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To leak or not to leak?

Land-Use Displacement and Carbon Leakage from Forest Conservation

Sabine Henders

Linköping University
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Abstract

This thesis investigates the question how emissions from land-use displacement can be assessed and accounted for, using the example of carbon-leakage accounting in the planned UNFCCC mechanism on 'Reducing Emissions from Deforestation and Forest Degradation' (REDD). REDD serves here as example of an international forest conservation policy that might be effective locally but could lead to displacement of deforestation to other countries. The first part of the thesis reviews existing accounting methods for land-use displacement from different research fields and assesses their usefulness to quantify carbon leakage from REDD. Results show that it is very difficult to assess policy-induced (or *strong)* carbon leakage due to the requirement to demonstrate causal links between the policy in question and the observed land-use changes, especially at international scale. Other accounting methods focus on demand-driven (or *weak*) carbon leakage, by establishing a link between international trade flows and environmental impacts arising in the production of traded commodities, such as land use or land-use changes. Methods to quantify such distant linkages, or teleconnections, between production and consumption locations commonly combine land-use accounting with trade-flow assessments to link local land-use changes with global consumption. A methodological challenge is currently the quantification of emissions from land-use change arising from trade teleconnections. Responding to this shortcoming, in the second part of the thesis a new method is developed to assess these teleconnections. Coupled with trade-flow analysis, the 'Land-Use Change Carbon Footprint' (LUC-CFP) allows quantifying the extent to which land-use changes and associated emissions in a given country are due to the production of export goods, and thus the international demand for - and consumption of - forest-risk commodities. The understanding of such distant deforestation drivers can be useful in several contexts. Examples are the design of conservation policies like REDD, which risk being less effective as globalized deforestation drivers pose a high risk for international leakage, or the planning of demand-side measures that could complement supply-side action in decreasing global deforestation levels. Demand-side measures, such as zero-deforestation embargos, regulations or certification schemes, could eventually contribute to decrease the risk for international land-use displacement by addressing global consumption levels and commodity demand as one of the underlying driving forces of land-use change and deforestation.

List of papers

This thesis is based on the following five articles, which will be referred to in the text by the Roman numerals (I-V):

I. Henders S. and Ostwald M., 2012. Forest Carbon Leakage Quantification Methods and Their Suitability for Assessing Leakage in REDD. *Forests* 3 (1): 33-58.

SH and MO designed the research, SH conducted the literature review, SH and MO performed the analysis, SH wrote the paper with contributions from MO.

II. Ostwald M. and Henders S., 2014. Making two parallel land-use sector debates meet: Carbon leakage and indirect land-use change. *Land Use Policy* 36: 533-542.

SH and MO designed the research, SH and MO conducted literature review and analysis, MO wrote the paper with contributions of SH.

III. Henders S. and Ostwald M., 2014. Accounting methods for international land-related leakage and distant deforestation drivers. *Ecological Economics* 99: 21-28.

SH designed the research, SH conducted literature review, SH and MO performed analysis, SH wrote the paper.

IV. Persson U.M., Henders S., and Cederberg C. A method for calculating a land-use change carbon footprint (LUC-CFP) for agricultural commodities – applications to Brazilian beef and soy, Indonesian palm oil. Submitted to Global Change Biology.

MP and SH designed the research, SH conducted literature search and data collection, MP performed analysis and method establishment with contributions from CC, MP wrote the paper with contributions from SH and CC.

V. Henders S., and Persson U.M. Land-use change emissions embodied in trade of agricultural forest-risk commodities from Brazil and Indonesia. Manuscript.

SH and MP designed the research, MP performed footprint analysis, SH performed trade-flow analysis, SH wrote the paper with contributions from MP.

Abbreviations and Acronyms

AFOLU	Agriculture, Forestry and Other Land Use
AD	Activity Data
AGB	Above-Ground Biomass
BGB	Below-Ground Biomass
BSI	British Standards Institution
C	Carbon
CFP	Carbon Footprint
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
CCBS	Climate, Community and Biodiversity Standards
CDM	Clean Development Mechanism (of the UNFCCC)
DMI	Domestic Material Input
EEE	Emissions Embodied in Exports
EET	Emissions Embodied in Trade
EF	Emission Factor
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FRA	Forest Resource Assessment
g	gram
GHG	Greenhouse Gases
Gt	Gigaton (1 billion tons)
ha	Hectares
HANPP	Human Appropriation of Net Primary Production
IBGE	Instituto Brasileiro de Geografia e Estatística
IIED	International Institute for Environment and Development
ILUC	Indirect land-use change
INPE	Instituto Nacional de Pesquisa Espaciais
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation mechanism (of the UNFCCC)
LUC	Land-use change
LUC-CFP	Land-use change carbon footprint
LUC-EET	Land-use change emissions embodied in trade
m	meter
M	million
Mha	million hectares
MFA	Material-flow analysis
Mg	Megagram (1 Mg= 1 t)
Mt	Megaton (1 million tons)
mol	Molecule
MRIO	Multi-regional input-output
NPP	Net primary production
PNG	Papua New Guinea
RED	Reducing Emissions from Deforestation
REDD	Reducing Emissions from Deforestation and Forest Degradation
REDD+	Reducing Emissions from Deforestation and Forest Degradation, plus sustainable management of forests, conservation and enhancement of carbon stocks
t	tons (1000 kg)
UNCBD	United Nations Convention on Biological Diversity
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
VCS	The Verified Carbon Standard
WoK	Web of Knowledge
yr	year

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1 Introduction

This thesis is about land as a global resource, and its different uses. The analysis focuses on displacement processes resulting from forest conservation measures that coincide with increasing human land demands to produce food, feed and fiber. The geographic displacement of deforestation or other land uses is commonly referred to as leakage and decreases the regional and global environmental benefits of policies aimed at conserving natural ecosystems (Meyfroidt et al. 2013). In this thesis I investigate how leakage effects can be assessed and accounted for based on the example of carbon leakage from REDD, which is an international mechanism to 'Reducing Emissions from Deforestation and Forest Degradation' being developed within the United Nations Framework Convention on Climate Change (UNFCCC).

Land-use changes (LUC) are commonly associated with the conversion of forest and other natural vegetation to cropland, pasture, settlements, and infrastructure. There is no doubt that humanity depends on land to meet basic needs for food, shelter, and freshwater (MEA 2005). However, land-use changes, and in particular the conversion of forests, often involve significant environmental damages such as biodiversity loss, soil degradation, and the disruption of hydrological and carbon cycles (Foley et al. 2005; Bala et al. 2007). Land-use changes are a major source of greenhouse gas (GHG) emissions to the atmosphere, responsible for about a third of global carbon dioxide (CO_2) emissions over the last 150 years (Brovkin et al. 2004), and around a tenth in the period 2000–2010 (Baccini et al. 2012). Increasing human demands from a projected world population of 9 billion by 2050, with increased dietary and (bio)energy demands (Godfray et al. 2010) thus present a central sustainability challenge to the finite global land resource.

Nowadays, forest loss is mainly concentrated in the tropics, where it often coincides with the expansion of agricultural production. Agricultural expansion is the single most important driver of tropical deforestation (Geist and Lambin 2002), with commercial agriculture gaining increasing importance in recent years. Industrial agriculture and agribusinesses were responsible for 40% of global deforestation between 2000 and 2010 (Hosonuma et al. 2012). Intensifying international trade in agricultural commodities makes global markets increasingly important for agricultural expansion and land-use change (Rudel et al. 2009a; DeFries et al. 2010). Almost a quarter of the global cultivated land area was dedicated to produce internationally traded products in 2004 (Weinzettel et al. 2013). Brazil, Indonesia and Malaysia alone produce over 40% of all sugarcane, soybeans, and palm oil consumed in the world (Gibbs et al. 2010). In 2007, 32% of all agricultural land in Brazil and 15% in Indonesia was used to grow export products

(Saikku et al. 2012). The globalized trade system leads to a geographic separation of consumption and production, which creates distant links, so-called teleconnections (Nepstad et al. 2006; Seto et al. 2012), between international demands and local environmental impacts incurred in the production of traded goods. These teleconnections are gaining increasing importance as distant drivers of tropical deforestation; however they are difficult to assess and quantify due to long and complex international supply chains (Kastner et al. 2011a).

Strong teleconnections linked to the consumption of forest-risk commodities[1] can also facilitate the displacement of deforestation from one country to another. Several tropical countries such as India, China, Costa Rica and Vietnam have in recent years achieved a forest transition; meaning a shift from decreasing to increasing national forest area (Rudel et al. 2005; Meyfroidt and Lambin 2009). However, in some cases the increase of domestic forest cover was accompanied by increases in imports of timber or agricultural products (Meyfroidt et al. 2010), thus outsourcing land-use changes to other countries by means of international trade. National-scale forest transitions and increasing forest cover were in these cases aided by land-use displacement. If this displacement of land-use activities leads to deforestation in the new location, a leakage effect occurs that can compromise the effectiveness of land-use and climate policies, such as REDD (Meyfroidt et al. 2010). Apparent conservation achievements within limited geographic scopes might then be illusionary or at least over-estimated (Berlik et al. 2002) whereas another location bears the resulting environmental costs (Dauvergne 2008).

In this thesis I study the climatic impacts of land-use displacement; or more specifically, CO_2 emissions from deforestation and forest degradation that are geographically displaced as unintended consequences of forest conservation policies. Despite the focus on forest conservation, carbon leakage is not limited to the land-use sector but refers to emissions shifting in general, thus affecting emission reductions in all sectors, including industry (Chomitz 2002). If unabated and unaccounted for, carbon leakage can significantly undermine or even nullify the net climate benefits of emission reduction activities (Gan and McCarl 2007). This compromises the environmental integrity of climate action, especially in the case of offset-mechanisms that allow carbon-credit buyers to maintain their own emissions. Nevertheless, surprisingly little conceptual research has been conducted on carbon leakage from land-use mitigation measures (Atmadja and Verchot 2012). Similarly, REDD "policy development is moving ahead with a somewhat vague notion that leakage is problematic and needs to be addressed, but with less than a

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[1] Agricultural or timber commodities that are linked to deforestation and land-use change, such as Brazilian cattle meat, responsible for ~80% of Amazon deforestation, or palm oil, which is a main deforestation driver in South-East Asia.

complete picture of why it occurs, how big a problem it might be, and what can be done to minimize its impact on the success of the policy" (Murray 2008: 7). This statement is the starting point of the thesis.

Both distant deforestation drivers acting through teleconnections and policy leakage effects are a challenge for global conservation initiatives such as REDD. If REDD fails to comprehensively address the factors behind forest conversion, there is a high risk for displacement of deforestation within and between countries. The REDD mechanism is designed to avoid within-country leakage through the national accounting scale (UNFCCC 2009); whenever deforestation shifts within the country it will be captured by national emissions inventories and accounted for in the national emissions balance. However, carbon leakage from REDD can be problematic in two cases. First, when national forest monitoring programs and accounting systems in REDD-countries are incomplete or non-functional, and within-country leakage goes undetected and unaccounted for. Second, when underlying international deforestation drivers are not comprehensively addressed due to vested interests or the tendency to consider the forest sector in isolation of other sectors (Angelsen et al. 2009). In that case continued global demand for land to produce food, timber and biofuels can shift the pressure on forests to countries that do not participate in REDD (Miles and Kapos 2008; Ghazoul et al. 2010). REDD policies, just as any other conservation policy, should therefore aim to minimize the risk for leakage effects where possible. Unintended leakage effects should be quantified and accounted for, to avoid the overestimation of conservation benefits. The required leakage accounting methods are the subject of this thesis.

The thesis consists of five appended papers and this summarizing preamble. In the following chapters I describe the applied definitions and the relevant background for the research (Chapter 2). Chapter 3 describes materials and methods, whereas results are presented in Chapter 4. A discussion of key findings and overall implications for carbon leakage is provided in Chapter 5. Chapter 6 presents some conclusions that can be drawn from this research, followed by Chapter 7 that provides a long-term perspective to place the topic and results in a larger context.

1.1 Aim and research questions

I pursued a two-fold objective with this thesis: 1. to systematically synthetize and assess existing knowledge and accounting approaches for land-related leakage, and 2. to contribute to the development of new methods to quantify distant deforestation drivers in the form of teleconnections, which increase the risk of international land-use displacement.

REDD is used here as entry point, providing a case of an international policy for forest conservation which might be subject to land-use displacement and carbon leakage that undermine its global climate effectiveness. The two overall objectives have been approached in an iterative research process that answered the following research questions:

- How is carbon leakage from forest mitigation activities defined and accounted for in UNFCCC-related and voluntary carbon markets? Are current methods suitable to account for carbon leakage from REDD? (Paper I)
- Which methods exist to quantify international land-related leakage and distant deforestation drivers; what are the main challenges and gaps? (Papers II and III)
- How can LUC emissions arising from teleconnections between the countries that produce and the countries that consume agricultural forest-risk commodities be quantified, in order to better understand potential magnitudes of international leakages through international trade? (Papers IV and V)

1.2 Where and how this thesis contributes

The thesis is set at the interface of several research areas. It is primarily situated in the field of land-change science, which considers land-use changes as human-induced processes that affect the functioning of the Earth System; as such it is closely linked to global environmental change and sustainability research (Turner et al. 2007). Another area this work contributes to is climate policy research, in particular to the fields of emissions accounting and land-based mitigation options. Accordingly, the research presented here contributes conceptually and methodologically to several scientific debates: the climate-policy issue of international leakage accounting in general and for REDD in particular; existing land-change science approaches for assessing land-related leakage effects from conservation policies; and the sustainability matter of teleconnections between spatially disconnected locations of food production and consumption.

Carbon leakage has been a subject of policy negotiations and scientific debate since the establishment of the Kyoto Protocol in 1997, and particularly since 2003 when modalities for the inclusion of land-based mitigation options were negotiated in the UNFCCC (Henders and Ostwald 2012). The UNFCCC has adopted a territorial approach in line with the ‘polluter-pays’ principle that holds countries accountable for emissions from domestic production (Rothmann 1998). This perspective of producer responsibility is common in many environmental policies, and is the reason behind the exclusion of international carbon leakage, or emissions displacement across country borders, from the UNFCCC emissions accounting framework.

