problem is countered by refining the FT concept to a testable regression model at the global scale. Thus, our first focus of investigation, was to find a global regularity of forest area development for a possible integration in REDD+ baselines. REDD+ focuses on measures addressing the forest area decrease on the national level in developing countries. As Grainger (1995) and others (see Section 2.1) have already proposed, the FT curve might be split into a decreasing and an increasing part (see Fig. 2). A decreasing function is modelled for the earlier part of forest area development (representing the deforestation

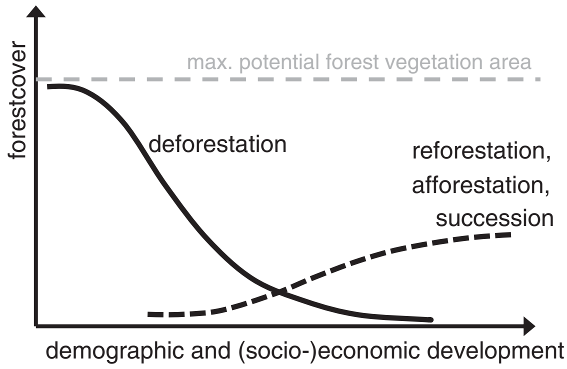

Fig. 2. Specification of the forest transition hypothesis (schematic diagram).

period), whereas it is assumed that a separate increasing function would have to be modelled for the later forest recovery period, so that the intersection of the two curves depicts the time of "transition". We are going to apply this separation in our study as well, which also solves the problem of modelling the curve in one single function (as depicted in Fig. 1), which seems barely possible. We concentrate only on the deforestation curve, which is the main focus of REDD+.

The original version of the FT concept describes the development of forest area [*FA*] (or alternatively, forest cover [*FC*]) as a function of time [*t*]. However, none of these three variables is directly suitable for modelling at the cross-national level, since countries are very different with respect to their area, their suitability for tree growth, and with respect to the starting year and speed of deforestation. Therefore, the variables had to be redefined and normalised for our purpose. Several studies further interpreted the original FT concept and proposed different formulations of variables and models for different objectives (see Section 2.1). The causal argumentations of the FT-studies can be synthesised as follows. The deforestation process reacts inversely to agricultural land expansion. In turn, this agricultural land development is driven by the need for farmland for an increasing population and it is restricted by country-specific physio-geographic circumstances. Simultaneously the land-use change is influenced by economic and socio-economic development, which speeds up and slows down the deforestation process at different stages of development. Especially the forest transition and the following forest cover increase is argued to be driven by the (socio-)economic development (cf., Lambin and Meyfroidt, 2010; Rudel et al., 2005), which becomes visible as agricultural intensification or reforestation. Data expressions of this (socio-)economic development are, e.g., infrastructure development, technological development, market and trade development, as well as political and cultural development. In the literature there is no consensus about the specific variables for (socio-)economic development, which might also be owed to restrictions in data availability.

In addition, land-use development is limited by non-human physio-geographic constraints of each country. These constraints are the extent of area and its general suitability for different forms of land-use and for other options of food supply. Not only the size, but also the natural fertility and the accessibility of the land places constraints on the land-uses. These naturally given factors hardly change in the course of time, but they differ strongly between the countries.

Although several highly detailed and complex attempts for causal explanations of the deforestation process exist, they are often not applicable and verifiable on global scale by the prevailing data availability. Our aim is therefore not a further refinement of the theory at the causal stage but to use the general causal theory described above to define suitable variables for the representation of physio-geographic

[2] Forest area data for 1995 (interpolated between 1990 and 2000) had to be used for a smaller group of developing countries (N = 27, see Section 3) to test lagged forest cover as an independent variable.

Table 1
Variables and data sources.

Variable	Definition and [unit]	Source	Years (AD)	Note
Dependent variable				
FC	Forest cover [%]	FA/FA_{pot}		
	FA: total forest area [km^2]	FAO (2010b)	1990–2010	*2
	(Including primary, secondary and planted forests)			
		MPI (Pongratz et al., 2007)	1820–1990	*1
	FA_{pot}: potential forest vegetation area [km^2]	MPI (Pongratz, 2010; Pongratz et al., 2007, 2008)	(Current)	*1
Physio-geographic variables				
SFA_{pot}	Share of potential forest on surface area [%]	FA_{pot}/A_{tot}		
A_{tot}	Surface area [km^2]	(World Bank, 2011)	2008	
SI	Suitability index of arable land [%]	FAO (2000, 2010a)	(Current)	
LLC	Landlocked countries [1 for LLC, 0 for other]	UN-OHRLLS (2011)	(Current)	
Demographic variables				
PP_{FA}	Population pressure [persons/km^2]	P_{tot}/FA (applied in Specifications 1–4)		
	P_{tot}: total population [persons]	UN (2009)	1950–2010	
		Maddison (2003)	1820–1949	
PP_A	Population pressure [persons/km^2]	P_{tot}/A_{tot} (applied in Specifications 5–6)		
SP_{rur}	Share of rural on total population [%]	P_{rur}/P_{tot}		
	P_{rur}: rural population [persons]	World Bank (2011)	1990–2010	
(Socio-)economic variables				
CY	Cereal yield [kg/ha]	World Bank (2011)	1990–2009	
		Different sources, see *5	About 1820	*5
GDP_{pc}	Gross domestic product per capita [internat. USD]	Maddison (2003)	1820–2008	*2,*3
AVA	Agriculture, value added [% of GDP]	World Bank (2011)	1990–2010	
LDC	Least developed countries [1 for LDC, 0 for other]	UN-OHRLLS (2011)	2011	
HIPC	Heavily indebted poor countries [1 for HIPC, 0 for other]	World Bank (2011)	2011	
D	Development status [1, if country is listed in Annex I to UNFCCC; 0 for other]	UNFCCC (1992/2012)	2010	*4

*1: Extracted from MPI grid maps.
*2: Missing years are linearly interpolated.
*3: Data of formerly unified countries was proportionally divided according to the current national borders.
*4: Including Cyprus as developed country (see footnote 5);Variable D is only applied in Specifications 4 and 6.
*5: Data around the year 1820 have been compiled from several studies, field surveys and models for single countries (Bairoch, 1997, 1999; Callaghan, 1970s; Clark, 1991; Evans, 1980; Glennie, 1988; Huang and Rozelle, 1995; Mitchell, 1975; Overton, 1979; Putnam, 1968; Turner, 1982; USDA/NASS, 2011; Zanden, 1988). We grouped the industrial countries according to their physical region and assigned cereal yields respectively according to the available information.

constraints, demographic and (socio-)economic development under consideration of data and model restrictions. The definitions, units and data sources of our applied variables are compiled in Table 1.

With regard to the dependent variable, forest cover [*FC*] might best be normalised if it were to be measured as a fraction of a country's initial forest area. In this way, area that is not suitable for forest vegetation, such as water, ice and rocky land, is ignored. Since data on initial forest area is not available for many countries, potential forest vegetation area may be used instead. The potential forest vegetation area limits the share of land that might be covered with forests without human influences, like irrigation.[3] Accordingly, in this study forest cover is expressed as the proportion of the total forest area on the country's potentially forested area (rather than on the total surface), which limits the dependent variable to the range between 0 and 100% of potential forest area.

3.1.1. Physio-geographic variables

A main physio-geographic constraint for land-use changes is the country's area available for vegetation (e.g., agriculture and forests). To distinguish countries with high and low shares of vegetation area, the share of the potential forest vegetation area on the total country surface is defined as an independent variable [SFA_{pot}]. The potential forest area will be correlated with other vegetation areas like the area suitable for agriculture without further land reclamation like irrigation, but it does not contain information about the fertility and productivity of the land. Countries with a high share of vegetation area are expected to have a higher forest cover than others, as they might have more options to choose productive locations for agricultural land. On the other hand, countries with a low share of potential vegetation area are more dependent on this relatively small share of vegetation land, which they might aim to completely exploit for food production within the country's borders.

Moreover, soil fertility influences agricultural productivity and thereby the area needed for production. With highly fertile land, less area is needed to feed the same number of persons and therefore less forest area is at risk of being deforested for conversion to agricultural land. To apply an averaged value per country, we apply an index according to FAO (2010a) about the suitability of land for rain fed crop production as an independent variable [*SI*]. The index weights the land according to its quality for agriculture in relation to the total country surface, and should explain the differences between countries with respect to their land productivity.[4] We expect countries with a high *SI* to have a higher forest cover.

[3] Unlike the "initial forest area", potential forest area may change (and indeed has changed) over time, specifically under changing climate conditions. However, potential vegetation data have only been available for contemporary conditions; any changes in the last two millennia had thus to be disregarded. We use the data for potential natural vegetation from the MPI database (Pongratz et al., 2007), which reclassifies the 15 natural biome categories applied in the SAGE database (Ramankutty and Foley, 1999) into 11 natural biomes (see Pongratz et al., 2008, for detailed description). As the FAO definition of forest (see footnote 1) extends the MPI definition, we applied the sum of the potential forest and shrub land categories as potential forest vegetation areas, excluding grassland and tundra vegetation types.

[4] The potential arable land of a country (even if it may be used presently for other purposes) is adjusted for its quality by giving weights to suitability classes. The weighted values give the equivalent areas of "very suitable land" in percent as a fixed value per country (FAO, 2000, 2010a).

The access of a country to the sea influences its opportunities for fishing and trading. If a country has access to other sources of food beyond farming or trade possibilities, less agricultural area is needed to feed the population. As a geographic constraint we apply a dummy variable for distinguishing landlocked countries from countries with access to the sea [*LLC*], expecting the latter to have a higher percentage of forest cover.

To cover any further possible differences between big and small countries which might occur in terms of political importance, trade and cooperation options or even space and land pressure, and which are not covered by other variables, we test a scaling variable by using the countries' surface area [A_{tot}].

3.1.2. Demographic variables

The influence of a country's demographic development has been proven by many studies to be a significant driver for deforestation and it is a main causal argument in the FT theory (cf. Mather and Needle, 2000). We expect an increasing population density to decrease the forest cover, because the demand for land for agriculture and settlement increases with population. We apply population density as an independent variable and test the two different formulations: population pressure on the existing forest land [PP_{FA}] and population pressure on the country surface [PP_A].

Population density in the rural areas is argued by, e.g., Mather and Needle (2000), Palo et al. (2000) to indicate the pressure put on forest land more directly, because it represents activities such as shifting cultivation or fuel wood collection. We therefore apply the share of rural population to total population as an independent variable [SP_{rur}] and expect a high relative population density in rural areas to decrease forest cover.

3.1.3. (Socio-)economic variables

Besides the demographic influences, a country's (socio-)economic development is argued to be a main driver of forest cover development (Angelsen and Kaimowitz, 1999).

A country's development status and wealth might influence the land-use policy and change the relation between environmental protection and poverty reduction goals. It can also be interpreted as a proxy for technological progress, which might in turn influence agricultural productivity, e.g., by the use of fertilisers or irrigation (Rudel et al., 2005). Per capita GDP [GDP_{pc}] is a widely applied proxy for a country's development status and it distinguishes low income from high income countries. Additionally, in the course of time an increase in per capita income is first expected to increase deforestation by stimulating the demand for agricultural and forest products, and later (at the time of transition) it is expected to slow down deforestation because options for more efficient land-use arise, as well as awareness and capital for forest protection (cf. Culas, 2007). The effect of income variables such as GDP on forest development is widely and controversially discussed in the literature, especially in the context of the EKC (see Section 2.1). As we are only considering the time period of forest cover decline before the forest transition, we expect an increase in GDP_{pc} to have a negative influence on forest cover in our model. Additionally, we give special attention to the world's least developed countries [*LDC*], by applying a dummy variable. LDC-countries are expected to be at the "beginning" of development and therefore to have higher forest cover compared to other countries. The same holds for highly indebted poor countries [*HIPC*], which we also test with a dummy variable.

The importance of primary sector food production and land-use related activities in a country is indicated by the dominance of its agriculture, forestry and fisheries sector. This is demonstrated by the proportion of this sector's value added in the country's total GDP. A high agricultural value added share [*AVA*] is associated with a high degree of natural resource use, including agricultural land expansion, but is expected to be weakened by an increased agricultural productivity resulting from intensification (cf. Barbier, 2004).

An increasing economic development is also expressed by an increasing technological progress, which in turn influences agricultural productivity. The realised agricultural area yield gives information on the agricultural productivity and intensification. Therefore, the cereal yield per hectare [*CY*] is used as an independent variable. The more cereals that can be harvested per area, the less area is required to feed the same amount of people, implying that pressure on forest area decreases (cf. Barbier and Burgess, 2001; Rudel et al., 2009b).

