A case-study approach to quantifying indirect land-use change due to expanding biofuels feedstock cultivation

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Abstract

Quantification of indirect land-use change (ILUC) remains a controversial process, and our understanding of it is not yet complete. This dissertation contributes to ILUC quantification and mitigation efforts by presenting a new deterministic case-study approach and applying it to ethanol production in specific regions of Malawi, Brazil and Germany. In contrast to existing models the new approach is a bottom-up approach that starts with biofuel feedstock expansion. It furthermore allows for consideration of regionally specific conditions and the implementation of compensation measures; thus it reflects the ILUC risk of a specific biofuel feedstock expansion more precisely than do existing models that do not consider such measures.

The best estimates for $ILUC_{GHG\_net}$, the net ILUC factor that considers both greenhouse gas (GHG) emissions from the final LUC *and* from the implementation of compensation measures, are –11 g CO_{2eq} MJ^{-1} of additional sugarcane ethanol produced in Malawi, 24 g CO_{2eq} MJ^{-1} of additional sugarcane ethanol produced in Brazil and 50 g CO_{2eq} MJ^{-1} of additional wheat ethanol produced in Germany. Several regional factors, e.g. the LUC CO_2 emission factor, as well as methodological decisions, e.g. the allocation approach, were found to have a significant impact on $ILUC_{GHG\_net}$. However, the ranges for $ILUC_{GHG\_net}$ are broad and strongly overlap when considering input parameter uncertainty (–200 to 74 g CO_{2eq} MJ^{-1} of sugarcane ethanol produced in Malawi, 1 to 144 g CO_{2eq} MJ^{-1} of sugarcane ethanol produced in Brazil, and 1 to 200 g CO_{2eq} MJ^{-1} of wheat ethanol produced in Germany). Thus, although the case studies do show that regional conditions influence $ILUC_{GHG\_net}$, this does not necessarily mean that a significant variation between the regional ILUC factors can be found when uncertainty is considered. In cases where compensation measures are being implemented, however, the ILUC case-study approach may detect significant differences between regionally specific values for $ILUC_{GHG\_net}$.

Compensation measures such as the implementation of irrigation systems, increased cattle stocking rates or reduced meat consumption were shown to be regionally specific and to lead to net GHG emissions savings (although some are accompanied by additional fertilizer applications); in fact, a negative value for $ILUC_{GHG\_net}$ is even possible, indicating the occurrence of overcompensation. The ILUC of one agricultural activity is always direct land use change (DLUC) of another. Therefore, LUC CO_2 emissions were allocated to the expanding biofuel feedstock and to the agricultural activity directly leading to the LUC; this appears to be an appropriate way of avoiding double counting and at the same time setting incentives to avoid DLUC. Allocation reduces the ILUC factor of additional sugarcane ethanol produced in Brazil by up to 10% as compared to debiting all emissions on the expanding sugarcane.

Finally, the carbon footprint (CF) of ethanol produced at the specific sites was calculated; sugarcane ethanol produced in Malawi (115 g CO_{2eq} MJ^{-1}) shows evidence of a significantly higher CF than sugarcane ethanol produced in Brazil or wheat ethanol produced in Germany (17 and 26 g CO_{2eq} MJ^{-1}). Thus, if $ILUC_{GHG\_net}$ were considered when analyzing the GHG savings compared to fossil fuels, wheat ethanol produced in Germany would no longer save 35% GHG emissions compared to fossil fuels. Sugarcane ethanol produced in Brazil, however, would still achieve the 35% reduction, even if the best estimate for $ILUC_{GHG\_net}$ was taken into account. In Malawi, ethanol does not fulfill the mandate, but considering $ILUC_{GHG\_net}$ when including the positive effect of the irrigation system could effectively reduce the overall GHG emissions. More research is particularly required on further compensation measures and on the allocation of LUC-induced CO_2 emissions between direct and indirect drivers.

Zusammenfassung

Die Quantifizierung indirekter Landnutzungsänderungen (ILUC) wirft methodische Fragen auf, die trotz intensiver Forschungstätigkeiten in den letzten Jahren nicht abschließend beantwortet sind. Die Dissertation trägt zur Weiterentwicklung der ILUC-Quantifizierung und -Vermeidung bei, indem sie einen neuen deterministischen Fallstudienansatz vorstellt und diesen auf drei Fallstudien zur Ethanolproduktion in konkreten Regionen in Malawi, Brasilien und Deutschland anwendet. Im Gegensatz zu bestehenden Methoden handelt es sich um einen Ansatz, der mit der Flächenexpansion von Rohstoffen für die Biokraftstoffproduktion beginnt. Er erlaubt es außerdem, die Implementierung von Kompensationsmaßnahmen zu berücksichtigen.