The focus of the scientific literature on land-use carbon leakage has therefore mainly been on project-based activities and local leakage processes within a country (e.g., Chomitz 2002; Schwarze et al. 2002; Aukland et al. 2003; Sathaye and Andrasko 2007). Only few modeling exercises address international leakage effects of forest-based mitigation strategies (e.g., Sohngen et al. 1999; Gan and McCarl 2007; Sun and Sohngen 2009). Although these indicate a risk for substantial international leakage effects, results show large ranges and involve high uncertainties. Most of those assessments concentrate on leakage effects in the timber market when faced with reduced timber supply and do not cover effects on agricultural markets, in spite of their outstanding role in driving deforestation. As shown in Paper I, it is therefore safe to state that the topic of international leakage is under-researched, especially when it comes to mitigation in the land-use sector and in the context of REDD. This thesis provides a first systematic account of assessment methods for leakage in the land-use sector, including an inventory of methods used in the carbon market (Paper I), a comparison of the related yet isolated debates about carbon leakage and indirect land-use change (ILUC) (Paper II), and a review of methods to quantify teleconnections as well as land-related leakage effects from policies (Paper III).

With this, the thesis can also inform assessment approaches for land-related leakage in general. Leakage can reduce the effectiveness not only of climate change mitigation but also of national land-use or conservation policies. Several studies investigate international displacement effects from forest transitions, focusing on the underlying land use rather than on associated emissions (e.g. Meyfroidt and Lambin 2009; Meyfroidt et al. 2010; Kastner et al. 2011b). Meyfroidt et al. (2013) recently presented a review on the topic of increasing globalization of land use and made a first attempt to bring together different literatures on distant drivers of land-use change and the geographic displacement of land use, to create a common discussion platform. The review of accounting methods for land-related leakage and distant deforestation drivers in Paper III complements this work with a discussion of methodological options.

Another angle on international carbon leakage is taken in a fast growing literature emerging from the field of industrial ecology, which discusses the topic in the context of consumer responsibility (Rothmann 1998; Munksgaard and Pedersen 2001; Lenzen et al. 2007; Peters 2008; Aall and Hille 2010; Harris and Symons 2012). Unlike the principle of producer responsibility adopted in the UNFCCC, in the consumer perspective a country is allocated all emissions from domestic consumption, including those connected to imports, and excluding those embodied in exports (Rothmann 1998). Consumption-based emissions accounts adjust conventional territorial-based emission inventories for the amount of emissions embodied in international trade (EET), which refer to the GHG emissions arising from the production of traded goods. A national carbon footprint of consumption is established by adding emissions generated in the production of imports and deducting emissions associated with the production of exports from the amount of emissions produced domestically (Hertwich and Peters 2009). Existing literature in this field focuses on emissions from fossil-fuel combustion and energy consumption (e.g., Peters and Hertwich 2008a,b; Davis and Caldeira 2010; Peters et al. 2011a,b), whereas the importance of land-use change emissions is acknowledged but remains under-researched (Karstensen et al. 2013). Previous studies on LUC emissions embodied in trade (LUC-EET) face severe data gaps and methodological challenges (e.g., Zaks et al. 2009; Saikku et al. 2012; Karstensen et al. 2013). This thesis contributes to the field of consumption-based emissions accounting by presenting a quantification method for LUC-EET of agricultural forest-risk commodities, and the first results of its application (Papers IV and V).

Emissions and other impacts embodied in trade flows are closely linked to the concept of teleconnections between consumption and production locations. The term originates from the atmospheric sciences, where it describes causal links between different weather systems (Haberl et al. 2009). More broadly, teleconnections can be defined as "the correlation between specific planetary processes in one region of the world to distant and seemingly unconnected regions elsewhere" (Steffen 2006:156). Whereas this definition encompasses all sorts of socioeconomic or biophysical processes and feedback effects that can cause teleconnections, the focus in this thesis and in the literature it contributes to is on international trade. Globalized trade flows have become one of the main factors that weaken the local links between production and consumption of natural resources, with causes and effects becoming increasingly spatially disconnected due to rapidly expanding infrastructure and transport capacities (Erb et al. 2009). Environmental impacts such as land or water use, soil degradation or emissions that occur at the place of production are thus linked not only to local but increasingly to distant resource consumption patterns (Kastner et al. 2011a). Also termed 'ecological shadows of consumption' these teleconnections can for example lead to environmental impacts such as pollution of rivers and soils in developing countries that mass-produce consumer goods for export (Dauvergne 2008). This poses a sustainability challenge as distant feedback effects and linkages are hard to trace and foresee, thus complicating the management and avoidance of negative environmental impacts. Research around teleconnections in the land-use sector combines different approaches and topics. Examples include dedicated resource-use indicators such as the Ecological Footprint, which determines the virtual land area required to produce the resources consumed by society (Wackernagel and Rees 1996) or embodied human appropriation of natural primary production (embodied HANPP), which estimates the amount of net primary production (NPP[2]) appropriated per ton of biomass consumed (Erb et al. 2009; Haberl et al. 2009). Carbon or land footprints can also be used to describe teleconnections, such as the land demand or deforestation associated with the consumption of agricultural and forest products in specific regions (e.g., Lugschitz et al. 2011; European Commission 2013; Yu et al. 2013). Paper III contributes to this research area by reviewing various methods available to assess teleconnections and land-related leakage.

Similar to the EET research described above, approaches to quantify teleconnections between local consumption and global emissions from land-use change currently face considerable data and methodological limitations. However, a few years ago a methodological framework was presented that allows the tracing of environmental impacts along the trade chain by combining impact factors with trade flow analysis (Kastner et al. 2011a). In order to use this approach for the analyses of LUC EET, in Paper IV we developed the LUC-CFP indicator that can be used as an impact factor in this framework. Its application has been tested in Paper V, which shows that the combination of the LUC-CFP with trade-flow analysis allows quantifying the extent to which LUC in a certain location is due to the global imports –and thus consumption- of forest-risk commodities. With this, the thesis contributes to overcome previous methodological limitations in the assessment of LUC emissions embodied in trade and provides a way to quantify distant deforestation drivers in the form of market demand and consumption.

1.3 Departure Point and Delimitations

This thesis focuses on land-use displacement effects that can arise from forest conservation and land-use policies such as REDD. The perspective taken is based on the equation by Lambin and Meyfroidt (2011):

Land available for conservation = Total land area– (Agricultural area + Settlements)

In this global systems-perspective forests act as a reservoir of land available for human settlement and food production. Forest is only one of the potential uses of the global land resource, and is in constant competition with other uses, mainly agriculture, human settlements and infrastructure (*ibid*). New land is required to enhance agricultural production to meet increasing global demands. Agricultural output can be increased through two main strategies: expansion of agricultural land and intensification of agricultural

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[2] NPP is a measure for the net amount of biomass produced each year by plants. Parts of NPP are appropriated by humans for use as, for example, food, fuelwood, biofuel, or fodder for livestock.

yields on existing lands (Ramankutty et al. 2008). Intensification usually involves the modification of existing land-use and land-cover systems, whereas expansion leads to land-use conversion processes such as deforestation. The focus of this thesis lies on the latter. However, intensification and expansion are closely linked through global demands for agricultural products (Lambin and Meyfroidt 2011): in a global perspective, the area needed for expansion is determined by the extent of yield increments attainable through intensification.

The focus of this thesis is on leakage and land-use displacement effects due to global economic factors that directly and indirectly cause deforestation. This means that proximate drivers such as relative prices, access to resources and markets, or availability of technology are considered together with underlying societal and macroeconomic factors, such as consumption levels, lifestyles, and market effects. The perspective adopted here thus emphasizes the role of external land-use change factors rather than that of individual land use agents. With this, agent-centered ways of assessing the role of subsistence activities, local livelihoods, and individual decision-masking aspects in deforestation are not considered. Moreover, the focus is on deforestation processes rather than forest degradation, mainly because deforestation comprises the main source of land-use emissions, whereas forest degradation causes less emissions as only part of forest biomass is lost (Houghton 2012). In terms of geographic scope, the focus of the thesis is on international displacement effects although within-country and regional leakage processes are initially considered.

With the choice of REDD as case study my analytical focus is on GHG emissions as selected impacts of land-use change and deforestation. Whereas the analysis of land-use changes offers many insights and is a research field of its own, emissions impacts resulting from land-use changes have received increased attention in recent years in the context of climate policy and climate change mitigation strategies. The overall objective of emissions accounting is to create standardized, measurable and comparable units of CO_2-equivalents that quantify anthropogenic impacts on the global climate. Whereas the underlying land-use changes can be observed on the ground, the resulting emissions are invisible, with emissions accounting procedures aiming to make virtual GHG flows tangible and to translate the global carbon cycle into measurable and manageable emission flows (Gupta et al. 2012). This creates an additional level of abstraction in the assessment of land-use changes and also causes additional uncertainties in the accounting process. At the same time, emissions accounting in the context of REDD happens within a central, standardized accounting framework, which can also facilitate the assessment of complex processes such as land-use displacement.

The focus on GHG emissions impacts omits other environmental impacts for the sake of emphasizing the interactions of land cover with the atmosphere and the climate system. In this perspective, land is mainly seen as a sink or source of carbon, which is interpreted according to its potential contribution to climate change mitigation. Choosing the carbon lens to interpret deforestation and land-use displacement from an emissions perspective by default allows insights into only one small aspect of land-use change effects (Gupta et al. 2012). Other LUC impacts such as changes in biodiversity, water availability, or land degradation, are not or only marginally considered.

2 Background

This section provides background information about the definitions, context, processes and policies relevant for the conducted research. In the spirit of the broad inter- and multidisciplinary research environment at the department where this thesis was written, this chapter seeks to provide a comprehensive overview that speaks to researchers from multiple fields rather than scholars specialized in deforestation, terrestrial carbon sinks, or emissions accounting.

2.1 Definitions

Land-change science is concerned with the dynamics of land use and land cover, including the human-induced modifications of the terrestrial surface. The terms ‘land cover’ and ‘land use’ are easy to confuse although fundamental differences exist in their meaning.

- *Land cover* means the observed biological and physical (hereafter: biophysical) attributes of the land surface and immediate subsurface (Lambin et al. 2003). It usually refers to topsoil and vegetation (FAO 1998); although water and bare rock are also included in the term.
- *Land use* describes the manner and the purpose of human employment of land cover and land resources; i.e., how and why the biophysical land-cover attributes are manipulated by people (Turner et al. 1994).

To illustrate the terms; "grassland" would refer to land cover, while "rangeland" or "golf course" describes the use of that land cover. Thus, the definition of land use establishes a direct link between land cover and the actions of people in the environment. *Land-use changes* therefore usually lead to changes in land cover, involving either slight modifications or complete conversions of land-cover types.

- *Land-cover modification* involves subtler changes within a remaining land cover category that only affects the attributes; such as switching agricultural systems from single to double-cropping, or selective logging in forests (forest degradation) (Lambin et al. 2003).
- *Land-cover conversion* describes the replacement of one land cover category by another, such as settlements replacing grasslands, tree plantations replacing savannahs (reforestation), or agricultural cropland replacing forest (deforestation).
- *A land-use transition* describes a series of land-use changes over time, for example from a forest system over a pasture system to an agricultural system; whereas the term *forest transition* describes both a change in land cover trends from net deforestation to net reforestation

(Angelsen and Rudel 2013), and the turning point from decreased to increased forest cover (Lambin and Meyfroidt 2010).

- *Land-use displacement* is a geographic shift of land-use to a new location.
- *Land-related leakage* describes land-use displacement processes that are an (unintended) side-effect of policies affecting land use (Meyfroidt et al. 2013). In the context of climate policy with a focus on GHG emissions, the term *emissions leakage* or *carbon leakage* is used to describe the shift of emissions-generating activities to outside the accounting boundary.

Some central terms around forest cover change include *deforestation* and *forest degradation*, *afforestation/reforestation* and *forest regrowth/secondary forest,* and not least the definition of what exactly constitutes a *forest.* The latter is not easily attained, as it implies the aggregation of numerous vegetation forms, whose attributes vary with geographic, climatic and biophysical conditions, into one common concept. The *forest definition* coined by the UN Food and Agriculture Organization (FAO) has been widely adopted in many national forest inventories. It combines quantifiable land-cover parameters with land-use characteristics and defines forests as land

- with tree crown cover of more than 10% and an area of more than 0.5 ha,
- where trees should be able to reach a minimum height of 5 meters (m) at maturity.

Young natural stands and forest plantations are included in this definition, even if they currently do not exceed the required thresholds, but can be expected to do so at maturity. The definition also covers areas which are temporarily unstocked as a result of human intervention or natural causes but which are expected to revert to forest.

Individual countries might use different definitions of forest due to specific biophysical conditions that make forests look very different in different parts of the world (Fig. 1 a-c). The definition of what a forest is might differ for example in places where the FAO criteria are not met; such as in very dry areas where tree height does not reach 5 meters and/or trees are spatially scattered (Fig 1b). It is also sometimes contested whether tree plantations should be defined as forests (Fig. 1c). The FAO differentiates the land-use purpose of the plantation; if the plantation produces forest products such as timber it is counted as forest. Oil palm plantations for example represent an agricultural crop that is not covered by the FAO forest definition.

Fig. 1a: This is a forest

Fig.1b: Is this a forest?

Fig.1c: And this?

The UNFCCC (2001) provides a more flexible approach to defining forests, where each member state determines its forest definition within a predefined range of 10-30% canopy cover, 2-5 m tree height, and 0.05-1 ha minimum area. This approach accounts for different national circumstances but it can also cause controversies such as Indonesia's attempt to classify oil palm plantations as forests (Jakarta Post 2010). While this re-classification would not be possible under the FAO definition, the UNFCCC definition does not explicitly eliminate this option. One implication of the Indonesian case is that the conversion of tropical rainforests to oil palm plantations would not be counted as deforestation, because the land cover in both cases classifies as forest. This issue has been addressed by creating safeguards which prevent the conversion of natural forests under the REDD mechanism (UNFCCC 2010).

This is directly linked to the definition of what actually constitutes deforestation, forest degradation, and reforestation:

- *Deforestation* occurs when forest is converted to other land uses (=*land-cover conversion*, see above). Using the FAO definition, this happens when the tree canopy cover is permanently reduced to below 10%, through natural or anthropogenic processes (FAO 2010). Land-based climate change mitigation activities use the deforestation definition of the Intergovernmental Panel on Climate Change (IPCC), which is direct human-induced conversion of forested land to non-forested land, where tree canopy cover decreases to below 10–30% (IPCC 2003). Important is the long-term effect of deforestation; when forest is replanted or grows back subsequent to clearing the land-cover classification does not change, and thus no deforestation occurs.
- Partial deforestation which leaves a canopy cover of 10-30% is considered *forest degradation*, for example through selective logging or fuelwood collection. It represents a form of land-cover modification as the land-cover classification "forest" does not change, although biomass and hence carbon stocks are decreased.