3.1.3.1. Data specification. Given that empirical historical data are not available for all countries in the world, particularly not for developing countries, a global time series analysis (which would be appropriate for analysing historical trends) is not possible. Cross-section analyses are applied to reduce data needs, with the reasoning that if the central assumption of the FT hypothesis holds true (i.e., that one uniform global curve of forest cover development exists on which only the positions of the individual countries differ), then time series analysis and cross-section analysis will lead to interchangeable results. As our aim is to empirically test the concept for a possible integration in REDD+ baseline design, it is essential to concentrate on the national level (addressee of REDD+ policy) and to integrate as many REDD+ target countries as possible.

As only the deforestation part is considered in our analysis, it is required to isolate the deforestation period of each country (i.e., the time before its transition phase) from the period of increasing forest cover. Correspondingly, we considered the time before the individual transition phases in our analysis. We focused on the latest possible year in order to obtain recent and empirical observations. As all developed countries already passed the transition in earlier years (generally, before 1900), no complete empirical data sets exist for such historic dates. Therefore, in a first step, we only use data from developing countries (REDD+ target countries) to define our forest cover model and identify influencing variables.

For practical reasons, our definition of the development status follows the UNFCCC's categorisation, i.e., countries listed in Annex I to the UNFCCC (1992) are interpreted as "developed" (these are industrialised countries and countries with economies in transition, which underlie emission reduction targets). All others are categorised as "developing" for our purpose (i.e., Non-Annex I countries without reduction targets). By March 2012, 41 Annex I and 152 Non-Annex I countries had signed the Convention.[5] As REDD+ is discussed as a process within the UNFCCC, we concentrated on these 193 countries and refer to the UNFCCC categorisation.

To analyse the deforestation curve of the developing countries, we grouped them according to whether they have already reached the time of transition or not and used data from before the transition phase accordingly. Therefore we refer to whether the forest cover is continuously decreasing according to the FRA 2010 data (1990-2010) or whether it is increasing during any of the reported periods (between 1990, 2000, 2005 and 2010). For 84 developing countries which still exhibit a steady decrease in their forest cover, the most recent data available from 2010 is used in the following analysis. For the remaining 29 developing countries which show an increasing forest cover or signs of stagnation in the last years, data from an earlier year (2000) is used instead.[6] In both cases empirical data reported by FAO (2010b) is

[5] For the country list see UNFCCC (1992/2012). The European Union as integration organisation is not considered in our study neither is the Observer State Holy See and the overseas territories of the Annex I countries. We treat Cyprus as a developed country, as its future inclusion in the Annex I was already decided in December 2011.

[6] China is an exception. Since it is not listed in Annex I to the UNFCCC, it is categorised as a developing country in our study; however, China already passed its forest transition long before 2000 (more precisely, around or even before 1980; see Mather (2007)), implying that using data from 2000 might bias results. In order to avoid this, we treated China as a developed country in this study phase and did not include it in the cross section analysis for parameterisation of the regression models.

used. Due to some missing observations, data are only available for 112 developing countries (see Table A.1 for the country list).

Subsequently, after definition and parameterisation of the regression model with this empirical data from developing countries, we test whether the model also holds for developed countries. Therefore we add modelled data of MPI for the developed countries to the sample (N = 29, see Table A.1). As the transition phase of most developed countries took place before industrialisation, data is used for the year 1825. In order to avoid circular reasoning, we essentially restrict our usage of these modelled data to the comparison with the results produced on empirical data.

3.2. Regression modelling

As mentioned above, forest cover at a specific time [FC_t] is defined here as the actual forest area [FA_t] fraction of the original (potential) forest area [FA_{pot}]: $FC_t = FA_t/FA_{pot}$ (which implies that potential forest cover [FC_{pot}] always equals 1). We are assuming that the relationship between forest cover and the independent variables is sigmoidal rather than linear, which has also been tested by, e.g., Palo et al. (2000), Scotti (2000) and Kaplan et al. (2009) (see Section 2.1). So forest cover decline has been modelled by an (inverted) growth function (approaching 1 as horizontal asymptote at the left side, and 0 at the right side, as delineated in Fig. 2). In order to permit linear regression techniques, we thus linearised the dependent variable [FC_t] by logistic transformation according to Eq. (1):

$$FC_t^* = \ln\left(\frac{1}{FC_t} - 1\right) = \ln\left(\frac{FA_{pot}}{FA_t} - 1\right), \quad (1)$$

with $FC_t{}^*$ = transformed forest cover at year t; FC_t (FA_t) = forest cover (area) remaining at year t; FA_{pot} = potential forest area.

A double-log model is expected to show the best fit, and has the advantage that the parameters can be interpreted as elasticities as well.

For the demographic and (socio-)economic variables, we assume that they cannot influence forest cover immediately, but rather need some time in order to become effective. Therefore we applied a time-lag to those time-related explanatory variables.[7]

In summation, the basic linear regression model to be tested in the following step has the form

$$FC^*_{t,i} = \beta_0 + \beta_v \ln X_{v,t-5,i} + \varepsilon_i \quad (2)$$

where FC^* is forest cover as defined in (1), X is a vector of further explanatory variables v (which are time-lagged if time-related), t is an index for the year applied in the cross-section analysis, i is an index for countries, β are the respective coefficients, and ε_i is the residual (assumed to be independent and identically distributed).

By this basic model the deforestation part of the FT hypothesis is specified into a testable form. Predicted forest cover values [$\hat{FC}$] can be calculated after some rearrangement according to the re-transformation

$$\hat{FC}_{t,i} = \left(\frac{FC_{pot}}{1 + e^{FC_{t^*}}}\right)_i. \quad (3)$$

[7] A time-lag of 5 years is chosen for the demographic variables for the practical reason of data availability. For the (socio-)economic variables, which have high annual fluctuations, a time-lag with a moving average of 5 to 10 years is applied, providing the advantage of a reduced possible bias by the influence of extreme values in individual years.

3.2.1. Specification 1 (basic)

We parameterise the basic model (Eq. (2)) by using cross-section data of developing countries, using the sample of 112 countries (see Section 3.1), which is the largest common set of observations for which the data set is complete. In a first step, influencing variables are selected from the variable set in Table 1 by employing OLS estimation (ordinary least squares) and stepwise backward elimination of the variables that influence the fit the least by a significance level of $p > 0.1$ (see Kennedy, 1998, p.95). After determination of the significant variables in the basic Specification 1, this defined basic model is tested in different specifications for the validation of results.

3.2.2. Specification 2 (weighted)

This specification uses the same data and variables identified in the basic Specification 1, but country observations are weighted by the area of their country surface [A_{tot}] here,[8] i.e., each country observation influences the results proportionally to the size of the respective country's surface. Hence, countries with a larger surface therefore have a stronger influence on results. This may be interpreted as an additional test for differences between countries: If the regression curve estimated by weighted data (Specification 2) differs significantly from that using unweighted data (Specification 1), then obviously the forest cover development of small countries (with regard to their surface area) is different from that of larger ones. Such a result would raise doubts about the supposed structural similarity between countries.

3.2.3. Specification 3 (simplified)

Specification 3 is applied to test the explanatory power of a simplification of the basic Specification 1. Therefore only the core relation consisting of population pressure [PP_{FA}] and forest cover [FC], is regressed. This specification is introduced since it may help to reduce data needs in a practical application (here the number of observations increases (N = 126) due to this reduction of variables). Again, it is calculated on the basis of unweighted observations of developing countries.

3.2.4. Specification 4 (including developed countries)

After defining and testing the forest cover model for developing countries in the three described specifications, a fourth specification is applied to test whether there are significant differences between developing and developed countries with regard to their deforestation patterns. Therefore in Specification 4 additional observations of developed countries have been added to the sample (thus samples used in Specifications 1, 2 and 3 are sub-samples of the one used in Specification 4, N = 142). As no empirical observations exist for the required historical time period, data modelled by the MPI is utilised for 29 developed countries (plus China) for the year 1825, as described in Section 3.1.

Additionally a dummy variable is included to distinguish developed from developing countries [D]. If the dummy's coefficient turns out to be significant, then differences between the countries exist and the supposed structural similarity between countries – as postulated by the FT concept – is falsified.

4. Regression results

The empirical results of the four model specifications described in Section 3.2 (Specification 1: basic, 2: weighted, 3: simplified (all with developing countries data), Specification 4: including developed countries data), are shown in Table 2 and are subsequently discussed.

[8] The weights W for each country i ($i = 1,\ldots,N$) are defined by $W_i = (A_{tot})_i / \sum_i^N (A_{tot})_i$, so that $\sum W_i = 1$.

The F-statistic reveals that altogether all four model specifications are statistically highly significant. When interpreting the signs of the coefficients, it has to be kept in mind, that they are reversed caused by the transformation of FC^*. Therefore a positive sign of the coefficient in the results table implies that the influence of the respective variable on the forest cover of a country is negative.

The final results in Table 2 are reported after stepwise backwards elimination of insignificant variables.

The most influencing variables remaining in the model are population pressure [PP_{FA}], the suitability index of arable land [SI], cereal area yield [CY] and share of potential forest area [SFA_{pot}]. Thus, at least one variable from each of the three categories of drivers (demographic, (socio-)economic, physio-geographic) remains in the model. Those explanatory variables are significant in all of the four specifications (except the simplified Specification 3, where only PP_{FA} was allowed). The other variables tested (i.e., A_{tot}, LLC, SP_{rur}, GDP_{pc}, AVA, LDC and $HIPC$) have been eliminated due to insignificance.

The positive sign of the highly significant PP_{FA} in all specifications implies that, as expected, increasing population pressure reduces the remaining forest cover of a country. This variable, together with the intercept, explains more than 72% of the total variation (as is shown by R^2 in the simple Specification 3). Thus the explanatory power gained by three additional significant explanatory variables is limited to about 10% altogether.

The physio-geographic variables land suitability for agriculture [SI] and share of potential forest area [SFA_{pot}], are not time related and therefore only explain differences between countries but not in the course of time. The land suitability index [SI] has a significantly negative influence on transformed forest cover [FC^*] in all three comprehensive specifications and accordingly, a positive influence on forest cover [FC]. This confirms the expectation that countries with highly productive land need less agricultural area and therefore have a higher forest cover compared to others. In contrast, share of potential forest area [SFA_{pot}] has a positive sign on FC^* (and thus a negative influence on FC) in all comprehensive specifications. The expected negative influence of SFA_{pot} on FC^* is not reflected in the multiple models, but can be traced back to the negative correlation with SI (−0.61), and CY (−0.41), which have themselves a negative influence on FC^*. Testing the influence of SFA_{pot} under exclusion of the other variables shows the expected negative sign.

The only (socio-)economic variable showing a significant influence in the model is cereal yield per hectare [CY]. CY has a significantly negative influence on FC^* and accordingly, a positive influence on FC. This agrees with the explanation, that an increase in area productivity releases the pressure on the forest.

Moreover, the coefficient estimates for the respective variables are quite close in the different specifications. A comparison of the models shows that the 95%-confidence interval of the basic Specification 1 contains 100% of the predicted values of Specification 2, more than 62% of the predicted values of Specification 3 and more than 80% of the predicted values of Specification 4.

In the weighted Specification 2 the coefficient of determination is highest among all considered specifications (adjusted R^2: 0.839), but very close to the basic Specification 1.

The simple Specification 3 has the lowest coefficient of determination of the four specifications (adjusted R^2: 0.724), which is not surprising and is attributable to the smaller number of explanatory variables. However, even this reduced model specification is highly significant in the overall F-test, and parameter estimates for the individual variables are close to those of the other specifications. In conclusion it can be said that the validity of the basic model cannot be rejected by the test for deviations of the different specifications.

All models have been tested for normal distribution of residuals (Shapiro–Wilk test) and homoscedasticity (O'Brien, Brown–Forsythe and Levene tests), which is assured in all specifications after exclusion of two outliers (Bhutan and Japan). Therefore the sample is reduced to N = 111 and N = 140, respectively.

4.1. Test for differences between developing and developed countries

The regression results from Specification 4, which includes the modelled historical data of the developed countries, conform to the first three specifications using developing countries data only. Regression coefficients and signs are quite close to the basic Specification 1; however the adjusted R^2 decreases by 3.7 percentage points. Turning to the test of structural similarity between countries in Specification 4, the dummy [D] is not significantly different from zero ($p = 0.0572$). This implies that developing countries follow the deforestation curve of the developed countries without any significant shift — the supposed similarity of deforestation patterns across countries could hence not be falsified.

Table 2
Estimation results from regression Specifications 1–4, using $\ln PP_{FA} = \ln(P_{tot}/FA)$.