- The terms *afforestation and reforestation* refer to the direct human-induced establishment of new forests, with the UNFCCC distinguishing between forestation of land that has not been forested for a period of at least 50 years (afforestation) and land that was forested but has been converted to non-forested land within the last 50 years (reforestation) (IPCC 2003). When forest is cleared but grows back naturally this is called *natural regeneration* or *forest regrowth*.
- *Gross and net deforestation*: Gross deforestation refers to the observed area of forest cover loss, whereas net deforestation considers areas where forest has regrown and provides a net account of lost and gained forest cover. Net changes are an important indicator for long-term land-use changes. In most non-tropical regions the net forest area is stable or expanding due to replanting or forest regrowth after clearing, while forest loss in the tropics is commonly only partly counteracted by vegetation regrowth and plantation establishment (Hansen et al. 2010). When looking at net forest loss, it is important to remember that not all forests provide the same ecological functions, and natural primary forest is not *per se* equivalent to planted forests. Forest regrowth or replanting might involve a change in forest structures and ecosystem services such as biodiversity levels, due to ecological differences between primary and secondary forests (Putz and Redford 2010). Primary forests have never been logged and have developed undisturbed from human intervention, whereas secondary forests have naturally or artificially recovered after human intervention, either through natural forest regeneration or planting activities (UNCBD 2013). Secondary forests therefore feature a different species composition and forest structure, and sometimes lower biomass and carbon contents than primary forests (Brown and Lugo 1990).
- *REDD*: The scope of the suggested REDD mechanism has evolved over time; from reducing emissions from deforestation (RED), over REDD (…from Deforestation and Forest Degradation) to REDD+, which stands for REDD plus forest conservation, sustainable management of forests and enhancement of forest carbon stocks. With this the mechanism has become more comprehensive over time to account for different national circumstances. For the sake of simplicity, throughout this thesis I refer to REDD as any activities related to maintaining and enhancing forest to keep carbon stored in the biomass.

2.2 Land use, land-use change and deforestation

Human transformation of the global land surface is not a new phenomenon. It has a long history, having provisioned human needs of food, fiber, water and shelter for millennia (Ellis et al. 2013). Early agricultural activities and land clearing thousands of years ago are assumed to have caused GHG emissions that constituted the first steps towards global warming (Ruddiman 2003).

Today, at least half of the global ice-free land area has been subject to modification in one way or another (Vitousek et al. 1997), with nearly 40% of land surface under agricultural use (Ramankutty et al. 2008). At the same time, forest land cover has decreased from about 50% of the total land area 8000 years ago to around 30%, or just under 4 billion hectares in 2005 (Ball 2001; FAO and JRC 2012). Between the 18th and the end of the 20th century the global forest area has declined by around 2.3 billion hectares (Lambin et al. 2003). The lion's share of these changes was due to large-scale land clearing processes accompanying an expansion of global croplands; mainly in Europe where deforestation rates peaked just before the onset of industrialization (Kaplan et al. 2009), in China where cropland expansion started in the 18th century and has continued until today (Ramankutty et al. 2002) or in the United States (US), where forest clearing amounted to 120 million hectares (Mha) in the second half of the 19th century (Williams 2006). In the 20th century, the global cropland area increased by 50%; with most intensive expansion processes in South and Southeast Asia and South America (Ramankutty et al. 2002). The world's most active deforestation frontier today, the Amazon *arc of deforestation*, was opened in the southern and eastern margins of the Brazilian Amazon in the 1990s (Macedo et al. 2012).

For a long time deforestation was thus the result of the principal human strategy to increase agricultural output - the expansion of cultivated land. Forest conversion also enabled the colonization of new areas, such as the expansion into North America's 'wild west' in the 19th century and the Brazilian Amazon in the late 20th century, which was encouraged by government policies and settlement programs (Rudel et al. 2009a). Since the 1960s, improvements in agricultural technology have led to substantially increased yields, which helped to partially de-couple food production and cropland expansion (Tilman 1999). The agricultural area increased slower than before, but still by a total of 434 Mha between 1960 and 2010 (FAOSTAT 2013). Whereas in developed countries the agricultural area has remained stable in the last decades or in some places even decreased (FAOSTAT 2013), the expansion of agriculture continues mainly in tropical regions, where it commonly involves the conversion of forests (Gibbs et al. 2010).

The regularly conducted Forest Resource Assessments (FRA) of the FAO have shown a decline in global deforestation rates in the last decades, with gross forest cover loss decreasing from 16 Mha per year in the period 1980-1990 (FAO 1990) to 13 Mha per year in the 2000s (FAO 2010). However, especially for forest cover developments in the tropics it is difficult to establish a reliable long-term trend (Grainger 2007). FAO FRA data involves high uncertainties as it is based on voluntary reports by 150+ countries that determine their forest area change based on different methodologies and definitions (Grainger 2007). Several recent remote sensing assessments of global forest cover indicate that overall deforestation rates are in fact increasing. The detailed estimates vary due to different definitions of forest and deforestation used in the assessments. The FAO itself conducted a remote sensing analysis alongside its 2010 assessment (FAO and JRC 2012), which yielded an increase in annual gross deforestation rates from 9.5 Mha in the 1990s to 13.5 Mha in 2000-2005. Hansen et al. (2010) estimated even higher global deforestation rates of 16.8 Mha per year in the period 2000-2005, with gross deforestation rates in the tropics comparable to those in temperate and boreal regions. Global net deforestation rates have increased from 2.7 Mha in the 1990s to 6.3 Mha between 2000 and 2005 (FAO and JRC 2012).

2.3 Drivers of land-use change and deforestation

The motivation for land use changes depends on complex interactions between environmental and socioeconomic factors. A general classification distinguishes *proximate* (=direct) and *underlying* (=indirect) functions of LUC drivers (Geist and Lambin 2002). Whereas the former are local-level causes or activities that lead to land-use conversions (e.g., direct interests such as agriculture or timber production, or infrastructure expansion), the latter are fundamental societal forces behind these local actions (such as political, economic, or institutional factors). These factors influence decisions made by *land-use agents*, who are persons or organizations in the position to make decisions about proximate land-use changes (Sunderlin and Resosudarmo 1996). Due to the interplay and feedback links between underlying and proximate factors and the (ir)rational behavior of deforestation agents, determining concrete causes of land-use change is difficult, especially as data that could demonstrate linkages is often scarce (Sunderlin and Resosudarmo 1996; Chomitz et al. 2007).

Deforestation drivers are usually analyzed in local case studies that only allow for limited generalization. Two major meta-analyses have been conducted that identify general patterns of direct and indirect causes from a broad foundation of local case studies of tropical deforestation: Geist and Lambin (2002) cover cases from the period 1880 to 1996, while Rudel et al. (2009a) focus on changes in deforestation drivers between 1975 and 2002. A recent study by Hosonuma et al. (2012) reviews available empirical information on deforestation drivers in the period 2000 to 2010, drawing on sources such as scientific literature, UNFCCC national communications, CIFOR country profiles and reports of tropical countries in the preparation for REDD. All three studies agree on the dominant role of agriculture as main proximate cause for tropical deforestation over time; responsible for 96% of analyzed deforestation cases until the 1990s

(Geist and Lambin 2002), and for 73% of cases in 2000 to 2010 (Hosonuma et al. 2012). Other direct causes include mining, infrastructure and urban expansion. Forest degradation happens mainly due to timber harvest, fuelwood collection and charcoal making.

In addition to the above proximate causes of tropical deforestation, Geist and Lambin (2002) described underlying economic factors in over 80% of analyzed deforestation cases, as well as institutional and technological factors. Rudel et al. (2009a) found that urbanization and economic globalization have been gaining importance as underlying driving forces of deforestation since the 1990s, which is confirmed by a positive correlation between tropical deforestation, exports of agricultural commodities and urban population growth in the period 2000 to 2005 (DeFries et al. 2010). Forty percent of global deforestation between 2000 and 2010 was due to commercial agriculture and agribusinesses, much of it for export (Hosonuma et al. 2012).

This mirrors the increasingly predominant demographic phenomena of urbanization and the decline of rural populations (Seto et al. 2012). With more and more people leaving agricultural subsistence lifestyles and moving to cities, global dietary trends have developed to involve a higher consumption of meat and other livestock products, whose production is more demanding in terms of land, water and energy resources. Therefore both urbanization and dietary trends are important (although not the only) factors behind an increasing global land demand and accelerating international trade in agricultural commodities (Boucher et al. 2011). This global demand channeled through international markets has been gaining importance as a distant driver of land-use change (Lambin and Meyfroidt 2011)[3]. Agricultural expansion for global markets often concentrates in countries with high forest cover and large available land reserves, such as Brazil and Indonesia, which have absorbed much of the global demand for agricultural commodities (Rudel et al. 2009a; Meyfroidt et al. 2010).

Indonesia and Malaysia together generate almost 90% of the global palm oil production, and the harvested area for oil palm plantations has quadrupled since 1990, which corresponds to an expansion of 6.5 Mha (Koh et al. 2011). The total oil palm area in Indonesia now covers over 7 Mha. Studies estimate that half of this expansion involved the conversion of forest (Koh and Wilcove 2008), which makes oil palm plantations one of the main deforestation in Indonesia (Carlson et al. 2012). The Brazilian cattle population increased from 25 million in 1990 to 172 million in 2006, when a quarter of all beef produced was exported

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[3] Note that land-use change in this context is not limited to deforestation; global demand for timber products for example can also lead to increasing forest cover as in the case of Chile or Southern Brazil (Meyfroidt and Lambin 2011).

(Cederberg et al. 2011). The expansion of beef production since 1995 has mainly occurred in the Brazilian Amazon and is responsible for nearly 80% of all deforestation in the region (Margulis 2004). The harvested area of soy has increased from 11 Mha in 1990 to almost 24 Mha in 2011 (IBGE 2013), with the expansion mainly occurring in the cerrado ecosystem (Margulis 2004). Beef, soy, and sugar cane together comprised about 60% of Brazil's agricultural gross domestic product in 2008 (Boucher et al. 2011).

These examples show that drivers of deforestation vary between countries and world regions. Houghton (2012) distinguishes land-cover change categories and the CO_2 emissions resulting from forest conversion (Table 1). He finds that the largest emissions are caused when converting forest to shifting cultivation, which is mainly important in Latin America and Tropical Asia. Forest clearing for cropland expansion is the second-most important LUC emission source, mainly in Tropical Africa and Latin America. Forest conversion that involves the draining and burning of peat soils contributes substantial emissions but is spatially limited to South East Asia; whereas forest conversion to pastures mainly occurs in Latin America and in some parts of Tropical Africa. Industrial timber harvest is equally important in Tropical Asia and Latin America.

Table 1: Selected net sources of carbon (per cent and GtC/yr) from activities driving deforestation and degradation in tropical regions 1990-2009, adapted from Houghton (2012).

		Latin America (%)	Tropical Africa (%)	Tropical Asia (%)	TOTAL EMISSIONS (GtC/yr)
Forest conversion to …	Shifting cultivation	46	18	36	432
	Croplands	35	43	22	370
	Draining and burning of peatlands	0	0	100	300
	Pastures	72	28	0	180
	Industrial timber	38	25	37	141

2.4 Climate impacts of land-use changes

Terrestrial ecosystems can be understood as sinks and sources of GHG emissions. Soils and vegetation act as carbon sinks due to biomass growth, where CO_2 is removed from the atmosphere through photosynthesis processes and converted to carbohydrates (carbon). A share of those is re-emitted later during plant respiration processes, but the major part is stored in vegetation biomass, primarily in woody parts. This carbon sequestration process continues as long as the forest grows, whereas at maturity the carbon cycle in forest ecosystems is roughly balanced by sequestration, respiration and decomposition. Land can become a source of emissions when the sink function is disturbed or destroyed, commonly when biomass is consumed by fire and when remaining plant material and soil carbon decompose (van der Werf et al. 2009). The carbon is then released back into the atmosphere in form of CO_2.

While the terrestrial system represents an overall sink of carbon, net emission fluxes from the land-use sector constitute one of the most uncertain parts of the global carbon budget (Houghton et al. 2012). This is because the net flux is not a static parameter; it depends on a combination of dynamics and processes on different scales. Sink or source functions are influenced by both anthropogenic and natural processes. Natural emissions arise from plant-physiological processes such as respiration, or natural disturbances like forest fires, pests and windbreaks. The sink function can increase through natural forest regrowth on abandoned sites or through enhanced plant growth due to favorable climatic changes, such as increasing temperatures and longer growing seasons in some regions (Houghton et al. 2012). Plant growth can also be improved through the *carbon fertilization effect,* when increased levels of CO_2 in the atmosphere lead to higher photosynthesis rates. Together with warmer temperatures, carbon fertilization is assumed to have caused recent increases in global forest growth (McMahon et al. 2010). In other regions, higher temperatures and reduced precipitation can cause increased fire frequency and greater vulnerability to pests and diseases, which might constrain plant growth and survival rates (e.g., Wu et al. 2012; Anderson-Teixeira et al. 2013)[4]. Human-induced changes in terrestrial sink and source functions go back to active management and land-use decisions that lead to a reduction or an increase in biomass and carbon stocks. It is often challenging to separate human-induced effects from natural processes (Houghton et al. 2012). Estimates of emissions absorbed or emitted therefore often vary and even contradict each other, as they strongly depend on the calculation methods and models used (Houghton et al. 2000).

Although the amount of net LUC emissions has been more or less stable over the last decades, the contribution of LUC to total anthropogenic CO_2 emissions has decreased over time - mainly due to a steep increase in fossil fuel emissions (Le Queré et al. 2009). On average, land-use changes have contributed about 35% to total CO_2 emissions over the last 150 years (Brovkin et al. 2004), and 20% in the 1980s and 1990s (Le Queré et al. 2009). In the 2000s, LUC and deforestation contributed between 7-11% of total anthropogenic CO_2 emissions (Harris et al. 2012; Baccini et al. 2012), and 15% if emissions from peatland degradation are included (van der Werf et al. 2009). To translate percentages to numbers, global net emissions from land-use changes reached 1.14 billion tons carbon per year (GtC/yr) for the period 1990-

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[4] Another feedback effect between the land base and the atmosphere that influences the global climate is the *albedo-effect,* which describes the reflection power of solar radiation from a surface that can be altered through changes in land cover (Sagan et al. 1979). In comparison to forests croplands reflect more of the incoming solar radiation, especially when snow-covered during winter, so that forest clearing for agriculture results in an overall albedo-related cooling effect (Brovkin et al. 2004).