Variables	Specification 1 (Basic model) N = 111	Specification 2 (Weighted by A_{tot}) N = 111	Specification 3 (Simple, only $\ln PP_{FA}$) N = 126	Specification 4 (Including developed countries) N = 140
Intercept	0.391 (*0.765*)	−0.152 (*0.629*)	−3.109 (*0.210*)	0.477 (*0.747*)
	0.51 n.s. (0.609)	**−0.24** n.s. (0.808)	**−14.80***** (<0.0001)	**0.64** n.s. (0.524)
$\ln PP_{FA}$	0.611 (*0.034*)	0.605 (*0.036*)	0.621 (*0.034*)	0.545 (*0.030*)
	17.64*** (<0.0001)	**16.56***** (<0.0001)	**18.15***** (<0.0001)	**18.14***** (<0.0001)
$\ln SI$	−0.193 (*0.037*)	−0.168 (*0.026*)	–	−0.209 (*0.037*)
	−5.20*** (<0.0001)	**−6.42***** (<0.0001)		**−5.60***** (<0.0001)
$\ln SFA_{pot}$	0.250 (*0.090*)	0.215 (*0.067*)	–	0.197 (*0.084*)
	2.77** (0.0066)	**3.19**** (0.0019)		**2.33*** (0.0214)
$\ln CY$	−0.363 (*0.096*)	−0.296 (*0.082*)	–	−0.305 (*0.098*)
	−3.76*** (0.0003)	**−3.61***** (0.0005)		**−3.11**** (0.0023)
D	–	–	–	−0.148 (*0.077*)
				−1.92 n.s. (0.0572)
R^2	0.832	0.845	0.726	0.795
Adjusted R^2	0.825	0.839	0.724	0.788
F-statistic (p-value)	131.299*** (<0.0001)	144.857*** (<0.0001)	329.532*** (<0.0001)	104.400*** (<0.0001)
Standard deviation	0.595	0.543	0.775	0.627

Note: Values in the first rows are coefficient estimates (with standard errors in *italics*); the second rows contain t-values (**bold**) and p-values (in parentheses), respectively.

The results are visualised in Fig. 3, which displays the deforestation curves resulting from all four model specifications (these follow from re-transforming the respective linear regressions back into their original sigmoidal form, as according to Eq. (3)).[9] The figure reveals that the mean curves of Specifications 1, 2 and 3 lead to almost similar results, while the mean curve of Specification 4 predicts lower forest covers at lower population pressure values (i.e., below about 1000 persons per km^2 forest area). The lower forest cover predicted in Specification 4 reveals that the developed countries indeed have a slightly lower forest cover, which however has turned out to be insignificant. When interpreting the curves it has to be kept in mind that the variation around the mean curves is not visible. For example, while the mean curves of Specification 1 and 3 are almost identical, the variance of the simple Specification 3 is the highest among the specifications. The maximum difference between the mean curves of any of the four model specifications amounts to about 8 percentage points of forest cover.

4.2. Test of a non-autoregressive specification

A further model validation is conducted by regressing Specifications 5 and 6, whose statistical results are reported in Table 3. The afore-mentioned Specifications 1–4 all indirectly include the forest cover of the previous period which is embedded in the independent variable population pressure [$PP_{FA}=(P_{tot}/FA)_{t-5}$]. Of course, this variable is well suited for predicting the forest cover in the following period, as the dependent variable is supposed to be dependent on its own past values (autoregression). To examine whether the forest cover development might as well be explained without this dynamic adjustment over time, we run the regression procedure again, not allowing PP_{FA} to be one of the explanatory variables but offering population pressure on the country surface [$PP_A=(P_{tot}/A_{tot})_{t-5}$] as a possibility. Regarding this change, the regressions are executed in the same way described previously for Specifications 1 and 4. Variables were first chosen by stepwise backwards elimination, applied to the sample of developing countries and a new Specification 5 is parameterised. Thereafter the model is applied to the extended sample including developed countries as well (Specification 6).

The regression results of Specifications 5 and 6 are comparable to 1 and 4 respectively, as the same three independent variables were chosen apart from the exchanged variable for population pressure. All variables except cereal yield [*CY*] have a significant influence on forest cover. *CY* is not significant in Specification 6 and its significance level decreased to 95% in Specification 5. The sign for SFA_{pot} is reversed and shows the expected negative influence on FC^* in Specifications 5 and 6. The overall explanatory power of those two specifications is decreased by applying PP_A (population pressure on the country surface) instead of PP_{FA} (population pressure on the forest area) (R^2 adjusted: 0.611 and 0.584 respectively). But still it becomes obvious that predicting forest cover by the assumed model is also possible without using the autoregression of applying the forest cover of the previous period in the independent variables set.

5. Applicability for REDD+ baselines

5.1. Deducing individualised baselines from the global deforestation curve

The regression analysis in the previous section confirms the existence of a uniform pattern of forest cover decline across countries. The regression functions make it possible to predict future deforestation by referring to an average forest cover development curve. Such a globally uniform methodology for predicting country-specific forest cover at a certain degree of statistical evidence seems appropriate for an application in REDD+ baselines. Apart from several advantages, several unsolved problems remain and should be discussed.

First of all, a differentiation should be made between a "business-as-usual (BAU) baseline", for the prediction of the forest development without the incentive of REDD+, and a "crediting baseline", as a benchmark for rewarding avoided emissions (cf. Verchot and Petkova, 2010). By the regressed deforestation curves, predictions of future forest cover can be made, which could be helpful in establishing BAU-baselines. The mechanism and benchmark for generating credits in REDD+ and for establishing a possible crediting-baseline, are not covered in this article and are issues of unpredictable political negotiations. Thus any estimates for quantifying possible credits cannot be derived from just the present calculations.

Requirements for REDD+ BAU-baselines are the application of a uniform methodology and the consideration of historical deforestation and country-specific circumstances. These requirements are fulfilled by applying one of the model specifications described in Section 4. National forest cover predictions (possible BAU-baselines) can be made by applying country-specific data to a single forest cover function. Subsequently we use the basic Specification 1 as an example for a BAU-baseline function. When predicting future forest cover by global standards, differences between individual countries are taken into account by allowing for different physio-geographic conditions, in the form of the countries' individual land suitability indices [*SI*] and their share of potential forest vegetation area [SFA_{pot}]. Additionally differences in the countries' demographic and (socio-) economic development progresses are considered in terms of population development [PP_{FA}] and cereal area yield [*CY*]. The historical forest area is contained in the PP_{FA}-variable. Fig. 4 shows those country-specific deforestation curves, predicted with Specification 1 for the time period 1995 to 2010, which is the time span that can be covered by the available FRA data. Without averaging the input data from the individual countries, as calculated in Fig. 3 for illustrative purposes, each country has its own deforestation curve. The countries displayed in Fig. 4 are those 84 developing countries which still exhibit a decreasing forest cover according to the recent FRA data (cf. Table A.1). Such country-specific forest cover predictions could be calculated with each of the regressed deforestation functions (Specifications 1–6, but with different accuracy) and for each year and country, for which the respective input data is available. Depending on which model specification is chosen, slightly different predictions can result. Due to the lagged model structure, pre-estimates of forest cover can be made for 5 years.

Fig. 4 demonstrates that the individual positions of the countries' forest cover estimates differ broadly, as some countries are still in the beginning of the deforestation process, whereas others have already run through major parts of the deforestation curve. Altogether, the resulting array of national curves very much resembles the global mean development depicted above (in Fig. 3). However, a departure from the deforestation pattern is predicted for some countries, which is caused by sizable changes of the underlying independent variables for the respective years. As an example, sudden changes in cereal area yield can be responsible for such peculiar deviations from the global regularity.

If the REDD+ system includes a baseline approach, then the BAU-baselines finally have to be compared with the real performance of the individual countries. Assuming Specification 1 to be interpreted as a BAU-baseline, Fig. 5 illustrates such exemplary BAU-baselines in comparison to observed forest cover (by FAO) for a subset of the developing countries not yet having passed the transition phase (some randomly selected countries are shown for illustration only). The figure shows the countries' observed forest cover

[9] In order to fit in a 2-dimensional image, the respective mean values of the variables *SI*, *CY*, SFA_{pot} and *D* have been used to visualise the deforestation curves of the respective specifications.

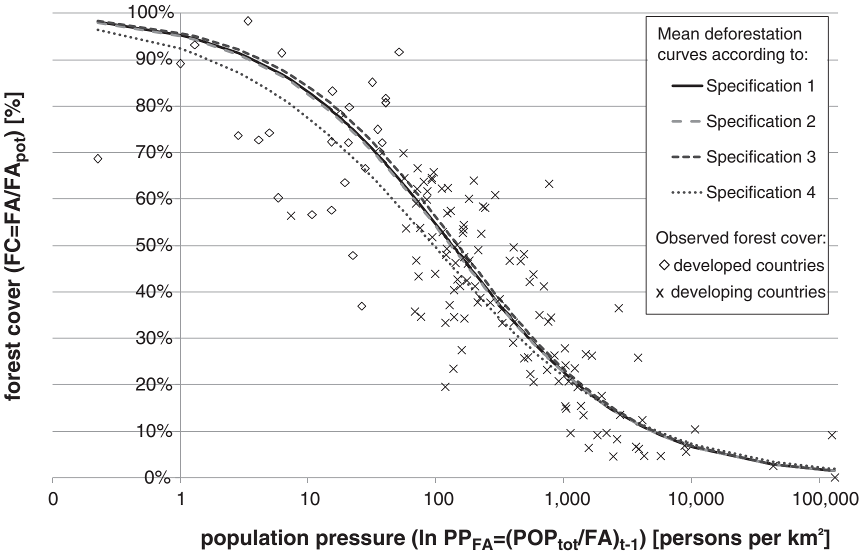

Fig. 3. Global deforestation curves according to the regression Specifications 1–4 and observed forest cover from the cross section analysis (N = 140).

for the years 1995, 2000, 2005 and 2010 and the respective baseline, i.e., the forest cover predicted for the respective years, calculated with model Specification 1 (same shades represent the same country). As the example shows, some countries still hold more forest than predicted, while other countries underachieve compared to their baseline.

It is possible to integrate these baselines in an accounting system and focus, e.g., on the final position of a country's observed forest cover in comparison to the respective baseline curve, or on its relative change during the commitment period (i.e., by how much the observed forest cover has moved towards or away from the baseline). A detailed study of the numerous possibilities of integration into an accounting system, and the practical implications of these alternatives for the concerned countries would be the topic of a separate investigation (and politically, an issue for negotiations).

The example displayed in Fig. 5 shows exemplary baselines of forest cover for 5-year time periods between 1995 and 2010. But neither the period of reference (commitment period) nor the unit of measurement has yet been decided in the REDD+ negotiations. This makes a realistic quantification impossible. On the one hand avoided emissions are the focus of REDD+, but on the other hand it is hardly possible to measure them by current data availability and by the state of technology, knowledge and equipment of the single countries. The transformation of forest areas into carbon emissions has neither been calculated by this study nor is it easily possible with the present data set. Nevertheless it is an important issue and a necessary, still unsolved step. The mere reference to forest area could not account for the very different amounts of carbon in the different forest types of the world, nor could it capture forest degradation. Nevertheless, the reference to forest area is often discussed for simplification and taken as a first discussion approach (cf. Pistorius, 2012; Verchot and Petkova, 2010).

In the past, further discussions were held on whether to include and credit afforestation and forest regeneration in the REDD+ approach as well and on how to include sustainability goals, such as biodiversity issues (see Pistorius, 2012, for a description on the evolution of the REDD+ approach). All of these attempts, even those not yet finally decided and elaborated, further complicate the REDD+ approach, its baseline setting and the related measurement of its impacts.

A detailed review and discussion of the contribution and applicability of the deforestation curve for REDD+ purposes, e.g., for transformation in carbon emissions and the implications for the single countries, is a necessary task for further investigations. At this stage it is important to note that the mere existence of a baseline does not automatically imply how it would have to be handled by REDD+ accounting rules.

6. Discussion and conclusions

There was little discussion in the past on the integration of the FT hypothesis in the REDD+ discourse. But this integration might provide useful options to find a globally consistent methodology for

Table 3
Estimation results from regression Specifications 5–6, using $\ln PP_A = \ln(P_{tot}/A_{tot})$.

Variables	Specification 5 (Unweighed) N = 111	Specification 6 (Unweighted, including developed countries) N = 140
Intercept	1.013 (*1.142*)	0.947 (*1.046*)
	0.89 n.s. (0.3773)	**0.91** n.s. (0.367)
lnPP_A	0.677 (*0.075*)	0.579 (*0.057*)
	9.01*** (<0.0001)	**10.11***** (<0.0001)
ln*SI*	−0.339 (*0.055*)	−0.337 (*0.052*)
	−6.14*** (<0.0001)	**−6.48***** (<0.0001)
lnSFA_{pot}	−0.487 (*0.129*)	−0.432 (*0.119*)
	−3.77*** (0.0003)	**−3.62***** (0.0004)
ln*CY*	−0.350 (*0.146*)	−0.272 (*0.138*)
	−2.39* (0.0187)	**−1.97** n.s. (0.0512)
D	–	−0.118 (*0.109*)
		−1.08 n.s. (0.2811)
R^2	0.625	0.599
Adjusted R^2	0.611	0.584
F-statistic (p-value)	44.284*** (<0.0001)	40.174*** (<0.0001)
Standard deviation	0.889	0.877

Values in the first rows are coefficient estimates (with standard errors in *italics*); the second rows contain t-values (**bold**) and p-values (in parentheses), respectively.