2009 (Houghton et al. 2012), or 1.4 GtC/yr when considering emissions from peatland draining and burning in Southeast Asia (Houghton 2012).

2.5 Climate policy and land-based mitigation options

2.5.1 UNFCCC and the Kyoto Protocol

Enhancing the terrestrial sink function or reducing emissions from land-use activities can contribute to the mitigation of climate change. This mitigation potential has been recognized in international climate policies such as the UNFCCC and Kyoto Protocol. All 194 member states to the UNFCCC are requested to report domestic GHG inventories of all sources, including the industry, energy and land-use sector in national communications (UNFCCC 1992). Parties with emission targets under the Kyoto Protocol[5] conduct mandatory annual emissions inventories, and terrestrial sinks and sources are included in these inventories as long as they are human-induced, or established through direct anthropogenic influence (e.g., activities such as reforestation or deforestation and forest management).

The Kyoto Protocol flexible mechanisms for *Joint Implementation* (JI) and *Clean Development* (CDM) allow Annex-B countries to invest in emission reduction projects abroad as an alternative to domestic mitigation measures. JI projects are implemented in Annex-B countries, whereas CDM projects are located in non-Annex B countries. The CDM recognizes fifteen different project categories; among them mitigation measures in the land-use and forest sector. Eligible activities in the first commitment period focus on enhancing the sink function through afforestation or reforestation, while activities such as reducing deforestation or forest management are excluded. However, when the Kyoto Protocol was extended to cover a second commitment period from 2013-2020 (UNFCCC 2012), a work programme was initiated to explore the expansion of eligible land-based CDM activities to activities such as wetland, forest and agricultural land management to ensure a more holistic landscape approach to enhance sinks and reduce sources (UNFCCC 2011). A decision on this issue has not yet been taken, so that for now the narrow focus on tree planting is retained. In addition, whereas the extension of the Kyoto Protocol was adopted at the 2012 climate conference, it is still awaiting official acceptance by each member state before it can enter into force.

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[5] The Kyoto Protocol differentiates countries with and without emission reduction targets by referring to the Annex where the commitments are specified; i.e., *Annex-B countries* have reduction targets, and *non-Annex B countries* do not (UNFCCC 1997).

2.5.2 REDD as a land-based mitigation strategy for climate change

After being excluded from the eligible activities in the CDM in 2003, forest conservation in developing countries was reintroduced as a potential mitigation option at the climate talks in Montreal 2005. The REDD mechanism has gained substantial political momentum since 2007 and has attracted increased attention on the land-use sector for climate change mitigation and adaptation (Skutsch and McCall 2010). Both developing and developed countries are interested in REDD. Developing countries have hopes of accessing substantial funds associated with the compliance carbon market, which was worth USD 176 billion in 2011 (World Bank 2012) and could potentially be a long-term funding source. Developed countries see a relatively inexpensive way to meet their emission reduction targets, and they also hope that REDD could be a first step for developing countries to take on voluntary sectoral emission reduction targets. This is why REDD negotiations have been rather successful and have come a long way compared to other negotiation topics under the UNFCCC (Angelsen et al. 2012). Despite this progress, the UNFCCC REDD scheme will only enter into force when a broader international climate agreement for the post-Kyoto era is ratified.

The objective of REDD, as stated in the Cancun Agreements is to “slow, halt and reverse forest cover and carbon loss” (UNFCCC 2010:12), a phrasing that is closely linked to the forest transition theory. This theory describes the shift from declining to increasing forest area, when after an initial phase of forest resource exploitation involving substantial deforestation a transition towards increasing forest area begins, through natural regrowth or reforestation (Fig. 2) (Mather 1992). Based on empirical regularities two general pathways for forest transitions have been described; the forest scarcity and the economic development pathways (Rudel et al. 2005). Both start from a decline in forest cover due to agricultural expansion, which at some point finishes. The forest scarcity pathway implies that forest cover has decreased to a level where the country starts feeling implications, such as the reduction of ecosystem goods and services, or a declining supply of forest products. In response to this situation, national reforestation or conservation policies induce a national recovery of forest area. The economic development path assumes that with increasing national development agricultural production concentrates in the most productive regions, while it becomes unprofitable in marginal and poor sites. Former farmers migrate to urban areas where they take non-farm jobs, thus freeing up large areas of previous agricultural lands where forests regrow.

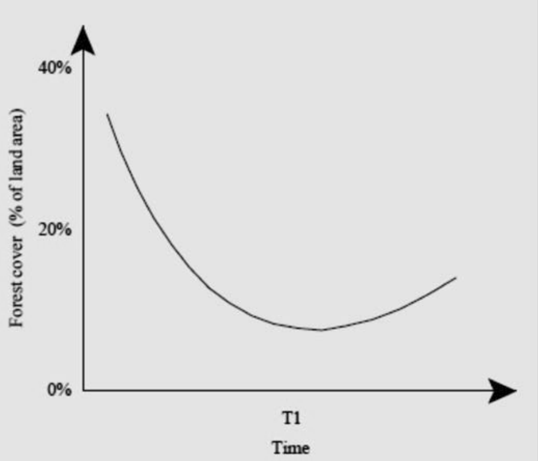

Fig. 2: The forest transition, with the curve representing the rate of forest cover loss in a given country (Rudel et al. 2005). After reaching a negative peak marked by the transition point, national forest area starts to increase again.

However, forest transitions are neither deterministic nor automatic. Whereas the forest transition theory was established based on case studies from developed countries, it was confirmed in some but not in all tropical countries (Mather and Needle 1998; Rudel et al. 2005). Moreover, land-sparing effects[6] of agricultural intensification have been observed mainly in regions with additional conservation policies (e.g. Rudel et al. 2009b; Barretto et al. 2013) which suggests an important role for policies such as REDD in achieving forest transitions.

Due to complex and geographically diverse deforestation drivers it is impossible to conceive a universal policy for controlling tropical deforestation (Geist and Lambin 2002; Angelsen et al. 2009). A detailed understanding of national circumstances and context-specific drivers for deforestation is therefore needed to devise successful REDD policies. Angelsen and Rudel (2013) suggest adjusting REDD policies according to the forest transition framework, with policy options oriented along the respective forest-transition-stage a country finds itself in. Three main phases are distinguished; 1. high forest cover and low deforestation; 2. high deforestation and low forest cover; and 3. stabilization and eventual reversal of the deforestation process. Figure 3 illustrates that countries with large, still unexploited forests like Suriname and Gabon would benefit from policies that incentivize the preservation of primary forest, whereas countries in group 2, such as Indonesia, Bolivia or Papua New Guinea (PNG) would devise REDD policies that reduce deforestation rates. Group-3 countries that have lost large parts of their primary forest, such

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[6] Land sparing effects occur when increasing productivity per area unit frees up or spares land for nature.

as Bangladesh, India or China, could induce forest recovery for example through reforestation programs or public incentives that enable forest regrowth on former agricultural lands.

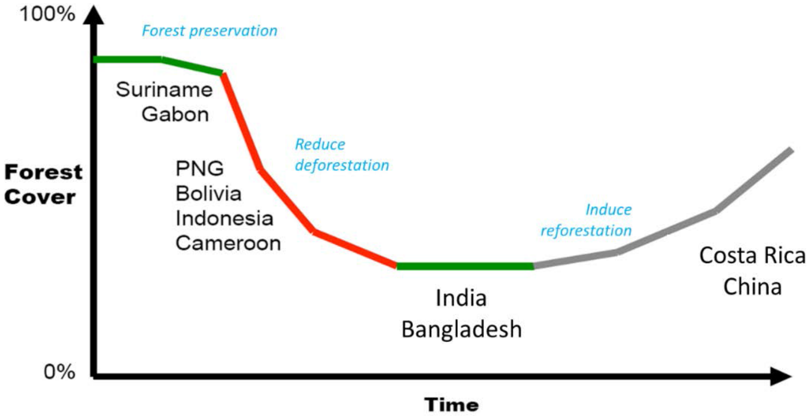

Fig. 3: Location of different REDD countries in the forest transition framework, and suggested targeted policy options.

REDD seeks to reward developing countries for reductions in deforestation rates and the enhancement of forest cover, in order to reduce GHG emissions from land-use changes. Financial rewards are based on the amount of avoided CO_2 emissions from reducing forest destruction. The concept of valuating standing forests is intended to create incentives to preserve forest cover at the local level (Angelsen et al. 2009). REDD as a UNFCCC mechanism is designed to work at the national level, with subnational on-the-ground activities considered in a national accounting framework (UNFCCC 2013a). The sum of emission reductions is then compared to a national reference emissions level to determine the overall achievements at national scale.

REDD will be implemented in three phases (UNFCCC 2010). After two publicly funded ‘readiness’ and ‘policy formulation’ stages, the third phase foresees a results-based mechanism, where only verified reductions of deforestation and degradation achieved against a predefined reference level will receive funding. Funds can come from different sources, such as carbon markets with REDD as an offset mechanism similar to the CDM, or from public sources such as Official Development Assistance, multilateral donor funds or carbon taxes (UNFCCC 2013b). In absence of an international climate agreement that could leverage compliance funding, at present most of the funding for REDD comes from development aid and individual bilateral agreements (Angelsen et al. 2012).

Several international REDD pilot programmes, such as the World Bank Forest Carbon Partnership Facility or the UN-REDD, aim to make interested non-Annex B countries ‘ready for REDD’ through support with the definition of national strategies to reduce deforestation rates or technical and policy capacity building (Westholm et al. 2009). Numerous demonstration projects on the ground aim at providing early lessons and advancing the policy formulation process (Cerbu et al. 2010). Several of these projects are implemented in the voluntary carbon market, which exists in parallel to the compliance markets associated with legally binding agreements such as the Kyoto Protocol or the Emissions Trading Scheme of the European Union (EU). Voluntary carbon markets are based on non-compliance buyers that wish to offset GHG emissions, mostly private sector entities acting for corporate social responsibility reasons. Forestry and land-use projects are among the most popular project types in the voluntary carbon market, constituting 32% of transaction volume in 2012 (Peters-Stanley and Yin 2013). REDD projects alone had a market share of almost 10%, which shows that in addition to a national-scale REDD mechanism under the UNFCCC, the voluntary market could be a funding source for individual REDD projects. These are independent of UNFCCC regulations and are developed according to one of several voluntary carbon accounting standards, such as the Verified Carbon Standard (VCS) or the Climate, Community and Biodiversity Standards (CCBS)[7].

2.6 Leakage and teleconnections undermining forest transitions and REDD policies

Conservation policies that restrict the use of land in one place can cause leakage effects through geographic shifts of activities to a nearby location or through market effects that cause land-use activities to be taken up somewhere else in the world. While this can lead to net land-sparing effects when displacement occurs to regions with higher land productivity, it can also induce new LUC and deforestation that decrease the net benefits of the conservation policy (Mayer et al. 2005).

Within-country leakage effects have been suggested for Brazil, where statistical correlations were found between soybean expansion into former pasture areas and geographic shifts of pasture into forested areas (Barona et al. 2010; Arima et al. 2011) and for the US, where up to 84% of a reduction in timber supply due to conservation policies targeting old-growth forest in the Pacific Northwest, was offset by increased timber production in other regions (Murray et al. 2004). Other studies find that ambitious

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[7] For more details on voluntary REDD standards, see for example Streck and Costenbader (2012): Standards for results-based REDD+ Finance. http://www.climatefocus.com/documents/standards_for_resultsbased_redd_finance

biofuel policies in the US, involving large amounts of domestic corn being redirected into biofuel production, are expected to cause substantial land-use changes for cropland expansion in other maize-exporting countries like Brazil (Searchinger et al. 2008; Dumortier et al. 2011; Villoria and Hertel 2011).

Such displacement effects are facilitated and even accelerated through the ever-increasing mobility of people and commodities that are connected through the globalized market and communication systems (Lambin and Meyfroidt 2011). The specific role of international trade in displacement can be described as redistributing "environmental impacts of policies and economic activities at the global scale, because it is associated with virtual exchanges of natural resources embodied in commodities being traded - e.g., water, biomass, and land use [and related emissions]"(Lambin and Meyfroidt 2011:3467). This indicates that, while in some cases leakage effects might primarily be caused by policies*,* the global society's demand for land-use products can be considered an underlying cause for land-use displacement. It is therefore useful to differentiate *policy-driven leakage* that can be linked to a specific policy intervention*,* and *demand-driven leakage* that arises from human consumption and lifestyle patterns (see e.g., Meyfroidt and Lambin 2009). These two terms are also referred to as *strong* and *weak leakage,* respectively (Peters 2010).

Demand-driven leakage is facilitated by teleconnections, which in this context describe distant trade links between global demands and local environmental effects that can facilitate conservation in one place by increasing forest conversion elsewhere. Through such teleconnections, Japan was able to feature one of the highest forest cover percentages worldwide in the 1990s due to cheap timber imports from Southeast Asia (Dauvergne and Lister 2011), and increased timber exports from Russia can contribute to forest conservation in Finland and China (Mayer et al. 2005). Several national-scale forest transitions were facilitated by increasing imports of agricultural commodities and timber from elsewhere; either through regional compensation within one country such as the US (Pfaff and Walker 2010) or through increasing imports from other countries (Meyfroidt and Lambin 2009; Meyfroidt et al. 2010). One implication of this is that the causes for tropical deforestation can at least partly be found in the high consumption levels of the developed world, where forest area tends to increase or remain stable (Dauvergne and Lister 2011). However, due to long and complex supply chains it is difficult to link the producing and the consuming locations (Dauvergne 2008), or to quantify distant drivers of land-use change that operate through international trade (Kastner et al. 2011a; Weinzettel et al. 2013).

2.7 Emissions accounting in the land-use sector

The evolution of climate policy approaches such as the UNFCCC has led to the development of an emissions accounting framework, which has been substantially steered by the IPCC. IPCC accounting guidelines usually apply to national inventories as required by the Kyoto Protocol and the UNFCCC, and will also be the basis for emissions accounting in the REDD mechanism (UNFCCC 2013a). IPCC accounting guidelines for national land-use sector inventories include the Good Practice Guide to Land Use, Land-Use Change and Forestry (IPCC 2003), and the guidelines for Agriculture, Forestry and Other Land Use (AFOLU) (IPCC 2006). In addition, accounting guidance for REDD projects include voluntary market documents such as the AFOLU guidelines of the Verified Carbon Standard (VCS 2012), and REDD accounting guidebooks such as the GOFC GOLD (2012). All guidelines share some underlying principles, such as the basic approach to quantifying emissions in all sectors. This involves multiplying activity data (AD) or the extent of the emitting activity, by emissions intensity coefficients that specify emissions per unit activity data (EF, for emissions factor) (IPCC 2006). The corresponding equation is

$$\mathbf{Emissions = AD * EF} \tag{1}$$

REDD emissions inventories combine changes in national forest area (activity data) expressed in hectares (ha), with changes in biomass and carbon density in that area (emission factors) in tons carbon per hectare (tC/ha), over time. This information is usually collected through a combination of field inventories and remote sensing techniques (Asner 2009).