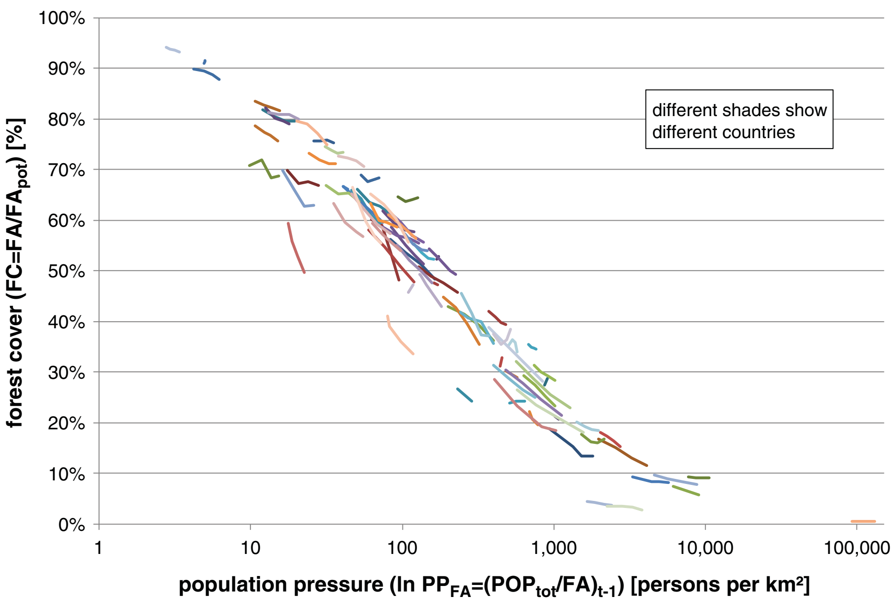

Fig. 4. Country-specific forest cover predictions for developing countries not yet having passed the transition phase, N = 84 (calculated by model Specification 1 for the years 1995–2010).

establishing REDD+ baselines while taking into account country-specific circumstances. Before such a discussion is warranted, however, proof of the empirical evidence of the theory is needed. Therefore, the objective of this study was to make an empirical contribution to the theory of uniform global forest cover patterns — focussing on the phase of forest cover decline.

By the regression analysis presented in this paper, the existence of a uniform pattern of forest cover decline across countries could be confirmed. Data from 140 countries could be fit into one function of forest cover decline, explaining 79% of the variances. This is possible by normalising country specific data by four national indicators identified as the most influential variables. Before the background of imprecise statistical forest area data, a much higher level of explanation cannot be expected.

A linear model of forest cover decline was defined by transforming the dependent variable according to an inverted growth function, and by testing influencing variables of demographic and (socio-)economic development, as stated by the FT hypothesis. Differences between countries were taken into account by testing physio-geographic variables. The regression model was parameterised in a cross-section analysis based on the FAO's most recent Global Forest Resources Assessment with developing countries data. Results of different model specifications confirm the overall significance of the model in statistical terms.

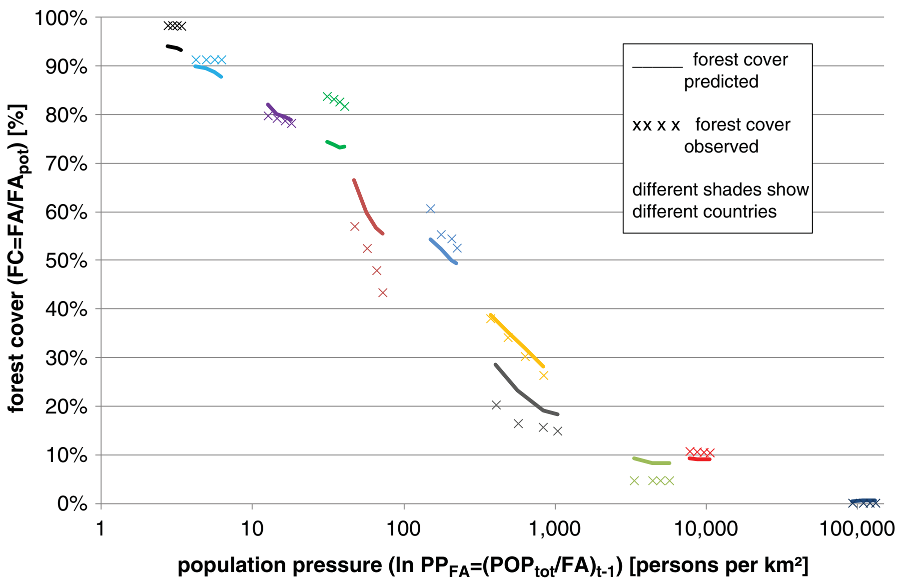

Fig. 5. Individual baselines (predicted by model Specification 1) and observed forest cover of selected countries for the years 1995, 2000, 2005 and 2010.

The main statements of the FT hypothesis could be confirmed by the regression results. The highly significant influence of population was confirmed by statistically attesting that an increasing population pressure drives deforestation forward. Simultaneously an improvement in agricultural productivity was confirmed to significantly release the pressure on the forest. Constraints by the countries' naturally given conditions were offset by normalising the different countries' proportions of potential forest area and land suitability for agriculture, which are proven to significantly influence forest cover decline as well.

With regard to the explanatory variables included in our model, it is conceivable that additional variables might exist which might further refine results (e.g., on technological progress, international trade, timber production). Due to restrictions in data availability, possibilities for including further explanatory variables are limited. The level of measurement is often limited to nominal or ordinal rather than cardinal scales. However, further refinements of the model seem possible, e.g., when additional data becomes available in the future, or when the analysis is concentrated on specific regions for which a more comprehensive information base exists.

The second question addressed in this study – whether a uniform deforestation pattern for developing and developed countries could be detected – was examined by applying the forest cover model to an increased sample including MPI data for developed countries. As an important result, no significant difference between developed and developing countries could be detected in this specification. The existence of a globally uniform deforestation pattern could not be rejected.

A problem again pertains to data availability, as empirical observations do not exist for historical times on a global scale. Although historical reconstructions like the MPI database utilised here offer a way out of this dilemma, it is worth remembering that such reconstructions are basically simulations of a possible past which contain a multitude of simplifying assumptions. Estimating the deforestation curve by cross-section analysis of recent empirical data, rather than by utilizing modelled data, circumvents many but not all of the associated problems. One of these problems is that for the comparison of developed and developing countries (in Specifications 4 and 6), our cross-section analysis had to resort partly (i.e., for the developed countries) to data which originates from historical reconstruction instead of current observation. This is because using observations from times when countries had already passed their forest transition phase (i.e., which show increasing forest cover with increasing population pressure) would have biased the right part of the deforestation curve upwards. Inevitably this requires mixing data from different sources, which have different reliability.

The data problem needs to be discussed in the context of FAO FRA data as well. Even though the recent FRA data is currently the most comprehensive source of global forest cover data, its reliability is not beyond doubt. These data share the FAO's common reporting framework; however, data collection takes place under national sovereignty, implying different data acquisition methods and different reference years. This can again reduce the comparability of data across countries and over time, which could even hide forest transitions (for some examples, see Grainger, 2008; Matthews, 2001; Rudel and Roper, 1997). Inconsistent and not fully reliable forest data is a major problem for all forest development studies and not least a still unsolved problem in the REDD+ context.

The identified globally uniform deforestation curve leads to the conclusion that an application is possible as a BAU-baseline in the framework of REDD+. As required in the negotiations, this baseline takes recent historic data and country-specific conditions into account. But until finally applicability is given, several steps (and political negotiations) still have to be taken.

It is important to remember that the deforestation curve presented in this paper concentrates on the development of forest area, but not on carbon emissions which are related to deforestation as well as to forest degradation. Since carbon emissions may vary with the density of forests in different deforested areas, the (change of) carbon density in different forests would have to be considered additionally if emissions rather than loss of forest area were the focus. However, this might require additional monitoring and control efforts and is not the focus of the modelling according to the FT hypothesis. Likewise, as the subject of this investigation, 'remaining forest cover' should not be confused with 'remaining percentage of virgin forests'. Even in an early phase of deforestation, a country's forest cover may be the sum of primary forests, forests already influenced by humans, and secondary forest areas.

The analysis presented here is still restricted to the deforestation phase of the global FT curve, but it does not yet describe the later recovery phase. This does not preclude its usability as a REDD+ baseline, because REDD+ obviously focuses on the reduction of deforestation (and forest degradation), while increases in forest area are addressed by a separate policy mechanism — the Clean Development Mechanism (CDM). Whereas REDD+ and CDM only address developing countries, forestry issues of developed countries are left to a different policy regime (as institutionalised by Articles 3.3 and 3.4 of the Kyoto Protocol). However, joining these separate sets of accounting rules into one comprehensive policy regime might become possible in the future if the reforestation phase could additionally be modelled and successfully integrated into a complete quantitatively specified FT curve, the first part of which has been established in this study.

Furthermore, for political reasons, this study concentrates on the national scale, leaving sub- and supranational forest transitions unconsidered. A combination with a full spatial analysis is recommended for further investigation, considering findings from different scale studies. This could be done by the application of a spatially explicit model using GIS and grid data (cf. Walker, 2004, 2012). Spatial interdependencies might be detected, e.g., originating in trade relations, colonialism or common policies, and are of great interest in the context of REDD+, as they may expose leakage effects (Meyfroidt and Lambin, 2009).

In any case, empirical estimates (of a global deforestation curve or even of a full FT curve) help in establishing a baseline, but they cannot prescribe how such a baseline would have to be handled politically. Options for integrating the empirical knowledge about global forest cover development into REDD+ baselines need to be further analysed. The distributive effects for the countries concerned are worthy of further investigation as are the effects on avoided emissions and the monetary impacts on global scale and on the single countries. However, the choice on the REDD+ mechanism is ultimately a normative issue, which has to be left to negotiation between the participating countries.

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The responsibility for any remaining errors and mistakes remains by the authors.

Appendix A. Annex

Table A.1
Countries and input data used for determining the deforestation curve in the final model.