2.7.1 Emission factors: Quantifying carbon stocks

Ecosystems with the largest terrestrial carbon sink capacity are forests, which contain carbon in different reservoirs, or carbon pools. Five different forest carbon pools are distinguished (Fig. 4); the living *above and below ground biomass* (AGB and BGB) consisting of stem, branches, leaves and roots; *dead wood and litter*; and *soil organic matter* (IPCC 2003). The distribution of carbon over different pools depends on the forest type and location. Whereas tropical forests hold nearly 60% of carbon in living biomass and just over 30% in soils[8], in boreal forests it is vice versa- only 20% of overall carbon is contained in the living biomass, with more than 60% contained in soils (Pan et al. 2011) and the rest distributed over litter and dead wood pools.

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[8] Exceptions to this are peatland forests in Southeast Asia, where the major part of carbon is contained in the peat soils.

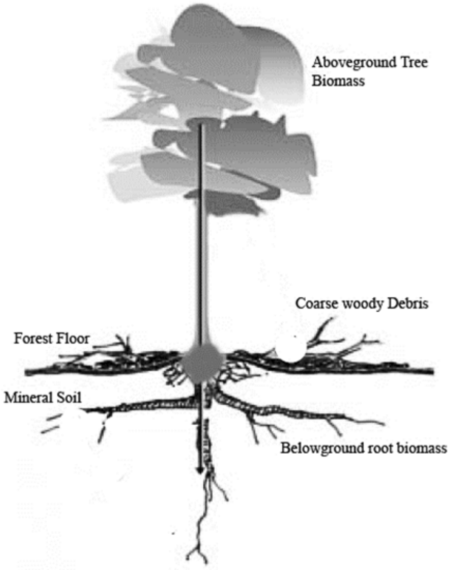

Fig. 4: The five forest carbon pools. *Source: http://carbon.sref.info/components*

The carbon stock of an area can be related to the biomass of vegetation; in general oven-dry biomass contains approximately 50% of carbon (Schlesinger 1991; Eq 2). Living ABG and BGB biomass is determined through the measurement of biomass stocks, either directly in detailed biomass inventories or, more commonly, using forest inventory methods (e.g., Brown et al. 1989; Chave et al. 2005).

$$\textbf{Carbon stock}_{\textbf{(t)}}\textbf{= biomass}_{\textbf{(t dry matter)}}\textbf{ * 0.5 (carbon fraction)} \qquad (2)$$

Deforestation emissions in the tropics are mostly caused by the loss of living biomass, because carbon in AGB and BGB pools is more susceptible to disturbances such as fire, pests and diseases, or wind-throw (Baccini et al. 2012). Soil carbon contributes less to overall emissions because it is not readily mobilized by disturbance processes. Therefore carbon stock inventories often focus on living biomass and omit soil carbon which is difficult and expensive to measure (e.g., Gibbs et al. 2007; Harris et al. 2012).

2.7.2 Activity Data: Monitoring Forest Area Change

Comprehensive monitoring of tropical forest areas has been difficult for a long time, but has quickly progressed with advances in remote sensing technologies since the 1990s (Lambin et al. 2003). Several satellites exist now that monitor forest cover, canopy loss and forest structure parameters at different resolutions, which have come to play a central role in the monitoring of changes in the global forest area and the development of regional and global forest cover maps (e.g., DeFries et al. 2002; Achard et al. 2004; Gibbs et al. 2007; Hansen et al. 2010). The main challenges for monitoring forest area changes include the detection of subtle and gradual changes, such as forest degradation, and the provision of consistent time series that allow the assessment of both short- and long-term dynamics (Asner 2009).

2.7.3 Emissions accounting and monitoring for REDD

The most common method to estimate emissions from changes in carbon stocks is the stock-difference approach that measures carbon stocks at two points in time and determines the difference[9]. To illustrate, the conversion of a tropical rainforest (carbon density of 300 tC/ha) to pasture (13 tC/ha, mainly in the roots), results in a carbon stock change of 300-13= 287 tC/ha. These carbon stock changes are converted to CO_2 equivalents, which are the basic accounting unit of emissions under the UNFCCC, based on the molecular weights of C (12.011 g/mol) and CO_2 (44.010 g/mol). This yields total land-use emissions of 287*(44/12)=1,052 tCO_2/ha. If the size of the cleared forest area is 100 ha, the resulting emissions reach 105,200 tCO_2. While this operation is fairly straightforward to implement on small areas, one of the main challenges in land-use accounting is the larger spatial application of measurements.

Whereas technical options are available, a significant gap exists however in technical, financial and institutional capacities of most developing countries to produce consistent time-series data about forest cover change and biomass densities, as required to evaluate the implementation success of REDD (Angelsen et al. 2012). Especially information about biomass stocks is not widely available, mainly because they require tedious and costly field measurements in sometimes remote and inaccessible forest areas. Especially large countries with high forest cover can face difficulties in producing representative biomass information, as this requires a wealth of plot samples (Asner 2009). This limited capacity to monitor LUC emissions over time currently hampers the establishment of national-scale inventory and monitoring systems for REDD in all but very few tropical Non-Annex B countries. Incomplete time-series of forest cover changes and sparse information on geographically-explicit biomass densities are among the main sources of uncertainty when quantifying LUC emissions.

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[9] Another option is the process-based *gain-loss* approach that determines the annual net balance of additions to and removals from specific carbon pools, focusing only on increments and losses rather than on total carbon stock (IPCC 2003).

3 Materials and Methods

This chapter provides a description of the overall methodological approach as context for the methods used in the research process, followed by a condensed description of the logic and steps behind the approaches taken in the two main thematic areas. The applied materials and methods are then briefly summarized for each article.

3.1 Methodological approach

The research questions in this thesis were addressed in a mixed-methods approach (Johnson and Onwuegbuzie 2004) that combines qualitative and quantitative methods to study carbon leakage caused by land-use displacement processes. Different ways to account for leakage emissions were explored in iterative steps of data collection and analysis, followed by additional data collection and new analysis. Therefore, the different steps of the research process build upon each other and both the empirical material and the research questions have been realigned with the respective outcomes of each step (Fig. 5). The qualitative assessment of leakage quantification methods served to synthetize existing information and narrowed down the problem to be investigated; see the orange highlighted steps in Fig. 5. The identified lack of methods for international carbon leakage was then addressed through quantitative method development; see the green highlighted steps in Fig. 5.

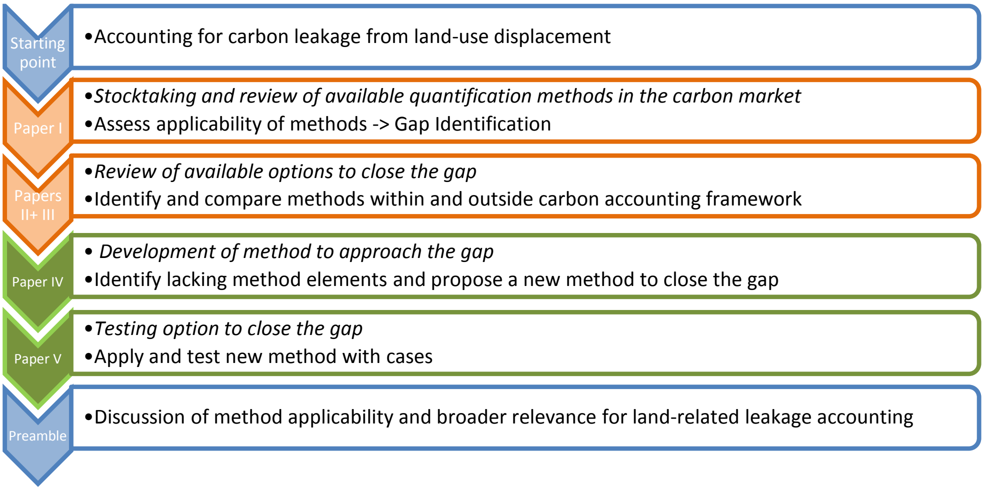

Fig. 5: Schematic illustration of research process presented in this thesis. Blue boxes are addressed in this preamble, orange boxes represent qualitative assessments of Papers I-III, and green boxes relate to quantitative method development.

3.2 Overview of the research process

The *qualitative assessment* (Papers I-III) included review and comparative analysis of literature and guidelines for leakage quantification from different research fields. The empirical material changed according to the outcomes of the different steps: Paper I took stock of existing accounting methods for land-related carbon leakage from the UNFCCC, carbon accounting standards in the voluntary market, and carbon accounting literature. A main finding was that most methods address the national or regional scale, whereas quantification methods for international carbon leakage are lacking.

Paper II explored quantification options for international emissions leakage explicitly, by broadening the analytical scope to look at the concept of indirect land-use change, which is a carbon leakage effect from biofuel policies with a focus on the international scale. Central in ILUC quantification are coupled economic-biophysical modeling methods, which were found to be suitable for the identification of causal leakage effects, but involve high uncertainties in the resulting estimates of land-use change emissions from displacement processes.

In Paper III the scope was then enlarged to explore broader underlying linkages between globalized trade flows, actual land-use changes and environmental impacts. To that end, another set of method approaches was reviewed, including methods for land-related policy leakage and teleconnections through international trade, which act as distant deforestation drivers. This process involved a turn to different but related research fields in the quest for a method that allows determining impacts of international land-use displacement, with a focus shift from GHG emissions impacts to other land-related effects.

Based on the combined findings from Papers I-III, the *quantitative assessment* further pursued the quantification of teleconnections as distant deforestation drivers that can increase the risk for international land-use leakage. Addressing a methodological bottleneck, in Paper IV a new indicator was developed to determine LUC emissions associated with the production of agricultural forest-risk commodities, the ‘Land-Use Change Carbon Footprint’ (LUC CFP). In Paper V this indicator was applied as part of an existing framework for linking international trade flows of agricultural commodities with environmental impacts at the place where the commodities are produced, to determine the amount of LUC emissions embodied in agricultural exports from Brazil and Indonesia.

3.3 Materials and Methods

Paper I combined a literature review with an assessment of quantification methods. A general literature search (Fink 2010) in the multidisciplinary bibliographic databases Web of Knowledge (WoK) and Scopus[10] was the first step to identify literature on carbon leakage from forest conservation activities and REDD. The resulting articles were used to establish classifications, leakage definitions and an analytical framework of forest carbon leakage. In the next step, 34 leakage quantification methods were identified as empirical material for the assessment. Sources were the scientific literature (8 methods) and current emissions accounting standards for forest carbon activities that involve quantitative leakage methods (26 methods). The latter include carbon accounting methodologies for REDD, improved forest management and afforestation and reforestation activities that were operational in the respective standards by June 2011. In a simple form of content analysis, the 34 identified methods were read several times to generate coding categories (Coffey and Atkinson 1996). We identified nine subcategories based on the methodological approach taken to leakage; six method groups that quantify primary leakage and three that estimate secondary leakage. These groups were then analyzed according to the analytical framework established above, for the geographic scale covered and the quantification tool applied.

Paper II presented a comparative analysis of quantification methods for carbon leakage from land-use activities (identified in Paper I) and methods to account for ILUC emissions. In addition to the method comparison, we analyzed the similarities and differences as well as common challenges within the two concepts to see if there was room for synergies in the attempt to optimize climate benefits. According to Walk (1998), a comparative analysis requires a thesis or objective, justified grounds for comparison, and a frame of reference. The objective was to explore potential quantification methods for international carbon leakage from land-use displacement, by turning to a closely related issue that is accounted for at international scale. ILUC was selected because it is, very much like carbon leakage, a land-use displacement process related to land-use policies (in this case biofuel regulations)[11]. ILUC quantification methods determine emissions generated by land-use displacement processes mainly at the international scale. Hence, *if* we could identify a suitable method to determine international ILUC emissions, that

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[10] Web of Knowledge (www. webofknowledge.com), formerly known as ISI Web of Knowledge, is a multidisciplinary academic database covering 23,000 scientific journals and 148,000 conference proceedings of the natural sciences, social sciences, arts, and humanities. Scopus (www.scopus.com) is a large abstract and citation database of peer-reviewed research literature, covering 15,000 peer-reviewed journals and providing a broad interdisciplinary coverage.

[11] ILUC occurs when land formerly used for cultivation of food, feed, or fiber is now dedicated to other uses, such as cultivating plant material for biofuel production, and the original land use shifts to an alternative area that might have a higher carbon stock (e.g., forest) (Gawel and Ludwig 2011).

method could probably be adapted to account for international carbon leakage from REDD, for which no method is currently available. The frame of reference used to compare the accounting methods under both concepts was adopted from Gawel and Ludwig (2011). The authors reviewed different methods and approaches to ILUC and establish three methodological categories; *impact-related methods, product-assignment strategies*, and *general governance approaches*. We applied these categories to the nine groups of leakage methods established in Paper I to create a common basis for comparison, which was then analyzed for similarities and differences.

In ***Paper III*** we conducted a literature review (Fink 2010) of existing approaches for quantifying international land-related leakage and distant deforestation drivers linked to global trade. The paper was structured along the two main phenomena addressed by current methods: leakage processes as unintended consequences of land-use policies, and teleconnections between geographically separated locations of production and consumption through international trade. The reviewed methods include environmentally extended input-output analysis and extended material-flow analysis, as well as quantification approaches used within the concepts of ILUC and the Ecological Footprint of Nations. The empirical material was selected based on various literature searches in the WoK database. We focused on peer-reviewed articles that summarize the selected methods in form of survey or review articles where available. Where these were lacking, we used peer-reviewed articles that presented quantification examples in the form of case studies. For the concepts of Ecological Footprint and ILUC that are also discussed in public and popular-science contexts, we included relevant grey literature such as EU policy reports in addition to scientific documents. The selected quantification methods were first described and then assessed for weaknesses and strengths as well as the conclusiveness of results.

In ***Paper IV*** a method was proposed to determine an environmental indicator for land-use change emissions that could be used in a material-flow analysis to determine LUC emissions embodied in trade. To that end, some basic methodological requirements had to be met, including the consideration of total national LUC emissions of a given country and the extent to which these are caused by specific activities, or deforestation drivers. To be applicable in a physical (as opposed to monetary) trade analysis the emissions had to be expressed per ton of agricultural production. This is a typical feature of carbon footprints, which can be defined as "[…] a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product" (Wiedmann and Minx 2008:4). Carbon footprints are commonly determined at national (e.g.

Hertwich and Peters 2009) or product (e.g., Cederberg et al. 2011) scale, where the latter typically entails life-cycle emissions occurring from production and/or transport of a specific commodity.

To account for carbon emissions from deforestation related to the production of agricultural commodities (e.g., soybean, beef meat and palm oil), we generalized an existing method that determines the carbon footprint of Brazilian beef (Cederberg et al. 2011). By assigning parts of the total national LUC emissions to the different agricultural commodities that promote deforestation in the respective country we developed a carbon footprint of a product. Contrary to the above definition, this product footprint does only account for LUC emissions and excludes other life-cycle emissions occurring in the subsequent cultivation, management, harvest and transport of the product. The latter are usually covered in conventional life-cycle assessments of land-use systems, whereas no established methodology exists to include emissions from land-use change in these assessments. Therefore we decided to focus on calculating a *deforestation footprint* of specific agricultural products, and to reflect this specific focus on land-use change emissions we called the indicator 'Land-Use Change Carbon Footprint'. The calculation of the LUC-CFP contains elements of carbon accounting (Chapter 2.7) through the use of carbon-stock changes as a basis for determining emissions, and of life-cycle assessments through the allocation of committed emissions over an amortization period. Calculating the LUC-CFP requires empirical data on several parameters, including on national-scale deforestation rates and their allocation to different driving factors, on forest biomass and carbon densities, carbon stocks of agricultural systems, as well as agricultural yield data and changes in yield dynamics over time. For illustration purposes we calculated LUC-CFP for the test cases of Brazil and Indonesia, obtaining the required empirical data from scientific literature, statistical databases (FAOSTAT 2013) and from the Brazilian national forest monitoring programme PRODES (INPE 2013).

Paper V combined the carbon footprint indicator developed in Paper IV with an extended material-flow framework (Kastner et al. 2011a) that links international trade flows of agricultural commodities with environmental impacts at the place where the commodities are produced. The method application consisted of two parts; 1) calculating LUC carbon footprints associated with the cultivation of different agricultural products, to be used as emission factors, and 2) assessing bilateral trade flows of forest-risk commodities from the country of production to the countries of apparent consumption. We applied this method for soy and beef products from Brazil and oil palm products from Indonesia, assessing export flows for the years 1990 and 2000- 2010.

The LUC-CFP as the first part of the calculation is not described in further detail here, as the process and the respective equations are presented in results of Paper IV (below). The trade-flow assessment applied in the second part of the calculation was suggested by Kastner et al. (2011a) in order to overcome a specific limitation of bilateral trade databases. These commonly list the location of the last value-added production step as the source country, which makes it difficult to identify the actual country of origin of a product when long supply chains are involved. For example, if soy produced in Argentina is exported to Sweden, but on its way first arrives to the port of Narvik (Norway) or Rotterdam (Netherlands) before being further transported to the final destination, the bilateral trade statistics will list Norway or The Netherlands as source countries for these soy imports (Fig. 6). The method presented by Kastner et al. (2011a) allows approximating the actual source country in long supply chains by tracing re-exports through the trade chain, based on domestic material input (DMI; =domestic production plus imports) that relates import and export flows to domestic production volumes in all countries of the trade chain. This approach allows identifying countries of apparent consumption, meaning the last country that imports the commodity (as opposed to the place of final consumption, which considers the final consumer of either raw material or products derived from it in subsequent processing steps). Fig. 6 below illustrates the origin of Swedish soy imports according to the FAO trade database and after adjusting for re-exports with the DMI-method.

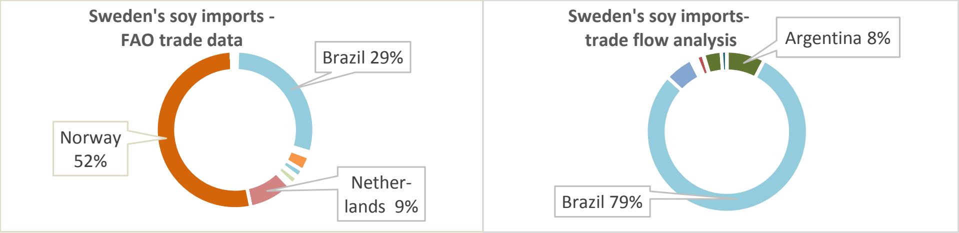

Fig. 6: Origin of Swedish soy imports according to the bilateral trade database of the FAO (FAOSTAT 2013) and after applying the trade flow analysis by Kastner et al. (2011a)

While Kastner et al. (2011a) applied the method to identify the actual source countries behind industrialized countries' imports of commodities, we used the method to identify the countries where deforestation-inducing crops from Brazil and Indonesia are consumed. To that end we used international bilateral trade statistics provided by the FAOSTAT database (FAOSTAT 2013) to analyze import trade flows and national production rates of all countries that trade soy, beef or oil palm products. The detailed steps taken in this analysis are described in Paper V and also by Kastner et al. (2011a).

4 Summary of Results

This chapter presents a summary of findings from the five papers in the context of the initially posed research questions. To that end, the chapter is divided into two thematic sections; the first one presenting the main results of the qualitative assessment and answering research questions 1 and 2, and the second one describing the results of the quantitative analysis, responding to research question 3.

4.1 Synthesis of existing assessment methods: Papers I-III

The *qualitative assessment* aimed to synthetize and assess existing quantification approaches to land-use displacement and associated emissions and to answer the following research questions:

1. How is carbon leakage from forest mitigation activities defined and accounted for in UNFCCC-related and voluntary carbon markets? Are current methods suitable to account for carbon leakage from REDD?
2. Which methods exist to quantify international land-related leakage and distant deforestation drivers; what are the main challenges and gaps? (Papers II and III)

The first research question is answered by ***Paper I,*** which provides both conceptual and methodological insights on carbon leakage within current emissions accounting frameworks. The existing definitions of carbon leakage vary slightly with the scale of the activities and the accounting boundary. The IPCC's more project-geared definition frames leakage as "the unanticipated decrease or increase in GHG benefits outside of the project's accounting boundary as a result of the project activities" (IPCC 2000:5.3.3.3). A broader definition sees leakage occurring when emissions regulations or policies are adopted in one place, and emissions shift to places where this policy is not effective (Murray 2008).

To understand the functioning of accounting methods it is helpful to be familiar with some key elements of the analytical leakage framework identified in Paper I. The framework distinguishes direct and indirect displacement processes and the geographic scale of leakage effects.

- Direct effects are referred to as *primary* or *activity-shifting leakage* (Aukland et al. 2003), which involves a geographic shift of deforestation activities or agents. Indirect effects are called *secondary* or *market leakage* (Schwarze et al. 2002); the difference to primary leakage being that market effects cause incentives for others to start deforesting, rather than moving the initial deforestation agent. Primary and secondary leakage can also overlap, for example when conservation policies affect operations of multinational agribusiness companies. A reduction in available land can cause market effects, but could also lead to a direct geographic relocation of activities by the same agent.

- The *geographical scale* of carbon leakage depends on the drivers of deforestation. Geographically limited leakage effects typically occur when smallholders or local communities are affected in subsistence activities. These local-scale processes are the responsibility of the country where they occur, and are included in the national or project emissions balances. International displacement occurs when forest conservation in one country induces new deforestation in another country, either through a direct shift of internationally mobile deforestation agents or through indirect market effects via trade. Due to complex international supply chains and teleconnections between producing and consuming countries it is difficult to account for international leakage (Skutsch and McCall 2010).

Leakage quantification methods in the carbon market can be grouped into basic methodological approaches, which differ in the way they measure displacement depending on the leakage type. Primary leakage is mostly quantified through direct field measurements, often in reference areas around a project where remote-sensing or ground measurements, interviews and household surveys are carried out. Secondary leakage that cannot directly be measured is commonly estimated through economic models or generically addressed by the use of discount factors that reflect the risk for leakage effects. All but two of the assessed methods address carbon leakage processes within a country, following the widely-applied principle that a country’s emissions responsibility ends at its borders. The main conclusion of Paper I was that leakage methods contained in current carbon accounting standards are suitable to account for within-country leakage from REDD in the absence of national monitoring and accounting systems. International leakage was identified as under-researched topic that requires attention and operational quantification methods to avoid counterproductive climate effects.

Papers II and III respond to the second research question, by reviewing different methods to quantify international land-related leakage and distant deforestation drivers, as well as assessing their main challenges and gaps. Land-related leakage was studied through the example of ILUC from biofuel policies, which is quantified with methods such as economic equilibrium modelling or statistical and causal-descriptive approaches. Distant deforestation drivers were assessed through methods to determine teleconnections between spatially disconnected locations of consumption and production of land-related commodities; namely input-output analysis and material-flow assessments.

Assessments of policy leakage employ two main approaches; scenario analysis and back-casting. The former compares a reference market scenario without the policy to a scenario that assumes implementation of the policy. The resulting market effects of the policy are then translated into potential land-use changes and associated emissions. Backcasting methods start from observed LUC effects and retrospectively link these to a policy, based on statistical correlations or specific allocation criteria.

Economic equilibrium modeling is a common scenario analysis tool to determine indirect market effects at national and international scale, through analyzing market reactions in a specific policy scenario compared to a counterfactual scenario without the policy. Equilibrium models trace a cascade of different price effects either in specific markets (in *partial equilibrium models*) or throughout the entire economy (in *general equilibrium models*) (Böhringer et al. 2003). This method provides comprehensive ex-ante simulations and allows establishing a clear link between market effects and a specific driver (Böhringer et al. 2012). In ILUC assessments, equilibrium models identify the magnitude and location of market-related displacement effects due to biofuel policies. They can then be coupled with biophysical models that determine the emission impacts from the expected changes in land use. Results however strongly depend on the underlying model assumptions about future market development, which is intrinsically uncertain (Plevin et al. 2010). Another source of uncertainty are the land-use emission factors used in the biophysical models, which often are global default values rather than spatially-explicit estimates, so that emission impacts can only be determined at a coarse geographic scale (Fritsche and Wiegmann 2011). Taken together, these uncertainties cause high variations between results from different assessments of the same policy. For example, assessing indirect effects of increased corn ethanol production in the US, Searchinger et al. (2008) expect substantial ILUC effects to occur mainly in India and China, whereas Villoria and Hertel (2010) suggest that the strongest effects will occur in the US itself or in other maize-exporting countries like Brazil. Resulting projections of ILUC emissions due to US biofuel policies vary according to the very different land productivity and carbon density conditions in these countries.

A conclusion is that at present, model-based ILUC approaches can provide general indications of when and where leakage effects might occur, but experts agree that due to high uncertainties results should not be used as policy foundation (Dumortier et al. 2011; Fritsche and Wiegmann 2011). Nevertheless, ILUC studies indicate potentially very high displacement effects, which illustrates the importance of considering global markets and trade relations in policy leakage assessments.

Statistical and causal-descriptive approaches analyze past land-use change patterns to identify correlations with specific drivers, such as biofuel production. One method to do this is with statistical regression analyses that investigate statistical relationships between land-use changes and the expansion of specific crops (e.g., Barona et al. 2010; Arima et al. 2011). While simple linear regression analyses yield qualitative statements only, coupling statistics with spatially-explicit LUC analyses allows the quantification of the land area affected by displacement. Such analyses are most conclusive on local-scale; previous attempts to establish spatially-explicit correlations between global deforestation and biofuel-production hotspots have failed due to serious data gaps (Gao et al. 2011). Whereas statistical methods establish correlations between different factors, they do not provide information about the direction of causation, so that results cannot be terminally conclusive as to which extent land-use changes are due to one specific policy only. Causal-descriptive methods combine historical data with allocation criteria to determine the contribution of individual drivers to the advancement of the agricultural frontier (e.g., Overmars et al. 2011). This approach is often criticized for the subjectivity of criteria used to allocate land-use changes to drivers, so that it is not possible to demonstrate a clear causal effect between the policy and displacement effects.

Methods to determine teleconnections between geographically separated locations of production and consumption link the consumption of land-related resources in one place to environmental impacts arising at the place of production. The main methodological options for this purpose are multi-regional input output (MRIO) analysis and extended material flow analysis (MFA). Both methods can be used to calculate resource consumption footprints, for example for land, water or carbon emissions. Such footprints quantify the resources needed to maintain a country's domestic consumption levels, such as the land demand (Lugschitz et al. 2011) or the area of deforestation (EC 2013) associated with European imports of agricultural and forest products, or the GHG emissions linked to each country's energy consumption (Hertwich and Peters 2009). Adjusting a footprint for the resources that are produced domestically yields the amount of resources embodied in trade; such as the GHG emissions from fossil fuel combustion that are embodied in global trade flows (Peters and Hertwich 2008a,b; Davis and Caldeira 2010; Peters et al. 2011a).

Environmentally extended MRIO analysis is a top-down approach to model global trade flows for specific years, based on bilateral trade information collected in global databases. The sum of environmental impacts, such as global emissions or land demand, is reallocated along these trade flows based on impact indicators per unit traded (Peters et al. 2012). As most trade-flow information is reported in value rather than mass units, the underlying trade units are monetary ones, so that impacts are usually determined per US dollar traded. MRIO models provide comprehensive life-cycle assessments of impacts embodied in trade-flows and can trace them along entire supply chains including intermediary countries and production steps (Peters et al. 2012). They thus cover the entire process from the location of production to the place of final consumption of the end-product. This comprehensiveness comes at the cost of low product resolution as global trade data is aggregated into broader product categories. Another contentious point is a possible distortion of results when monetary trade flows are linked to land demand, as higher-price products will appear to incur higher land requirements than low-price products, which might not be the case (Kastner et al. 2013).

Extended MFA methods are based on physical trade flows in mass units instead of monetary terms, which are linked to associated environmental impacts in a bottom-up approach. An advantage is that mass units can be more easily linked to land impacts, thus avoiding the above-described distortions. Physical trade flows are first converted into consistent virtual units that can be analyzed, such as land area, timber equivalents or forest carbon stocks. Together with national production data this first abstraction step yields national footprints of resource consumption or embodied trade flows. In a second step the resources embodied in trade (e.g., land area) can be linked to down-stream environmental impacts at the actual place of cultivation (e.g., LUC emissions). To that end trade-flow analyses are combined with life-cycle assessments and full carbon accounting elements. MFA methods permit the identification of receiving and remitting countries only at the level of apparent consumption, which means that the country that imports the primary resource is considered the place of consumption, regardless of potential further processing steps and re-exports.