ISO	*FC*	*PPFA*	*SI*	*SFA pot*	*CY*	ISO	*FC*	*PPFA*	*SI*	*SFA pot*	*CY*	ISO	*FC*	*PPFA*	*SI*	*SFA pot*	*CY*	ISO	*FC*	*PPFA*	*SI*	*SFA pot*	*CY*
Country code	[%]	[persons/ km²]	[%]	[%]	[kg/ha]	Country code	[%]	[persons/ km²]	[%]	[%]	[kg/ha]	country code	[%]	[persons/ km²]	[%]	[%]	[kg/ha]	country code	[%]	[persons/ km²]	[%]	[%]	[kg/ha]
N = 84, developing countries not yet having passed the forest transition						IRN	35	639	1	18	2067	SUR	98	3	47	92	3747	TJK	14	1412	9	21	948
						JAM	35	787	10	89	1201	TCD	60	84	19	15	645	TUN	24	1207	14	22	1126
Years:	2010	2005	current	2005	2000–05	JOR	5	5680	3	23	1626	TGO	7	1552	53	78	1095	UZB	23	733	5	31	1936
AFG	9	1815	2	22	1298	KAZ	47	455	1	3	970	TKM	33	117	1	25	2527	VNM	41	692	23	86	3321
AGO	67	28	44	70	585	KEN	15	1017	16	39	1511	TTO	44	573	44	100	2734	CHN[a]	60	179	15	36	1000
ARG	37	127	26	28	3842	KHM	58	129	51	97	2321	TZA	62	110	49	57	1269	N = 29, developed countries having passed the forest transition during the industrial revolution					
ARM	21	1083	8	42	1693	KOR	63	760	25	99	6406	UGA	26	837	40	47	1536						
AZE	21	903	28	52	2464	LAO	70	36	16	95	3297	VEN	65	56	42	79	3297	Years:	1825	1820	current	1820	~1800
BDI	12	4076	30	50	1315	LBR	54	74	44	72	1284	YEM	6	3830	0.005	17	899	AUS	89	1	11	5	800
BEN	54	164	67	74	1119	LBY	14	2729	1	1	626	ZAF	26	520	15	29	3033	AUT	59	69	28	97	1000
BFA	58	231	55	35	993	LKA	28	1010	47	101	3403	ZWE	43	72	37	92	996	BEL	33	327	62	100	1300
BGD	10	10524	53	96	3533	MDG	35	137	39	62	2202	N = 29, developing countries recently having passed the forest transition						BGR	36	68	54	79	700
BIH	43	173	38	100	3402	MEX	53	161	19	62	2946							CAN	69	0	8	53	600
BLZ	64	20	34	95	2731	MLI	65	92	14	16	1048	Years:	2000	1995	current	1995	1990–95	CHE	64	92	19	81	1000
BOL	83	16	42	63	1784	MMR	50	145	25	94	3390	ALB	33	402	19	80	2818	CYP	81	40	27	95	600
BRA	75	35	46	81	2772	MNG	48	23	0.06	15	628	BTN[b]	100	16	0.3	67	1276	CZE	41	200	61	100	1000
BRN	66	95	36	100	761	MOZ	92	52	55	53	804	CHL	52	93	3	40	4046	DEU	57	121	61	100	1000
BWA	58	15	9	34	375	MRT	10	1118	1	2	854	CIV	43	146	58	75	888	DNK	35	76	70	99	1200
CAF	78	18	57	46	995	MWI	50	401	43	55	1227	CRI	46	141	16	100	3437	ESP	48	165	30	30	700
CMR	62	85	56	68	1593	MYS	62	123	29	99	3223	CUB	26	486	52	85	2156	FIN	60	6	28	97	1000
COD	72	38	45	91	772	NAM	37	26	8	24	378	EGY	9	123996	0.06	1	5803	FRA	53	112	54	95	1000
COG	72	15	47	91	765	NER	15	1035	5	6	363	FJI	64	79	10	84	2415	GBR	39	220	51	100	1300
COL	62	71	42	85	3797	NGA	20	1270	52	50	1297	GMB	58	240	55	70	1016	GRC	54	58	30	56	700
DOM	48	483	29	84	4381	NIC	28	157	28	87	1733	IND	27	1474	55	75	2001	HUN	34	165	75	76	900
DZA	10	2139	3	6	1192	NPL	34	749	11	73	2227	IRQ	8	2586	7	22	931	IRL	38	264	50	99	1200
ECU	49	120	36	70	2538	OMN	0	130900	0.001	5	3282	ISR	26	3771	22	27	3309	ITA	46	176	39	81	700
ERI	61	288	2	21	420	PAK	7	8718	5	30	2512	KGZ	22	542	2	19	1630	JPN[b]	90	98	22	94	1400
ETH	21	574	26	54	1239	PAN	44	98	21	98	1957	KWT	3	43125	0.02	11	5039	NLD	41	153	37	87	1300
GAB	91	6	50	90	1636	PER	82	40	24	65	3321	LBN	37	2665	17	34	2224	NOR	56	7	3	73	1000
GEO	54	162	26	73	1687	PNG	72	21	21	86	3877	LSO	5	4210	6	29	905	NZL	93	1	20	31	1200
GHA	29	397	55	71	1371	PRK	47	374	20	100	2966	MAR	42	535	19	27	783	POL	24	136	72	99	900
GIN	40	137	36	66	1494	PRY	85	32	33	51	1980	MDA	16	1350	67	62	2989	PRT	49	212	39	34	700
GNB	67	71	42	84	1319	SAU	5	2417	0.0002	10	4135	MKD	38	210	25	98	3007	ROM	47	69	52	81	700
GTM	36	323	26	92	1572	SDN	70	55	25	40	504	PHL	24	1022	23	98	2164	RUS	73	4	13	60	600
GUY	74	5	47	95	3832	SLB	80	21	10	96	3825	RWA	26	1644	19	50	1090	SWE	57	11	21	93	1000
HND	48	119	19	96	1450	SLE	47	181	39	81	1043	SWZ	64	196	27	47	1723	TUR	81	41	19	39	600
HTI	6	8962	19	64	945	SLV	18	1961	28	77	2394	SYR	7	3634	19	35	1206	USA	74	3	28	49	1000
IDN	53	224	26	94	4169	SOM	20	117	2	54	611	THA	39	312	45	96	2258						

For data sources see Table 1.
[a] For China same years as for developed countries are used, see footnote 5.
[b] Japan and Bhutan were later excluded as they were outliers in the regression.

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National REDD+ reference levels deduced from the global deforestation curve

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Highlights

- REDD+ reference levels are deduced from the forest transition hypothesis
- A multi-national regression model estimates forward-looking forest cover
- The model combines a uniform global method with national circumstances

Abstract

This article proposes a solution to one of the most prominent problems for the establishment of a REDD+ regime – namely reference level determination. We have developed national reference levels under Business as Usual (BAU) conditions, drawing on the identification of a global deforestation curve which was created by applying the forest transition concept (Köthke et al., 2013). This allowed us to develop a uniform global method for identifying reference levels which consider country specific circumstances. The article identifies national BAU reference levels for 86 REDD+ target countries which are still in their deforestation phase, and compares estimated to actual deforestation over the period 2005-2010. This is the first time a uniform global deforestation pattern has been applied to determine national REDD+ reference levels. The quantitative results provided here may be an important basis for further policy discussions.

Keywords: REDD+ reference levels, multi-national, deforestation model, forest transition, national circumstances

National REDD+ reference levels deduced from the global deforestation curve

1. Introduction

Deforestation (including forest degradation) is a significant source of anthropogenic greenhouse gas emissions as well as a threat to biodiversity globally. About 17% of the global anthropogenic greenhouse gas emissions were induced by tropical deforestation in 1990 (Gullison et al., 2007; IPCC, 2007). According to the Intergovernmental Panel on Climate Change (IPCC, 2007), reducing emissions from deforestation is the most effective and comprehensive mitigation option in the short term and, according to the Stern Review (Stern et al., 2006), among the cheapest. The REDD+ mechanism was therefore initiated in the United Nations Framework Convention on Climate Change (UNFCCC) with the primary aim of fighting climate change (REDD+: Reducing Emissions from Deforestation and forest Degradation and the role of conservation, the sustainable management of forests and enhancement of forest carbon stocks in developing countries) (UNFCCC, 2005, 2008, 2009a, 2010).

The discussion about a feasible REDD+ mechanism is ongoing (*ibid.*) with several methodological issues still needing to be resolved. One problem is the determination of national reference levels (also called baselines) against which the countries' reductions of emissions due to deforestation and forest degradation can be benchmarked (for overviews see, e.g., Angelsen, 2009, : Ch.3; Eliasch, 2008, : Ch.9.3; Verchot and Petkova, 2010).

To determine a reference level, it is helpful to distinguish a 'Business as Usual (BAU) reference level' from a 'crediting baseline' (Angelsen et al., 2011). The BAU reference level describes how forests would develop in the absence of incentives by a REDD+ regime. In contrast to the crediting baseline, it has no normative content. The crediting baseline defines the minimum amount a country would have to reduce its deforestation in order to be rewarded. This minimum level is ultimately a matter of negotiation amongst the parties, and is at the core of most party submissions to the UNFCCC. The determination of national BAU reference levels (the focus in this paper) could become the basis for further negotiations about crediting baselines.

Reference level determination is complex because all REDD+ target countries[1] have to agree upon one methodological approach despite having very different country specific conditions and interests. The inclusion of all target countries in the agreement is essential to avoid international leakage and guarantee environmental integrity (Olander et al., 2008; UNFCCC, 2011). In the political discourse it is agreed that a BAU reference level shall consider historical deforestation and further national circumstances (UNFCCC, 2008, Decision2/CP.13).

Experts demand equity, effectiveness and efficiency of the mechanism and seek a uniform

[1] Potential target countries for the REDD+ mechanism are the so called Non-Annex I countries to the UNFCCC (UNFCCC (1992); UNFCCC, 1992/2012).

methodology for all parties (Angelsen, 2008, : Ch.6; Angelsen et al., 2011). However the causes and drivers of deforestation differ considerably amongst regions and may be complexly intertwined. Despite these regional differences, changes in a region's forest cover seem to follow a determinable pattern of decline and later re-expansion over time. This development is described and explained by the forest transition hypothesis (originating from Mather, 1992). According to the forest transition curve, this forest cover pattern is supposed to be similar across time, regions and countries. The consideration of the country's stage on the forest transition curve could account for the national circumstances and therefore guarantee equal development opportunities for the different countries (proposed and requested, e.g., by Angelsen, 2008, : Ch.6; Angelsen et al., 2011; Culas, 2012; UNFCCC, 2009b). A few authors have grouped countries according to their stage on the forest transition curve into high or low forest cover and high or low deforestation countries (see Griscom et al., 2009; Murdiyarso et al., 2008) but have not quantified and modelled the forest transition concept. Köthke et al. (2013) recently parameterized a regression model of global deforestation based on the forest transition concept which seems suited for reference level application.

Simple linear extrapolations of historical deforestation rates from a reference period to a commitment period were discussed early in the REDD+ process (called 'Simple Historical Reference Level' or 'Compensated Reduction Approach' (Santilli et al., 2005)). This approach has been criticised by experts because of potential systematic underestimation and overestimation of the BAU forest cover development (Angelsen, 2008, : Ch. 6). Experts fear that countries with high forest cover and low historical deforestation rates could be disadvantaged by historical extrapolated reference levels which would neither guarantee future development opportunities nor honour early action. Vice versa, countries with high deforestation rates in the past could be advantaged by less demanding reference levels, which allow high deforestation rates in the future. This could produce 'hot air' and would not be climate and cost effective. Perverse incentives by overestimating or underestimating BAU emissions from deforestation must therefore be avoided (Angelsen, 2009; Skutsch et al., 2007; UNFCCC, 2011). Figure 1 schematically displays possible consequences of simple historical forest cover extrapolations for countries in different stages at the forest transition curve (adapted from Angelsen, 2008, : Ch.6).

Concepts for adjusting of simple historical reference levels to national circumstances, which would shift the historical extrapolations upwards or downwards have also been proposed (*e.g.*, a 'Development Adjustment Factor' was proposed by the Coalition of Rainforest Nations). But the extent and conditions for adjustment have not been defined and quantified (overview provided by, e.g., Angelsen et al., 2011; Parker et al., 2009; Verchot and Petkova, 2010).

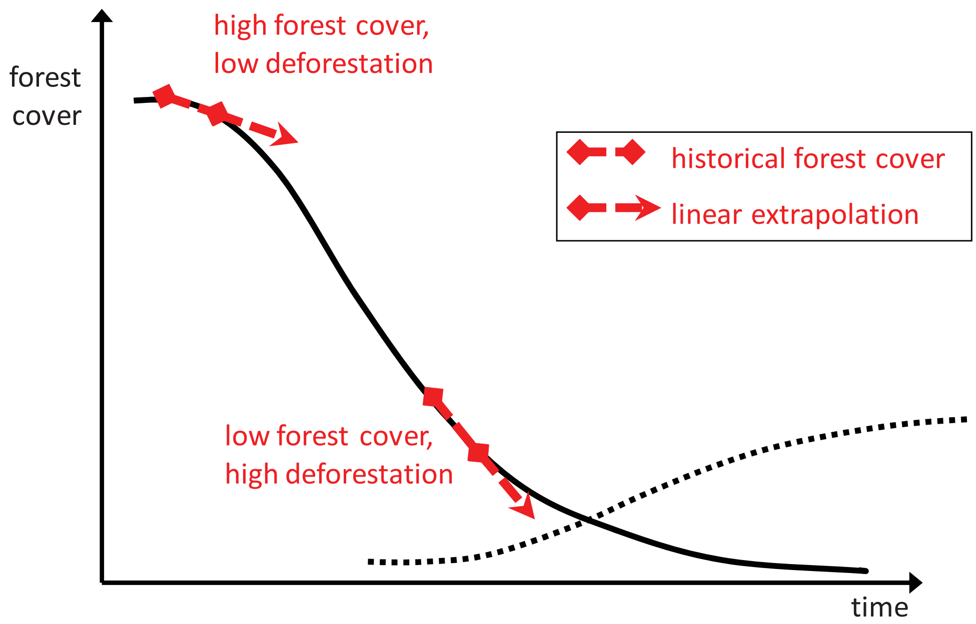

Figure 1:
Forest cover development divided in the curves of deforestation and forest enhancement according to the forest transition concept (adapted from Mather 1992 and Grainger 1995).
The concept of simple historical reference levels by linear extrapolation of historical forest cover in contrast to the forest transition development is schematically displayed (adapted from Angelsen 2008).

An alternative option to using historical extrapolations is to project BAU reference levels by forest cover models. Plenty of deforestation models currently exist, but not all are suited for forward-looking forest cover estimates and only a few have been applied to REDD+ reference level proposals. Most applications for REDD+ reference levels have been calculated using simulation or spatial regression models on sub-national scales, *i.e.*, regional or project level. Kaimowitz and Angelsen (1998) provide a review and discussion of deforestation models. They distinguish analytical, simulation or programming approaches and empirical regression models.
Empirical multi-national regression models have not been previously applied to determine REDD+ reference levels. They are able to give quantitative BAU estimates at the global and national scale. See Köthke et al. (2013) for a review on multi-national regression models for forest cover estimates.
In this paper we apply such a regression model (developed by Köthke et al., 2013) and propose a new approach for setting national REDD+ BAU reference levels. The regression model applied considers the countries' position on the forest transition curve and accounts for country specific circumstances like physio-geographic conditions, demographic and (socio-)economic status. The regression model and its results are summed up in Section 2.1 of this paper.
The application of the model is demonstrated by the estimation of national BAU reference levels for 86 REDD+ target countries in a hypothetical retrospective REDD+ scenario (Section 2.2).