4.2 Development and application of a method to quantify teleconnections: Papers IV and V

The *quantitative part* of the thesis focused on the third research question:

3. How can LUC emissions arising from teleconnections between the countries that produce and those that consume agricultural forest-risk commodities be quantified, in order to better understand potential magnitudes of international leakages through international trade?

Paper III showed that the combination of environmental impact indicators and trade-flow assessments seems a promising approach to determine teleconnections between local deforestation impacts and global market demand. However, while both MFA and MRIO methods are useful to determine *land use* embodied in trade, the bottleneck is currently the quantification of dynamic emissions from *land-use changes* embodied in traded products. The few existing studies (Zaks et al. 2009 and Saikku et al. 2012 using MFA methods; Karstensen et al. 2013 using MRIO) are constrained by elementary data gaps, mainly due to high uncertainties and lack of information on emission factors and the allocation of deforestation emissions to specific LUC drivers. The second part of the thesis thus focused on the development of a new environmental indicator called 'Land-Use Change Carbon Footprint' (LUC-CFP), which contributes to overcoming some of these limitations. The indicator determines LUC emissions of agricultural and other land-based products that are associated with the clearing of natural vegetation (Paper IV). Combining the indicator with a trade-flow analysis allows quantifying the extent to which distant consumption acts as driver for deforestation in a given country (Paper V). This directly contributes to the understanding of teleconnections between producer and final consumer countries of agricultural forest-risk commodities.

Paper IV presents the new indicator, which is calculated in two steps: 1. determining the LUC emissions from land cleared for the establishment of new agricultural production of a given commodity (e.g., beef or palm oil) and 2. deriving the average emissions load per ton of the commodity produced in a specific region, by distributing the LUC emissions resulting in Step 1 over the total production from that region.

The carbon footprint of agricultural products from cleared land established in step 1 describes the annual amount of carbon emissions from land clearing processes linked to the production of specific agricultural crops, and distributes these evenly over the total production of the crop in the years following deforestation (Eq. 3). The footprint is expressed in tCO_2 per ton commodity *j* produced on cleared land, and is calculated for land-use changes in a given country *i* and year *t*.

$$E_{i,j,t} = \frac{\left(C_i^f - C_{i,j}^a\right) \times \gamma_{i,j}}{\sum_{\bar{t}=t}^{t+T}\left(a_{i,j,\bar{t}-t} \times y_{i,j,\bar{t}}\right)} \qquad (3)$$

In this equation, the bracket in the numerator describes the average carbon stocks for forests (C^f) cleared in country *i* and for agricultural land (C^a) producing product *j*, respectively (in tC/ha). Above and below ground carbon stocks in the new land cover (agriculture) are compared to the previous land cover (forest) - the difference is the carbon stock lost in the land-use change process. If the agriculture system produces more than one crop, for example through intercropping between soy and corn that is common in Brazil, emissions are allocated between the two crops based on the revenues achieved over time; i.e., the net present value of the different income streams. If for example soy yields 70% of the total income from one hectare land and corn yields 30%, the total carbon stock change is multiplied by $\gamma_{i,j}$ = 0.7 in the footprint for soy and $\gamma_{i,j}$ =0.3 in the footprint for corn. This allocates greater emissions responsibility to the more profitable crop, based on the assumption that it is the main driving force behind land-use change. If only one crop occurs on the land, the factor $\gamma_{i,j}$ is 1 and all emissions are allocated to that crop. In the denominator, $a_{j,t}$ is a crop-specific factor that accounts for land-use and yield dynamics over time; for example yield variations in oil palm plantations that provide no yield in the first few years after planting. $y_{i,j,t}$ is the average yield of product *j* on cleared land in country *i* at time $\bar{t}$ (in t/ha/yr), and *T* describes the number of years over which emissions are distributed, the amortization period.

The results from Step 1 relate only to agricultural products originating from land that has been deforested during the amortization period. As it is usually not possible to clearly identify whether or not a specific product has been sourced from recently deforested land, it makes more sense to estimate an average LUC-CFP for the production of the commodity in the larger region or country (e.g., beef from Brazil or palm oil from Indonesia). This is done by accounting for the total national production of the commodity and the share of that production that comes from cleared land.

The full year-by-year approach as well as a simplified equation are described in detail in Paper IV, but to provide a very simple example of the average approach, let's assume that in 2006 the LUC CFP of Brazilian beef determined in step 1 reached 1200 tCO_2 per ton marketable meat produced, and 4% of total production came from deforested land. The average emissions load per ton marketable beef meat produced in Brazil in 2006 is then 48 tCO_2.

Paper V tested and confirmed the applicability of the LUC-CFP indicator for quantifying teleconnections that induce deforestation. Results showed strong teleconnections between the countries consuming (=importing) forest-risk commodities such as beef, soy and palm oil, and land-use change emissions in Brazil and Indonesia that occur in the expansion of export commodity production.

The expansion of soy, beef and palm oil production into forest and cerrado ecosystems incurred total LUC emissions of around 17.4 $GtCO_2$ over the assessment period 1990-2010 (Fig. 7). Note the very high amount of LUC emissions associated with Brazilian beef production, as the expansion of cattle production into the Amazon forest is responsible for around 80% of total Amazon deforestation. LUC emissions from soy are lower as the crop mostly expands into the cerrado biome that has a much lower carbon stock, or on former pasture areas that are not considered in this assessment. Despite a much higher overall carbon stock of Indonesian forests (including peatland forests) oil palm plantations were responsible for less than 50% of total national deforestation over time, so that LUC emissions from Indonesian palm oil production are lower than those of Brazilian cattle ranching. Emissions from Brazilian commodities decreased over time in line with the substantial reduction in overall deforestation rates since 2004, whereas Indonesian deforestation rates are stable and are increasingly driven by oil palm expansion, resulting in slightly increasing LUC emissions due to palm oil production.

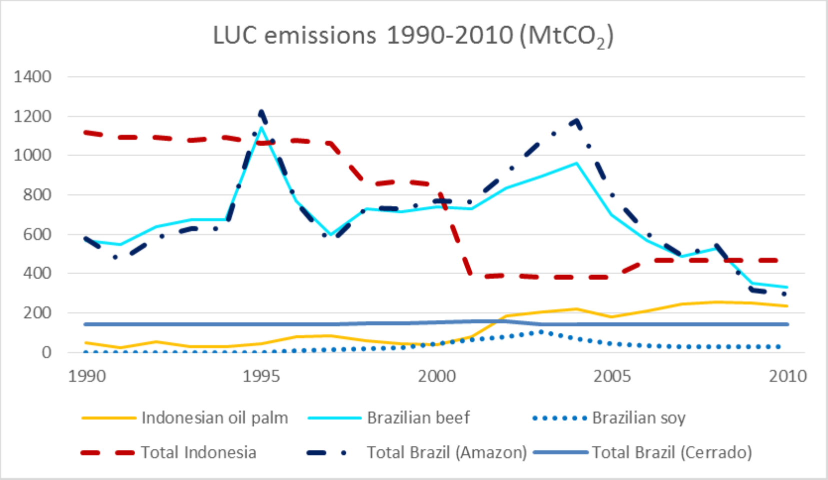

Fig. 7: LUC emissions due to the expansion of soy and beef production in Brazil and oil palm plantations in Indonesia; 1990-2010, in $MtCO_2$

Tracing whether national production volumes of these three commodities, including the LUC emissions embodied in them, are consumed domestically or leave the country as exports shows that the major part of soy and palm oil production happens for export purposes. Between 1990 and 2010, more than 60% of both Brazilian soy and Indonesian oil palm products were exported, which corresponds to average embodied LUC emissions of 20 and 59 $MtCO_2$ per year respectively. An exception is Brazilian beef that was mainly consumed domestically; only 11% of beef products were exported over time, corresponding to annual average embodied LUC emissions of 76 $MtCO_2$. A main finding of this paper is the increasing trend of emissions embodied in exports (EEE) since 1990. Until 2010, EEE of Brazilian beef increased by a factor of 2.4, whereas EEE of both soy and oil palm products rose nearly sevenfold. This shows a growing importance of export production in promoting deforestation and land-use change in both countries. In 2010, total emissions embodied in exports reached 89 $MtCO_2$ for soy and beef from Brazil and 118 $MtCO_2$ for oil palm products from Indonesia, whereas domestic consumption of these commodities was associated with 563 $MtCO_2$ and 76 $MtCO_2$, respectively.

Tracing trade flows to the places of apparent consumption over time shows that main consumers of forest-risk commodities in the 1990s were the EU and the US. Since the early 2000s, increasing imports can be observed in emerging economies such as China (mainly beef and soy), India (mainly palm oil), and Russia (mainly beef). In the future, increasing market demand and consumption levels in the old world and the emerging economies together can be expected to cause substantial pressure on tropical forest areas that are suitable for agricultural production. In the face of high demand for forest-risk commodities, forest conservation policies in some countries are likely to cause a shift of deforestation and agricultural production to other countries with less stringent legislation.

5 Discussion

The research presented here was conducted to meet two objectives: to synthesize existing knowledge and accounting methods for land-related leakage, and to contribute to method development regarding the analysis of teleconnections as distant deforestation drivers, which increase the risk of international land-use displacement. The first objective has been reached in Papers I,II and III, which provide accounts and analyses of the different concepts, definitions and quantification methods for carbon leakage and other land-related displacement processes that are available today. The second objective was reached in Papers IV and V, which present and apply a method to quantify LUC emissions embodied in international trade, by tracing LUC emissions arising in the production of agricultural forest-risk commodities to the countries in which these products are consumed. The following section discusses the key findings and their policy implications.

One of the main findings of this research project is that leakage assessments at least partly are a political issue rather than a technical one. The answer to the question 'to leak or not to leak?' posed in the title strongly depends on the definition of leakage adopted in the assessment. Both a strong and a weak definition can be distinguished, corresponding to policy-induced or demand-driven displacement.

5.1 Assessing policy-induced leakage

Carbon leakage as defined in current emissions accounting frameworks refers to policy-driven leakage, which requires the demonstration of a displacement effect due to one or several policies, followed by the quantification of the resulting emissions. One main challenge involves developing a *counterfactual scenario*- what would have happened in the absence of the policy? The answer to this question can only be hypothetical and is thus, given the complexity of the systems analyzed, by default subject to huge uncertainties.

The assessment of ILUC approaches in Papers II and III showed that methods to determine policy-induced leakage, including economic equilibrium modeling, statistical regression analysis and causal-descriptive attribution of LUC to specific drivers, face a dilemma. Methods either isolate a clear leakage effect but yield highly uncertain estimates, or they provide detailed emissions estimates but no clear causal effect between LUC and policy. More conclusive assessments of policy-induced leakage are possible when the counterfactual scenario is built on the extrapolation of historic trends and on the basis of well-researched local contexts, such as in the assessment of policy-driven leakage from Vietnam's forest transition (Meyfroidt and Lambin 2009). However, such approaches are rare in the literature as they require indepth analyses and a sound understanding of detailed national political, social and economic conditions and the success of specific policies, which cannot pragmatically be applied at larger scale or adopted for other countries.

While it is useful to assess impacts of specific policies and understand their intended and unintended consequences, the exclusive focus of leakage assessments on one specific policy as the sole driver of displacement has been criticized, as single-cause explanations are often inappropriate in today's world of complex relations and feedback effects (Peters 2010). Accounting for carbon leakage only when climate policy can be isolated as a single cause of displacement might underestimate actual emissions transfers, which occur due to a mix of socioeconomic conditions (Fischer 2011). Consumption-related net emission transfers between Annex B and non-Annex B countries quadrupled between 1990 and 2008, with net imports of embodied emissions by developed countries exceeding the emission reductions achieved under the Kyoto Protocol (Peters et al. 2011a). Emissions transferred via international trade are not accounted for in current emissions frameworks, due to the territorial approach adopted by the UNFCCC and voluntary carbon standards. While this is a pragmatic way to deal with accounting difficulties, it means that at present a large share of international emissions transfers that cannot be clearly linked to climate policies is not considered in global emissions balances.

5.1.1 What does this mean for leakage accounting in REDD?

Although this thesis was initially intended to contribute to leakage accounting in a future REDD mechanism, I realized that the current leakage definition and national accounting boundary does not allow for capture of the potentially most important displacement effects at international scale. Within-country leakage from REDD can be quantified with existing methods, as shown in Paper I. The most common approach to international displacement is equilibrium modeling, but results are so uncertain that they cannot be used to quantify emissions to a satisfying level of detail, let alone allow assigning responsibility to individual parties. The main point however is that even if there was a method to quantify international leakage from REDD policies, emissions would not be accounted for due to the current national accounting boundary. As REDD will be part of a future UNFCCC climate agreement, any option to address international leakage would also apply to the broader UNFCCC framework. The ideal policy response to eliminate risks for international leakage would be to expand the accounting boundary to the global scale, as leakage only occurs when the accounting scope is smaller than the overall problem scope (Wunder 2008). However, considering the currently very slow progress in the UNFCCC process, this approach might face limitations from political realities. The alternative would be to find a way to integrate emissions embodied in trade into existing climate-policy and emissions accounting frameworks. A widely discussed option in this context is the establishment of border tax adjustments that levy carbon tariffs on imports from regions without emissions regulations (e.g., Dröge 2011; Böhringer et al. 2012). Such measures are however contentious as they might be incompatible with international trade regulations under the World Trade Organization (Fischer and Fox 2009). Springmann (2014) discusses two other options that involve accounting of emissions embodied in trade: a mechanism similar to the CDM where net-importing Annex B countries would fund emission reduction activities in the exporting non-Annex B countries, or a consumption-based accounting approach in which Annex B countries adopt higher reduction targets if they are net importers of emissions embodied in trade. These two approaches would imply the use of methods to determine emissions embodied in trade in the first place, which are discussed further in the following section.

5.2 Assessing demand-driven displacement

Several authors point out the role of consumption as driving force behind all production processes, and thus as strong underlying cause of environmental degradation and global emissions (e.g., Dauvergne 2008; Davis and Caldeira 2010). The use of consumption-based emissions accounting has for several years now been discussed as an alternative or complementary approach to the current production-based system (e.g., Rothmann 1998; Peters 2008). This is in line with the above suggested integration of consumption-based approaches with current production-based accounting frameworks. However, adopting this accounting principle implies defining carbon leakage differently and considering societal demands instead of specific policies as the causes behind displacement processes[12]. Demand-driven leakage occurs when countries with emissions targets increase their imports of emissions-intense commodities from countries without climate legislation (Peters 2010).