National deforestation rates and net forest area losses are estimated and compared to net forest area changes according to FAO's Global Forest Resources Assessment (FRA) (2010) data in a hypothetical commitment period from 2005 to 2010 (Section 3). The approach and results are discussed and related to other elements of the policy regime that governs forestry under the UNFCCC (Section 4).

The approach concentrates on forest area development (rather than emissions development) to relate national BAU reference levels to the deforestation activity (the first out of the five REDD+ activities (UNFCCC, 2010, III.C.70.(a))). Further financing issues are not the focus of this paper.

2. Materials and Methods

2.1. Background: the global deforestation-model

The ‘global deforestation curve’, as determined by Köthke et al. (2013), is the result of a regression analysis of the world’s forest cover development at country level prior to forest transition (*i.e.,* during net deforestation)[2]. The regression model has been developed using cross-section data of forest cover in the world’s developed and developing countries and is theoretically based on the forest transition hypothesis. FAO FRA 2010 is used as the primary data source. This analysis is outlined here only briefly. For the theoretical framework and for technical details of the data analysis refer to the aforementioned article.

The basic model measures the ‘forest cover’ of a country that has remained until a specific year [FC_t] as a function of physio-geographic, demographic and (socio-)economic country circumstances five years earlier [X_{t-5}]. In order to be comparable across countries, FC is expressed as a fraction of each country’s potential forest area [$FApot$], *i.e.*, $FC_{t,i}=FA_{t,i}/FApot_i$ (where t is an index for the year, i is an index for countries). Since FC appears to follow an inverted growth function, it is transformed according to

$$FC^*_{t,i} = \ln\left(\frac{1}{FC_{t,i}} - 1\right), \quad (1)$$

in order to fit in a linear regression system. The linearised regression model has the equation

$$FC^*_{t,i} = \beta_0 + \sum_{v=1}^{n} \beta_v \ln X_{v,t-5,i} + \varepsilon_i , \quad (2)$$

where FC^* is the linearised forest cover after logistic transformation, X is a vector of explanatory variables v (which are time-lagged if time-related), β are the respective coefficients, and ε_i is the residual (assumed to be independent and identically distributed).

Köthke et al. (2013) ran several specifications of this model and identified significant variables affecting forest cover. The results of all specifications proved highly significant and exhibited high determination coefficients (R^2 between 0.599 and 0.845). All countries where data was available (111 developing and 29 developed countries) were included in a comprehensive model specification (Köthke et al., 2013, : specification 4). A dummy variable for distinguishing developing (Annex I countries to the Unfccc) from developed countries (Non-Annex I countries) was included in this specification for analytical purposes. It proved to be insignificant, *i.e.*, no statistical difference between both groups was found.

In the present paper, we recalculated the comprehensive model specification with the same data set, but skipped the dispensable insignificant dummy variable for the development status. The regression results are presented in Table 1. These results differ only marginally from the previous

[2] In order to avoid confusion, note that the ‘deforestation’ curve has ‘forest cover’ as a response variable (rather than ‘*changes* in forest cover’).

results in Köthke et al. (2013). The results shown in Table 1 are applied for reference level estimates in this paper.

Table 1:
Regression results of the comprehensive model specification used for BAU reference level calculation (note that signs are related to the transformed linearised model [*FC**], and are opposite when related to *FC*).

variables	**comprehensive Model** N=140
intercept	1.029 (*0.714*); **1.44** n.s.
$\ln PP_{FA}$	0.530 (*0.029*); **18.08*****
$\ln SI$	-0.215 (*0.038*); **-5.68*****
$\ln SFA_{pot}$	0.220 (*0.085*); **2.58***
$\ln CY$	-0.378 (*0.093*); **-4.04*****
adjusted R²	0.784
F-statistic (p-value)	127.125***
standard deviation	0.633

Note: Values are coefficient estimates (with standard errors in *italics*); **t-values** (**bold**) with significance level ***p<=0.001, *p<=0.05.

PP_{FA} [persons/km²] = population pressure (inhabitants (UN 2009) divided by forest area (FAO 2010b)); SI [%] = suitability index of arable land (FAO, 2000, 2010a); SFApot [%] = share of potential forest area (Pongratz, 2010; Pongratz et al., 2007, 2008, extracted from grid maps) divided by surface area (World Bank, 2011); CY [kg/ha] = cereal area yield (World Bank, 2011).

The regression model shows a significant influence from the logarithmic variables: population pressure [PP_{FA}], cereal area yield [*CY*], share of potential forest area [*SFApot*] and soil quality [*SI*]. The greatest influence on *FC* can be traced back to population pressure on the remaining forest area of the previous period. This has a negative influence on *FC*.

After the parameterization (see Table 1) the model can be transformed back to the sigmoid form to estimate a country's forest cover $[F\hat{C}]$ of a specific year according to

$$F\hat{C}_{t,i} = \frac{FCpot_i}{1 + e^{FC^*_{t,i}}}, \qquad (3)$$

where *FCpot* is the potential forest cover of the country (=1). The time lag of the variables allows five year forward-looking forest cover estimates.

2.2. Hypothetical REDD+ scenario and BAU reference levels

The reference level calculation by the deforestation model was conducted for 86 REDD+ target countries which are still in their deforestation phase (according to FAO FRA 2010 data (FAO, 2010)) and for which data was available. The respective countries are listed in Table 2, variables and data sources for calculation are given with Table 1.

The BAU reference levels are calculated for the period 2005-2010, which serves as a hypothetical retrospective commitment period (CP). A retrospective period is chosen for an ex post comparison with observed data. The BAU reference levels are calculated for each country in terms of a net annual change in forest area [km²/a] within the commitment period by Equation 4:

$$\Delta F\hat{A}_{CP,i}/5 = \Delta F\hat{C}_{CP,i} * FApot_i/5 = \left(F\hat{C}_{2010,i} - F\hat{C}_{2005,i}\right) * FApot_i/5 \qquad (4).$$

To evaluate the results the BAU reference levels [$\Delta F\hat{A}_{CP}/5$] are compared to observed net annual forest area changes according to FAO FRA data for the same period 2005-2010 [$\Delta FA_{CP}/5$], *i.e.*, $\Delta FA_{CP,i}/5 - \Delta F\hat{A}_{CP,i}/5$. Figure 2 schematically displays the comparison of observed and estimated national forest cover changes.

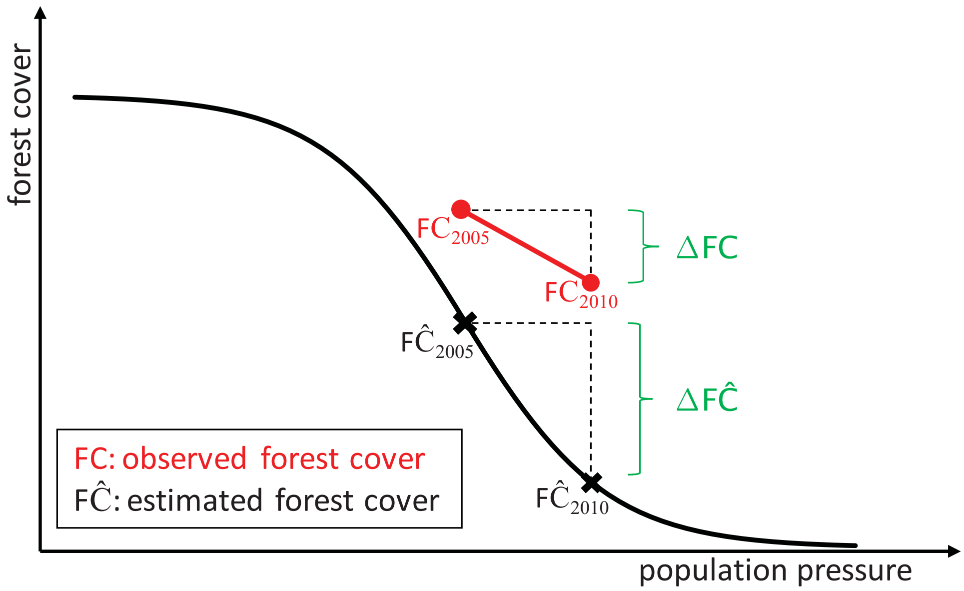

Figure 2:
Scheme of national BAU reference level estimation in comparison to observed forest cover development. Estimated forest cover changes within the commitment period (2005-2010) are translated into BAU reference levels.

3. Results

Figure 3 shows the national BAU reference levels from 2005-2010 for 86 REDD+ target countries together with the global mean deforestation curve. In this figure the forest cover is plotted against population pressure. The 86 countries are in different stages on the deforestation curve with remaining forest covers between maximum 91 % and minimum 0.64 % of their initial forest area. The estimated deforestation rates differ greatly among the individual countries (between -4.1 % and +1.6 % net annual forest area change).

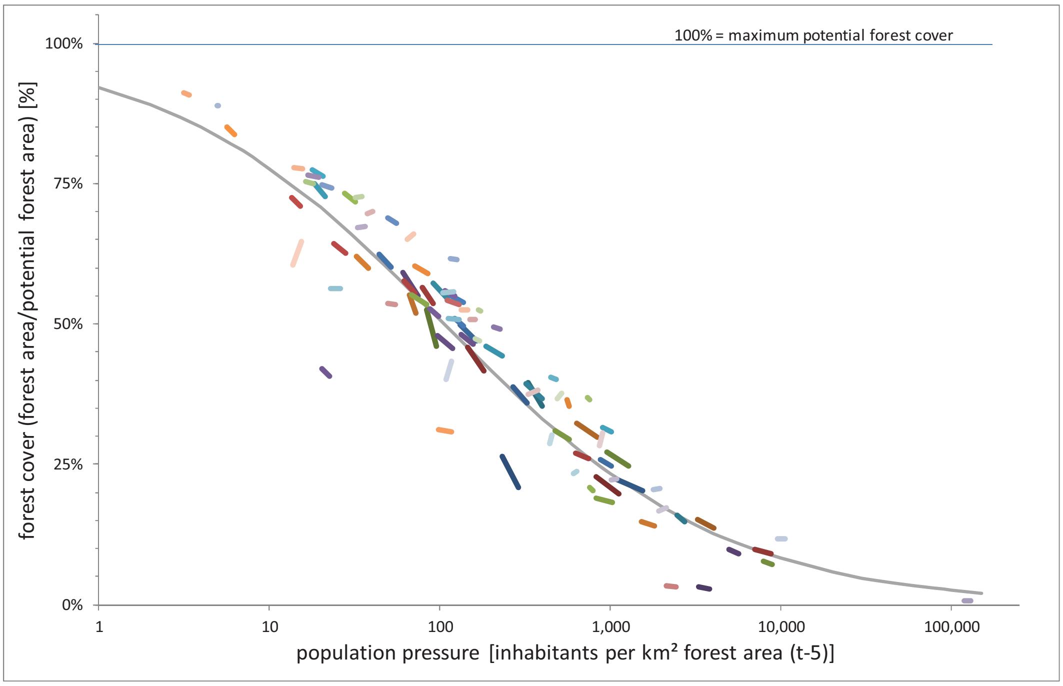

Figure 3:
Estimated forest cover 2005-2010 for 86 REDD+ target countries (different shades show different countries) and the global mean s-shaped deforestation curve (calculated by the comprehensive regression model).

Table 2 is the main result of this study. It contains numerical results for each of the 86 REDD+ target countries, namely the country specific reference level values for the period 2005-2010 and the deviation of the observed forest area development in the hypothetical commitment period. Some of the results will be further highlighted in this chapter.

When analysing the individual reference level values it is immediately noticeable that a declining development of forest area under Business as Usual is estimated by the regression for most of the considered REDD+ target countries (n=66), but not for all (n=20). This is caused by the development of the underlying explanatory variables. By adding the individual reference levels it becomes evident that the positive reference level values have a marked influence on the total results. The estimated BAU reference levels add up to just about 40 % of the total actual observed deforestation (see Table 3).

Table 2:

Estimated BAU reference levels and deviation from FAO data 2005-2010 for 86 REDD+ target countries.

ISO 3 country codes	Potential forest area	**BAU reference level: forest area change 2005-2010**		observed forest area change FAO 2005-2010		Deviance from reference level
	[km²]	**[km²/a]**	**[%/a]**	[km²/a]	[%/a]	[km²/a]
AFG	146,084	-182	-0.845%	0	0.000%	182
AGO	877,410	-3,221	-0.570%	-1,248	-0.211%	1,973
ARG	789,527	-298	-0.061%	-2,398	-0.784%	-2,100
ARM	12,583	5	0.166%	-42	-1.484%	-47
AZE	44,856	206	1.624%	0	0.000%	-206
BDI	13,784	-40	-1.929%	-18	-0.994%	22
BEN	83,701	-480	-1.150%	-500	-1.039%	-20
BFA	96,615	-311	-0.701%	-600	-1.009%	-289
BGD	137,562	47	0.295%	-26	-0.179%	-73
BIH	51,364	-15	-0.057%	0	0.000%	15
BLZ	21,934	-19	-0.114%	-96	-0.666%	-77
BOL	687,899	-111	-0.021%	-3,076	-0.524%	-2,965
BRA	6,936,254	1,364	0.027%	-21,944	-0.414%	-23,308
BRN	5,770	-76	-2.502%	-18	-0.463%	58
BWA	197,222	1,620	1.356%	-1,184	-0.991%	-2,804
CAF	288,865	-271	-0.124%	-300	-0.132%	-29
CMR	322,500	-908	-0.467%	-2,200	-1.047%	-1,292
COD	2,137,493	-9,264	-0.699%	-3,114	-0.200%	6,150
COG	310,270	-948	-0.422%	-120	-0.053%	828
COL	971,855	1,796	0.284%	-1,010	-0.166%	-2,806
DOM	40,893	-28	-0.171%	0	0.000%	28
DZA	153,377	166	0.649%	-88	-0.573%	-254
ECU	199,788	50	0.045%	-1,976	-1.821%	-2,026
ERI	25,139	-270	-4.085%	-44	-0.283%	226
ETH	594,816	-1,880	-1.022%	-1,408	-1.083%	472
GAB	240,838	-665	-0.325%	0	0.000%	665
GEO	51,191	33	0.138%	-26	-0.094%	-59
GHA	169,548	-896	-1.345%	-1,154	-2.092%	-258
GIN	161,750	-479	-0.580%	-360	-0.535%	119

ISO 3 country codes	Potential forest area	**BAU reference level: forest area change 2005-2010**		observed forest area change FAO 2005-2010		Deviance from reference level
	[km²]	**[km²/a]**	**[%/a]**	[km²/a]	[%/a]	[km²/a]
GNB	30,310	-119	-0.681%	-100	-0.483%	19
GTM	100,671	-558	-1.431%	-562	-1.427%	-4
GUY	204,606	19	0.010%	0	0.000%	-19
HND	108,034	-508	-0.982%	-1,200	-2.072%	-692
HTI	17,796	-19	-1.406%	-8	-0.762%	11
IDN	1,795,098	-1,763	-0.199%	-6,850	-0.700%	-5,087
IRN	315,550	175	0.238%	0	0.000%	-175
JAM	9,749	-12	-0.565%	-4	-0.118%	8
JOR	20,606	-34	-1.659%	0	0.000%	34
KAZ	70,847	214	1.054%	-56	-0.168%	-270
KEN	224,295	-456	-0.789%	-110	-0.312%	346
KHM	175,446	-275	-0.289%	-1,274	-1.187%	-999
KOR	98,200	-80	-0.222%	-66	-0.106%	14
LAO	224,093	47	0.031%	-782	-0.484%	-829
LBR	80,378	-654	-1.377%	-300	-0.670%	354
LBY	15,946	-40	-1.571%	0	0.000%	40
LKA	66,580	-101	-0.479%	-146	-0.755%	-45
MDG	362,100	-891	-0.447%	-570	-0.444%	321
MEX	1,227,654	96	0.015%	-1,552	-0.237%	-1,648
MLI	193,262	-1,130	-1.034%	-790	-0.613%	340
MMR	633,563	149	0.045%	-3,096	-0.929%	-3,245
MNG	227,822	-609	-0.636%	-820	-0.725%	-211
MOZ	425,549	-1,835	-0.692%	-2,114	-0.527%	-279
MRT	24,955	-151	-2.663%	-50	-1.873%	101
MWI	65,158	-545	-2.120%	-330	-0.970%	215
MYS	327,487	-692	-0.378%	-868	-0.416%	-176
NAM	197,545	-39	-0.035%	-742	-0.969%	-703
NER	80,472	-114	-0.750%	-124	-0.979%	-10
NGA	461,466	-2,260	-1.803%	-4,096	-3.694%	-1,836

ISO 3 country codes	Potential forest area	**BAU reference level: forest area change 2005-2010**		observed forest area change FAO 2005-2010		Deviance from reference level
	[km²]	**[km²/a]**	**[%/a]**	[km²/a]	[%/a]	[km²/a]
NIC	113,014	-394	-0.725%	-700	-2.021%	-306
NPL	107,932	-220	-0.756%	0	0.000%	220
OMN	15,059	0	-0.055%	0	0.000%	0
PAK	242,157	-334	-1.407%	-430	-2.261%	-96
PAN	73,931	-219	-0.561%	-118	-0.356%	101
PER	831,649	735	0.127%	-1,500	-0.218%	-2,235
PNG	398,405	-1,030	-0.334%	-1,422	-0.483%	-392
PRK	121,093	183	0.403%	-1,266	-2.010%	-1,449
PRY	206,767	-586	-0.387%	-1,786	-0.967%	-1,200
SAU	209,933	-9	-0.136%	0	0.000%	9
SDN	1,000,000	-323	-0.060%	-542	-0.077%	-219
SEN	69,506	-37	-0.104%	-400	-0.461%	-363
SLB	27,740	-129	-0.620%	-56	-0.250%	73
SLE	58,205	-482	-1.806%	-196	-0.694%	286
SLV	16,212	4	0.107%	-44	-1.424%	-48
SOM	343,371	-171	-0.160%	-768	-1.077%	-597
SUR	150,210	-117	-0.085%	-36	-0.024%	81
TCD	192,215	-685	-0.646%	-792	-0.664%	-107
TGO	44,142	-185	-1.867%	-198	-5.130%	-13
TKM	123,449	764	1.540%	0	0.000%	-764
TTO	5,152	-12	-0.615%	-8	-0.348%	4
TZA	536,319	-2,857	-0.930%	-4,034	-1.138%	-1,177
UGA	113,168	-565	-1.548%	-882	-2.572%	-317
VEN	716,702	-1,452	-0.294%	-2,876	-0.603%	-1,424
YEM	87,258	-67	-2.478%	0	0.000%	67
ZAF	355,270	746	0.573%	0	0.000%	-746
ZMB	484,322	-516	-0.143%	-1,666	-0.331%	-1,150
ZWE	359,721	-2,304	-1.161%	-3,270	-1.895%	-966

Table 3:
Annual forest area change for 86 REDD+ target countries 2005-2010 [sum, km²/a] according to observed FAO data and different reference level approaches.

Reference levels 2005-2010:	**Annual forest area change [sum of 86 countries, km²/a]**
BAU reference levels (model estimates)	-37,524
	-45,941 (net deforestation)
	+8,417 (net forestation)
Simple historical reference levels:	
a) linear extrapolated from 2000-2005 *	-99,502
b) linear extrapolated from 1990-2000 *	-123,023
Observed forest area change *	-92,550

*data from FAO FRA 2010

The greatest absolute forest area changes in the BAU estimates can be attributed to only a few countries. More than 50 % of the total net forest area loss of all 86 countries is expected by merely five countries: the Democratic Republic of the Congo, Angola, United Republic of Tanzania, Zimbabwe and Nigeria. The Democratic Republic of the Congo is estimated to have by far the greatest absolute forest area change of -9,264 km²/a, which is almost 25 % of the expected net forest area change of all 86 countries together. However, relative to the country's forest area, the deforestation rate of -0.699 %/a is in the medium deforestation range.

In accordance with FAO FRA 2010 data, most countries are supposed to continue with deforestation according to the model estimates. Eritrea has the maximum deforestation rate in the BAU reference level with -4.1 %/a, however, this is only -270 km²/a in absolute terms. Colombia is estimated to have the greatest absolute forest area increase of +1,796 km²/a (+0.28 %/a). Azerbaijan, with +1.6 %/a (+206 km²/a), has the greatest relative forest area increase in the BAU reference level.

Brazil is known to have a huge absolute forest area and huge forest area losses, although deforestation has slowed down in the past years to -0.4 %/a between 2005-2010 (FAO, 2010). According to its national circumstances, however, our BAU reference level expects Brazil to increase its forest area by 0.027 %/a between 2005 and 2010.

Figure 4 shows the estimated deforestation rates [%/a] for all 86 countries in comparison to observed deforestation rates by FAO data in the retrospective commitment period. The examples mentioned above are labelled in the figure. The estimated deforestation rates for countries with small forest areas are deviating most from the observed deforestation rates. It can be seen that for most countries the deforestation rate (both observed and estimated) is in the low range. 31 countries are estimated to have even lower deforestation rates than the global average deforestation rate, which was -0.14 %/a between 2005-2010 (FAO, 2010).

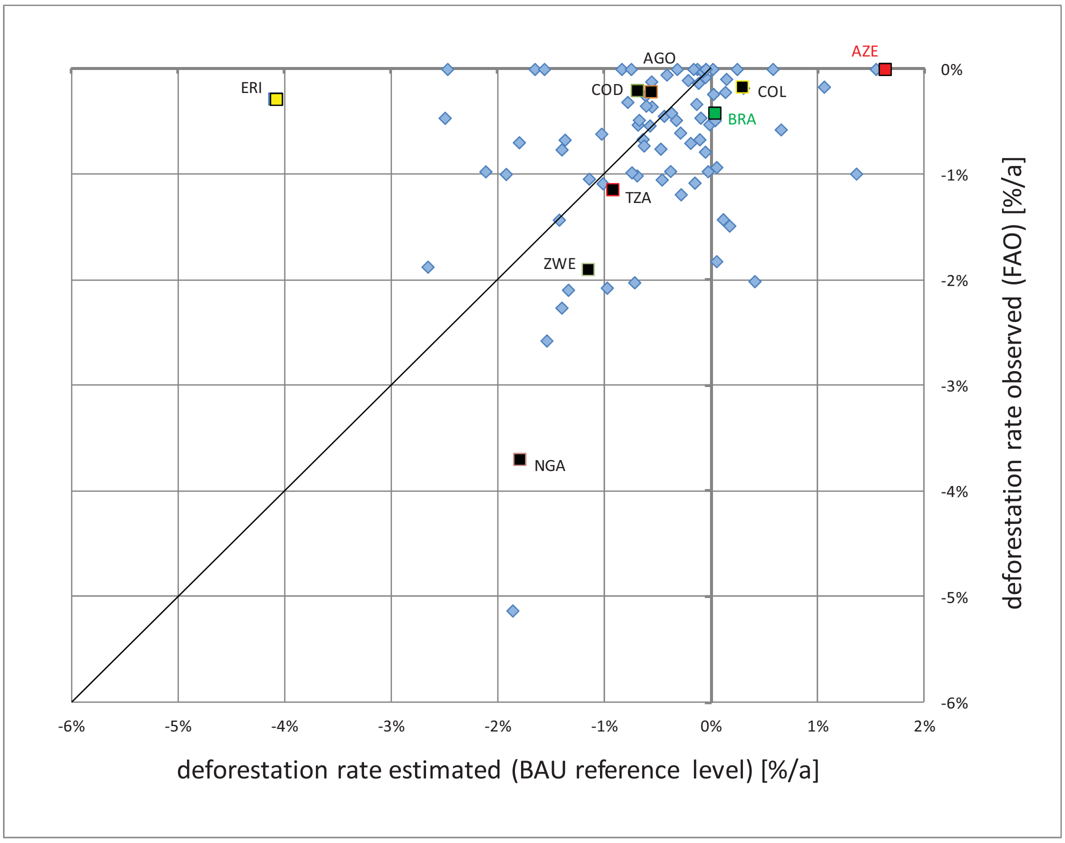

Figure 4:
Comparison of annual deforestation rates 2005-2010 [%/a] of 86 REDD+ target countries estimated by BAU reference levels (x-axis) and observed according to FAO FRA data (y-axis).

Figure 5 shows the deviation of the observed from the estimated forest area changes in the retrospective commitment period 2005-2010 (FAO FRA 2010 data relative to the BAU reference levels). It is evident that most of the countries (n=53) have deforested more area between 2005 and 2010 than estimated by the BAU reference levels (underperformance). 33 countries have deforested less area than estimated by the BAU reference levels (overperformance).