Assessments of weak leakage compare emissions reductions in Annex B countries with emissions increases in non-Annex B countries, where the latter supply products to meet continued or increasing demand in the former. In this context, emissions embodied in international trade can be used as proxy for market leakage because trade is a mechanism that facilitates displacement. A closely related concept is trade-related teleconnections that link consumption in one location to emissions impacts at the

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[12] Note that weak leakage assessments in principle also require the understanding of causal effects between driver and emissions, but that assessment methods are not required to demonstrate a causal effect as part of the quantification process, which facilitates the assessment.

production location. It is important to distinguish though that the existence of teleconnections does not automatically indicate displacement effects. Rather, teleconnections can increase the risk for international leakage, as they constitute land-use change and emissions drivers that are not regulated in national policies, which makes it important to investigate and if possible quantify these linkages.

The methods found most suitable to assess EET and teleconnections are multi-regional input-output analysis and extended material-flow assessments. MRIO models allow for comprehensive global-scale assessments albeit at a low product resolution, and are suitable to identify global displacement effects through trade. MFA methods usually determine emissions or other impacts embodied in trade in geographically limited bottom-up approaches. The main differences between MRIO and MFA, as established in Paper III, are results at the final versus apparent levels of consumption, and the use of monetary versus physical trade information. The results of MRIO and MFA assessments can therefore vary substantially or even be contradictory even when analyzing the same topic, as in the case of China which appears as net importer of embodied cropland in several MFA assessments, whereas MRIO studies identify the country as a net exporter of the same (see Kastner et al. 2013). As both methods involve uncertainties and are limited by data quality and availability, it is difficult to say which approach provides more accurate results.

5.2.1 What does this mean for leakage accounting in REDD?

Weak leakage assessments for REDD would involve testing whether countries that introduce forest conservation targets increase their imports of forest-risk commodities from countries that do not participate in REDD. While this effect has been demonstrated for several countries that recently underwent a forest transition (Meyfroidt et al. 2010), it is not the main challenge for the global effectiveness of REDD. Results of Paper V suggest that strong teleconnections between land-use changes in agricultural export nations and global market demand increase the risk for policy leakage effects from REDD if agricultural export countries like Brazil or Indonesia introduce conservation policies that affect land availability. Such teleconnections could jeopardize the long-term success of REDD efforts, by fostering leakage. It is therefore important to analyze and understand teleconnections to more successfully address distant deforestation drivers and eventually minimize the risk for international displacement.

5.3 The LUC-CFP as a method to quantify teleconnections

The quantification of LUC emissions embodied in trade is needed to understand and analyze teleconnections in the context of REDD; however approaches face methodological limitations (Paper III). This is where the LUC footprint method suggested in Paper IV comes in, as it offers an option to quantify LUC emissions embodied in trade of agricultural products that induce deforestation. Combining the LUC-CFP method proposed in this thesis with a physical trade-flow assessment allows the quantification of LUC emissions due to trade-related teleconnections between producer and consumer countries of forest-risk commodities. With this it is possible to determine the extent of LUC emissions in a given country that arises from agricultural production for export, and thus due to foreign consumption. Considering that between 41 and 54% of tropical deforestation in the period 2000–2005 (excluding Brazil) occurred in countries with commercial drivers similar to Brazil (DeFries et al. 2013), the LUC-CFP method could be widely applied. It is not directly applicable though in countries where the dominant deforestation drivers are logging or subsistence agriculture.

Advantages of the method include its broad applicability in a generalized setting through the use of information on quantified agricultural deforestation drivers rather than local land-use models. The distribution of emissions over the entire amortization period in the LUC-CFP avoids assigning all the responsibility to the first crop after deforestation by also taking into account subsequent crops that might be equally important driving forces behind forest clearing. While other amortization schemes exist and are comprehensively discussed by Zaks et al. (2009), the option of constant amortization over time is common in carbon footprinting standards (BSI 2011).

Limitations of the LUC-CFP include the fairly high data requirements in the original equation. Parameterizing the equation requires combining data from several sources, and making a number of assumptions, which leads to uncertainties. It is however possible to use a simplified version of the equation which yields similar results and requires much less data (Paper IV). Nevertheless, it is important to keep in mind the uncertainties affecting the quantification of LUC emissions in general, especially regarding the assessment of forest area changes due to differing underlying forest definitions, and LUC emission factors that involve uncertainties of up to 60% (Angelsen et al. 2012; Houghton et al. 2012). The main limitation to a broad applicability of the method is a lack of quantified deforestation drivers; i.e., information about the extent to which specific agricultural production systems induce deforestation. A recent attempt to compile this data (Hosonuma et al. 2012) found quantitative estimates of direct deforestation drivers for only 11 out of 100 tropical countries. While the data situation could improve in the course of formulating several national REDD strategies and action plans, the estimation of LUC-CFP for a broad set of agricultural commodities requires intensified research in this area.

5.4 Teleconnections increasingly important as distant deforestation drivers

Applying the method to Brazilian soy and beef products and Indonesian oil palm commodities shows that large amounts especially of soy and palm oil are produced for export, whereas Brazilian beef is mainly consumed domestically. In spite of comparably small export volumes, beef production however has a high climate impact due to the strong role of cattle ranching in promoting Amazon deforestation and the low yield per hectare compared to soybeans and palm oil. All three of these commodities showed an overall increasing trend in LUC emissions embodied in trade since the 1990s, which corresponds to findings from Karstensen et al. (2013) who analyzed emissions embodied in Brazilian beef and soy exports over the same period. This is in line with observed trends in agricultural trade, that 70% of cereal exports during the past decade originated from only eight countries (Fader et al. 2013), including Brazil and Indonesia who absorb global agricultural land demand through increasing exports (Meyfroidt et al. 2010). Similar trends are observed in other fields, such as steadily increasing trade flows of energy emissions (Davis and Caldeira 2010; Peters et al. 2011a), raw materials (Wiedmann et al. 2013) or land resources (Weinzettel et al. 2013; Yu et al. 2013). A conclusion from this is that international trade is increasingly important as vector that connects locations of high consumption levels with locations that offer favorable production conditions. These kinds of teleconnections can be expected to become even more pronounced in the future, as growing imports by emerging economies together with historically high import volumes by developed regions, such as the EU or US, will lead to a rising pressure on global land resources (Yu et al. 2013) and higher risks for environmental impacts. One projection scenario suggests that roughly 50% of the global population could be dependent on crop imports by 2050 (Fader et al. 2013). If these crops are forest-risk commodities, environmental and climate impacts in the producing countries induced by world market demand can be substantial. Teleconnections are hard to control and quantify, and have the potential to jeopardize the effectiveness of global sustainability efforts, for example forest conservation policies such as REDD. The LUC-CFP method developed in this thesis contributes to a better understanding and quantification of such teleconnections related to LUC emissions. Results could be used in several contexts, such as the sharing of emissions responsibility between producers and consumers, or the design of demand-side measures to complement conventional supply-side measures like REDD.

5.5 How to make consumers responsible for environmental impacts?

Our results show that large parts of LUC emissions in Brazil and Indonesia occur in the production of export commodities for the world markets. Similarly, parts of the fossil-fuel based emissions increases in non-Annex B countries are generated in the production of export goods that are consumed in Annex B states (Davis and Caldeira 2010). Although options on how to share responsibility for these emissions have been discussed in literature (e.g., Lenzen et al. 2007; Zaks et al. 2009), most of the mitigation strategies designed under the UNFCCC and other compliance schemes target supply-side measures that seek to reduce or tidy up production processes. This is in line with the "tendency of economic policy in market-driven economies not to interfere with consumers´ preferences", which makes the producer perspective the "dominant form of viewing the environmental impacts of industrial production" (Lenzen et al. 2007:27). In recent years however, support for the inclusion of consumption aspects in climate change research and policy-making has been growing (Aall and Hille 2010). Approaches such as footprints of resource use that assign emissions responsibility to the consumer have become widely accepted and implemented, especially in the business sector (e.g., the carbon footprint, Minx and Wiedmann 2008). Whereas consumption-based accounting has many supporters in the scientific literature (Rothmann 1998; Lenzen et al. 2007; Peters 2008; Springmann 2014) the topic is not prominent in the climate policy negotiations. The main problem with consumer responsibility is jurisdiction over processes and emissions, as developed countries will be reluctant to take responsibility for emissions they cannot control (Fischer 2011).

An alternative to changing the underlying UNFCCC emissions accounting principle from producer to consumer responsibility is the development of demand-side measures that can complement supply-side policies. In the land-use sector such demand-side measures have been discussed for a while already as new conservation opportunities (Nepstad et al. 2006; Rudel et al. 2009a; Meyfroidt and Lambin 2011). Considering rapidly developing trade relationships and growing importance of commercial deforestation drivers, demand-side measures are increasingly being considered as necessary to successfully reduce global deforestation in general (Angelsen et al. 2012) and "forest footprints" of agricultural commodities in particular (IIED 2013). These measures could target importers of agricultural commodities, or consumers that orient their consumption behavior based on certification schemes or information campaigns (Karstensen et al. 2013), but could also include public-procurement policies or regulations that promote sustainably-sourced commodities (IIED 2013). Examples of consumer-led initiatives are zero-deforestation embargos such as the Brazilian Soy Moratorium (Rudorff et al. 2011) or the ban of beef sourced from deforestation areas in the Amazon by both domestic and international food retailers (e.g., Wal-Mart and Carrefour). This led to the establishment of the G4 Cattle Agreement, which is a moratorium on buying cattle from newly cleared areas in the Amazon that was agreed by the four biggest cattle producers and traders worldwide. A pre-requisite for these kinds of demand-side measures is that consumers have access to information about the distant environmental impacts of their consumption and that producers have the possibility to communicate environmental stewardship.

In conclusion, findings from this thesis support a growing relevance of demand-side approaches in a fast-developing trade universe, where national-scale policies are jeopardized by macro-economic factors (Gasparri et al. 2013). Strong leakage assessments are useful to understand direct and indirect effects of specific policies but become increasingly meaningless in the face of strengthening international drivers and feedback effects. The assessment of teleconnections helps to better understand and quantify the risk of international leakage effects from policies like REDD. Overcoming previous limitations in the assessment of land-use change emissions embodied in trade, the LUC-CFP method developed in this thesis can thus contribute to inform the design of demand-side measures that target strong teleconnections.

6 Conclusions

The key question posed in this thesis was how international carbon leakage, or emissions impacts from international land-use displacement, could be effectively quantified. One of the main conclusions is that emissions accounting, and also the question posed in the title of this thesis “to leak or not to leak?” is a political rather than a technical question, since the definition of what constitutes carbon leakage is closely linked to the underlying emissions accounting boundaries.

Other key conclusions are summarized in the following:

- Papers I-III showed that policy leakage as defined in the current emissions accounting frameworks is difficult to assess due to the missing counterfactual scenario. Excluding international leakage emissions from accounting, as inherent in the current jurisdictional accounting boundary, is pragmatic but ignores substantial international emissions shifts that cannot be clearly linked to policies.
- Consumption-based accounting approaches that assume leakage to be driven by consumption and market demand might provide an alternative to consider these emissions, and could be used alongside territorial assessments. Paper III showed that methods to assess teleconnections combine environmental impact assessments with trade-flow analysis. This approach faced limitations in the past for emissions from LUC.
- This thesis proposed a method that contributes to overcome previous limitations and data gaps, the LUC-CFP. In combination with physical trade-flow analyses, the LUC-CFP can be used to quantify the extent to which deforestation is driven by distant demand and consumption, and thus allows the quantification of trade-related telecconections between places of consumption and production of agricultural forest-risk commodities. The application of the method is currently constrained by gaps in quantified information about the extent to which specific agricultural production systems induce deforestation, which does not allow calculating LUC-footprints for a broader range of countries and agricultural commodities. Further research is needed to close these data gaps, and could benefit from ongoing REDD processes that compile this kind of data to formulate national-scale REDD strategies.
- Results of the LUC-CFP method could also inform the design of potential demand-side measures to complement supply-side policies for a more effective reduction of global deforestation rates and LUC emissions.

7 The long-term outlook

This thesis shows that whether international carbon leakage from a future REDD-mechanism will be accounted for is a political question rather than a technical one. A general sustainability issue is whether the world will succeed in conserving natural ecosystems and forests when increasing agricultural output is needed to feed a growing world population (Godfray et al. 2010; Lambin and Meyfroidt 2011). Brazil's recent experiences with reducing deforestation rates while maintaining high levels of soy and beef production indicate that this might be possible. In a long-term forest transition perspective, international land-use displacement could be part of a global adjustment process during which agricultural production concentrates in the most productive locations. This could spare land for nature in other regions so that eventually a global forest transition might be achieved (Meyfroidt and Lambin 2011). While it is possible that the short-term leakage perspective overlooks such longer-term signals, several global indicators imply negative overall effects: increasing global emission levels and growing deforestation rates coupled with often unproductive, extensive agricultural production in the tropics suggest that the global land-use system is not by default approaching a global forest transition, so that additional policies are needed to achieve conservation effects.

In the context of a general trade-off between conservation and food production, REDD can be seen as mechanism that promotes the conservation option, which then gains profitability compared to agriculture. However, several authors caution that the focus of REDD payments on direct opportunity costs is not sufficient to halt deforestation in the long term. Up and downstream benefits of deforestation, such as employment and secondary industries contribute to the attractiveness of non-forest land-use options and are often not considered in REDD cost estimates (Ghazoul et al. 2010). A long-term effect of valuating forest carbon might be increasing land competition and rising land prices over time, which could make conservation again less profitable than agricultural development and therefore accelerate land-use displacement. As a result, REDD might not turn out to be the cheap mitigation option it was previously considered, and carbon prices covering current land opportunity costs might be insufficient as incentives for long-term conservation (Persson and Azar 2010; Persson 2012). Therefore several authors question whether local land-sparing trends such as found in Brazil can be sustained in the face of growing demand for agricultural products (Gibbs et al. 2010; Pfaff and Walker 2010; Karstensen et al. 2013). If de-coupling increasing agricultural output and expansion into forest cannot be achieved at global level, the trade-off between conservation and food production can be expected to increase. Questions of land-use displacement and leakage effects can therefore be expected to remain relevant in the future.

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