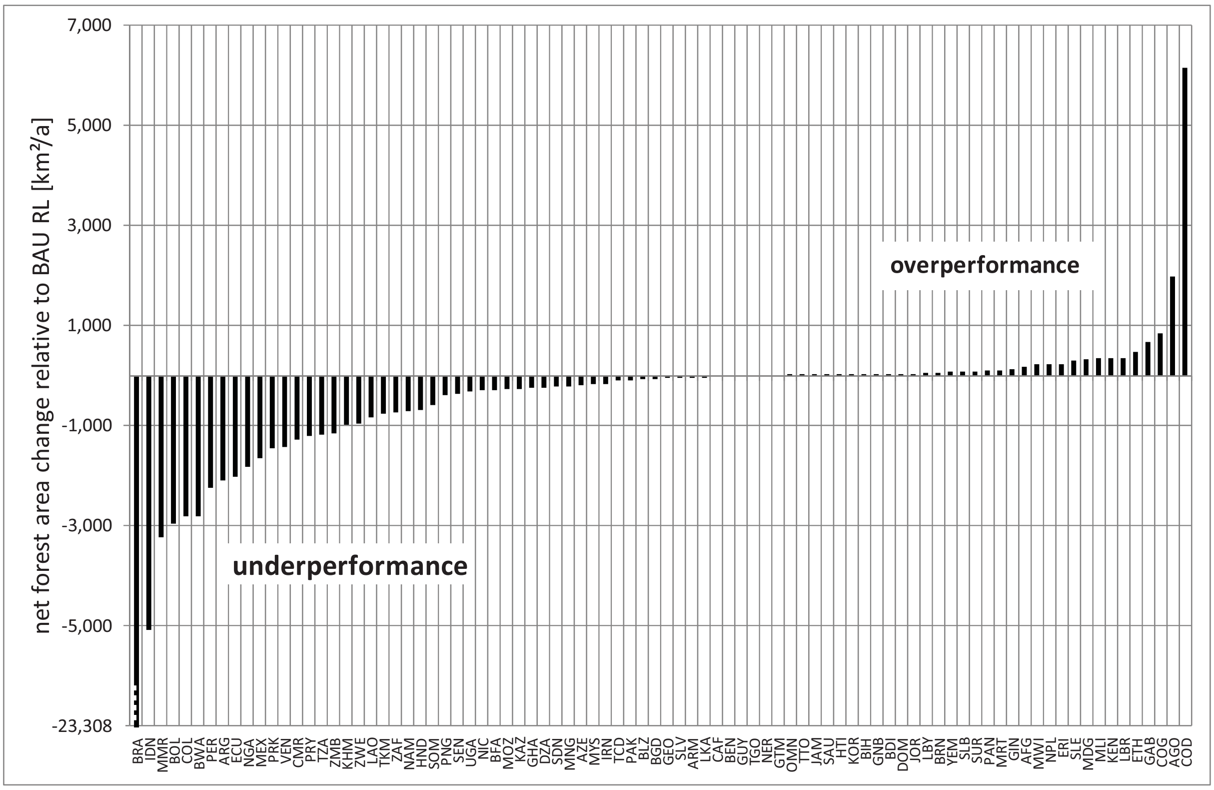

Figure 5:
Deviation of the observed annual forest area change (by FAO data) relative to the BAU reference levels (2005-2010) of 86 REDD+ target countries (countries are abbreviated by ISO-3166-1 alpha-3 country codes).

4. Discussion

The paper proposes a method for national BAU reference level estimates which is based on a globally uniform deforestation model applicable for all countries. The average global influence of certain physio-geographic, demographic and (socio-)economic circumstances is considered; the input data however is country specific.

The implications of applying this method and the associated results, uncertainties and gaps will be discussed in this section. Furthermore some reliability issues as well as the links to existing policy elements of the LULUCF[3] regime will be discussed.

Implications and interpretation of method and results

The method for estimating national forest cover development is based on the mean global forest cover development with consideration of national data. In general a single country's forest cover development is supposed to deviate from the mean global development, but in our method certain national circumstances (namely the explanatory variables of the model) are subtracted from this deviance. Using these significant variables the deviance from the national to the global development is reduced but not 100% explained.

The first step for reducing the deviance is the normalization of the different country and forest area sizes. This is done by defining forest cover as a fraction of the country's initial forest area (expressed by area of potential forest vegetation). Area not suitable for forests, such as water bodies, deserts, ice and rocky land, is not accounted for. Hence, a country is only made responsible for those areas which are suitable for forest growth. For example the countries Brunei Darussalam and Angola are very different in absolute surface and forest area. Also their natural potential for forest vegetation is different (about 100% and 70% respectively). Both, however, have a remaining forest cover [*FC*] of 67% in 2005, which makes them comparable.

The explanatory variables of the model further shift the estimated BAU forest cover of an individual country according to its national data. The extent to which this is shifted is, however, always the mean global influence of the respective variable. The share of potential vegetation area [*SFApot*] and the land fertility [*SI*] are considered as physio-geographic national circumstances. They are not time dependent and therefore have no influence on the estimated deforestation rate (speed of deforestation) but on the level of forest cover, *i.e.*, they shift the expected absolute forest cover upwards or downwards on the deforestation curve. For example, countries with generally rather unproductive land (*e.g.,* dryer countries like Oman, Somalia, Afghanistan, Turkmenistan) are expected to have a lower forest cover compared to others. Therefore their forest cover is shifted downwards in the estimates.

The estimated deforestation rate (speed) is however influenced by the agricultural area

[3] LULUCF: Sector under the UNFCCC and activity area under the Kyoto Protocol on the issue: Land use, land-use change and forestry.

productivity of the previous years. Countries with a higher cereal area yield are assumed to have greater agricultural productivity and intensification which may be related to greater technological progress. According to the global trend they are expected to have a higher forest cover. The faster the cereal area yield increases, the more challenging the BAU reference level will be, *i.e.*, less deforestation is estimated.

The greatest influence, however, is population pressure (demographic circumstance). Countries with a high population pressure are expected to have a lower forest cover, and fast population growth will lead to high deforestation rates in the estimated BAU reference levels.

An increasing forest area in the period 2005-2010 is estimated for 20 countries. This is mainly due to slow population growth in combination with increasing area productivity in terms of cereal area yield in the previous period 2000-2005. For example Turkmenistan and Azerbaijan are estimated to have an increasing BAU reference level (+1.5 %/a and +1.6 %/a) although according to FAO FRA data their forest area has not changed between 2000 and 2010. Their cereal area yield has increased from 2000-2005 by +11 %/a and +8.5 %/a respectively, combined with a moderate increase in population pressure.

This also holds for Brazil, which had a moderate growth of population pressure (+0.2 %/a) and an increasing cereal area yield of +3.2 %/a in the period 2005-2010. According to the global average development our model expects Brazil to increase its forest area by +0.027 %/a between 2005-2010. The challenging target proposed by our BAU reference level estimates can be opposed to less demanding simple historical reference levels. Simple historical extrapolations of Brazil's historical deforestation rates without consideration of those country circumstances would lead to even higher deforestation rates than currently observed (-0.56 %/a and -0.4 %/a, according to FAO (2010) for 2000-2005 and 2005-2010 respectively).

The trend described for Brazil can be used to explain the whole approach. On average the estimated BAU reference levels are more challenging (estimating less net deforestation) than the current FAO data. This would result in more ambitious reduction targets for the single countries. Simple historical extrapolations predict, however, much higher deforestation rates than the current FAO data. This could in reverse produce more "hot air" (see Table 3).

It has to be kept in mind that the retrospective comparison of a BAU reference level to a BAU development without existing incentives by a REDD+ scheme, might possibly be influenced by other already ongoing incentives for deforestation reduction or forest enhancement (*e.g.,* regional REDD pilot programs, Clean Development Mechanism (CDM)). So the displayed "overperformance" might also be influenced by early action or "hot air".

Translation of BAU reference levels into crediting baselines

In the current status of negotiations, a challenging reference level, with increasing forest area or very low deforestation rates, seems unlikely to be accepted as a crediting baseline in the REDD+ system. On the one hand the concerned countries might not to sign targets which may seem high and risky. Not including all countries in the agreement would, in turn, cause international leakage. On the other hand neither rewarding of reforestation nor debiting of underperformance is likely to be negotiated as a REDD+ goal (Pistorius, 2009; Pistorius, 2012).

Setting crediting baselines equal to the proposed BAU reference levels would imply the full remaining national deviance from the mean global development is assigned to the individual countries and treated as their responsibility. The assignment of responsibilities and the options for rewarding emission reductions, however, are a matter of political negotiation. It is, though, not necessary to set a crediting baseline equal to the BAU reference level. Several modifications of the proposed BAU reference level are possible if politically desired.

To reduce deviations from national responsibilities or from prediction inaccuracies it is possible, *e.g.,* to fix the crediting baselines at some percentage of the BAU reference levels; to set a cap or a 'bar' like in the first commitment period of the Kyoto Protocol; or to introduce a corridor or a phased approach (see Angelsen et al., 2011; Parker et al., 2009). For example the 'Combined Incentives Approach' proposes to combine country specific reference levels and the global deforestation rate by a weighting factor (Strassburg et al., 2009). Any such negotiated modifications will be easily applicable to the estimated BAU reference levels (see Table 2).

A differentiated treatment for low and high deforestation countries has been discussed by experts as well. The Joint Research Center proposed a "weakened" reference level for low deforestation countries (*e.g.,* half of the global deforestation rate) (Achard et al., 2005; Mollicone et al., 2007). Such a differentiation between countries with high and low forest cover changes might be politically desired to increase the acceptance of, *e.g.*, high forest cover and low deforestation countries.

The proposed method compares the forest area changes between the observed development and the estimated development, *i.e.*, the "speed" of deforestation in the commitment period is taken as the assessment basis. Besides taking the forward-looking perspective, the relative position of the observed forest cover above or below the deforestation curve could also be considered (see the position of observed forest cover in the schematic Figure 2). Accounting for this position in the crediting baseline would shift the responsibility more on the countries' past performances, which again is a political decision.

In general, any downwards adjustment of the BAU reference level would produce more "winners" of the system (*i.e.,* there would be more countries overperforming the crediting baseline). This could thus enhance the acceptability in the negotiations. However, the trade-off is this will also diminish the incentives to actually reduce deforestation since any given monetary amount for the REDD+ instrument would then be distributed over more countries, thus reducing the individually possible gains.

A single comprehensive regime for carbon accounting from LULUCF would have to include all sinks and sources to guarantee superior environmental integrity. Specifically it would have to include both enhanced forest carbon stocks and avoided deforestation. But so far such a comprehensive approach does not exist. Deforestation is treated differently from forest enhancement (REDD+/ CDM) and the whole accounting approach differs for developing and developed countries (Angelsen et al., 2011; Dutschke and Pistorius, 2008). A comprehensive approach would require the analysis of the whole forest transition curve rather than only the deforestation curve, *i.e.*, it would include the phases of transition and forest area enhancement.

Considering this at the smaller scales, the knowledge of sub-national forest area developments might be of great importance for setting project reference levels and for understanding the aggregated national development. Such resolutions have not yet been regarded in our approach. However, the method is applicable to regional and sub-national data as well.

Calculation of carbon emissions

The method for reference level determination proposed here still focuses on changes in forest area, rather than on the associated carbon emissions. Even though a conversion into carbon emissions seems theoretically straightforward, it would practically complicate the present method due to additional data needs and substantial supplemental calculations (see, e.g., Gibbs et al., 2007). Elaborate rules for converting forest area changes into carbon emissions have already been established in the framework of the UNFCCC (IPCC, 2006). We therefore do not explore this problem further here. Likewise, integrating forest degradation seems to be a problem of data availability in the first instance, and was not pursued further here.

Data issues

The input data needed for this analysis are of different quality and reliability. Data availability and many of the associated technical problems have been discussed previously (see Köthke et al., 2013) and will not be repeated here, but some practical consequences have to be mentioned.

The reliance on estimates of potential forest area is probably the weakest data element of the presented approach. Although the size of potential forest area is not subject to much debate, *e.g.*, in Central European countries; the respective estimates may be more dubitable in those countries where tree growth faces more adverse natural conditions. Here, the borderline between forest and non-forest is largely subject to expert appraisal which cannot be easily verified independently. Additionally climate change may influence conditions for vegetation areas. Switching to empirical

data of ‘original’ rather than ‘potential’ forest area (*e.g.*, by using pollen analysis) seems a theoretically appealing remedy, but would require much additional research on a global scale.
The FAO data on forest area (and consequently on forest area change) also have their specific weaknesses (see Grainger, 2008, for detailed discussion on FAO FRA data quality). However, it is conceivable that once a REDD+ regime becomes reality, a separate monitoring system would have to be established anyway. This would create to more reliable terrestrial or satellite based forest inventories. This upgraded data can easily be integrated into the proposed approach.
The proposed deforestation model is also valid for future possible commitment periods as the theory and method are time independent.

5. Conclusions

The paper presents a method for estimating BAU reference levels for a possible future REDD+ mechanism based on a multi-national regression model. The proposed BAU reference level considers national circumstances rather than only past performance. The method proposed applies a defined theoretical framework, *i.e.*, the concept of forest transition. A country's stage on the deforestation curve is influenced by the national demographic and socio-economic development and by its physio-geographic conditions. These factors are considered and quantified in the estimates of forest area change. This approach has often been discussed but never quantified at multi-national scale.

A reproducible process for deriving country individual BAU reference levels from independently verifiable data is proposed. This is a major advantage over earlier reference level approaches.

The paper provides new aspects for the political negotiations on REDD+ reference levels as the results are different from simple historical extrapolations and since no quantified consideration of national circumstances exists so far.

We recognise many future tasks relevant in the REDD+ process have not been treated by our approach, *i.e.,* data improvements, crediting baseline negotiation and financing issues. However the presented method provides the basis to discuss quantified considerations of national circumstances in the REDD+ BAU reference level setting.

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Eidesstattliche Versicherung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

Hamburg, den 05.01.2014

M. Köthke

Unterschrift