Der netto ILUC-Faktor ($ILUC_{GHG\_net}$) beinhaltet Treibhausgas-(THG)-Emissionen aus der finalen Landnutzungsänderung (LUC) *und* aus der Implementierung von Kompensationsmaßnahmen. Die besten Schätzwerte betragen –11 g CO_{2eq} MJ^{-1} zusätzliches Zuckerrohrethanol aus Malawi, 24 g CO_{2eq} MJ^{-1} zus. Zuckerrohrethanol aus Brasilien und 50 g CO_{2eq} MJ^{-1} zus. Getreideethanol aus Deutschland. Regionale Faktoren und methodische Entscheidungen beeinflussen $ILUC_{GHG\_net}$ signifikant. Allerdings überlappen die Spannweiten der Ergebnisse deutlich, wenn die Unsicherheit bezüglich der Inputparameter berücksichtigt wird (–200 bis 74 g CO_{2eq} MJ^{-1} Zuckerrohrethanol aus Malawi, 1 bis 144 g CO_{2eq} MJ^{-1} Zuckerrohrethanol aus Brasilien, 1 bis 200 g CO_{2eq} MJ^{-1} Getreideethanol aus Deutschland). Obwohl die Fallstudien also zeigen, dass regionale Faktoren $ILUC_{GHG\_net}$ beeinflussen, können signifikante Unterschiede zwischen regionalen ILUC-Faktoren bei Berücksichtigung der Unsicherheit nicht unbedingt festgestellt werden. Nur in Fällen, in denen Kompensationsmaßnahmen umgesetzt werden, kann der neue Ansatz signifikante Unterschiede aufdecken. Konkrete Maßnahmen wie die Implementierung von Bewässerungssystemen, die Steigerung der Rinderbestandsdichte und eine Reduktion des Fleischkonsums sind abhängig von den regionalen Bedingungen als Kompensationsmaßnahmen geeignet oder nicht. Diese Maßnahmen führen in den Fallstudien zu einer Nettoreduktion der THG-Emissionen, obwohl teilweise ein zusätzlicher Düngemitteleinsatz erforderlich ist. $ILUC_{GHG\_net}$ kann auch negative Werte annehmen, wenn eine Überkompensation stattfindet. Außerdem wurde ein Allokationsansatz angewandt, der die Emissionen aus den finalen LUC auf den expandieren Biokraftstoffrohstoff und auf die agrarwirtschaftliche Aktivität verteilt, die der LUC direkt folgt. Dies ermöglicht es, eine Doppelzählung der THG-Emissionen zu vermeiden und gleichzeitig einen Anreiz zu setzen, direkte LUC zu unterlassen. Die Allokation verringert den ILUC-Faktor der zus. Zuckerrohrethanolproduktion in Brasilien um bis zu 10%.

Zuletzt wurde der Carbon Footprint (CF) berechnet; Zuckerrohrethanol produziert in Malawi hat einen signifikant höheren CF (115 g CO_{2eq} MJ^{-1}) als solches produziert in Brasilien und als Getreideethanol produziert in Deutschland (17 und 26 g CO_{2eq} MJ^{-1}). Würde $ILUC_{GHG\_net}$ bei der Berechnung der THG-Einsparung gegenüber fossilen Kraftstoffen berücksichtigt, so würde Getreideethanol die 35 % THG-Einsparung im Vergleich zu fossilen Kraftstoffe nicht länger erfüllen. Brasilianisches Zuckerrohrethanol würde auch bei Berücksichtigung des besten Schätzwerts für $ILUC_{GHG\_net}$ 35 % THG-Emissionen einsparen. Ethanol aus Malawi hat bereits einen zu hohen CF. Die Berücksichtigung von $ILUC_{GHG\_net}$ inklusive des positiven Effekts des Bewässerungssystems könnte jedoch die THG-Emissionen insgesamt senken. Weiterer Forschungsbedarf besteht vor allem bezüglich der Untersuchung weiterer Kompensationsmaßnahmen sowie bezüglich der Allokation der LUC induzierten CO_2-Emissionen zwischen direkten und indirekten Treibern.

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Abbreviations

AGLINK	Worldwide Agribusiness Linkage Program
ALCA	Attributional life cycle assessment
BDBe	Bundesverband der deutschen Bioethanolwirtschaft e.V.
BMBF	Bundesministerium für Bildung und Forschung
CAPRI	Common Agricultural Policy Regionalised Impact Modelling System
CET	Constant elasticity of transformation
CDM	Clean Development Mechanism
C	Carbon
CET	Constant elasticity of transformation
CF	Carbon footprint
CGE	Computable general equilibrium
CH_4	Methane
CLCA	Consequentiall life cycle assessment
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalents
CU	Cereal unit
DDGS	Dried distillers grains with solubles
dm	Dry matter
DLUC	Direct land-use change
DOM	Dead organic matter
EC	European Commission
EEG	Erneuerbare-Energien-Gesetz
EU	European Union
FAO	United Nations Food and Agriculture Organization
FAPRI	Food and Agricultural Policy Research Institute
GGI	Greenhouse gas inventory
GHG	Greenhouse gase
GTAP	Global Trade Analysis Project
GWP	Global warming potential
HY	High yield
IFUC	Indirect fuel-use change
ILUC	Indirect land-use change
IFPRI	International Food Policy Research Institute

ILCD	International Reference Life Cycle Data System
IMAGE	Integrated Model to Assess the Global Environment
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
INPE	National Institute for Space Research (Brazil)
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JRC	Joint Research Centre
K	Potassium
KTBL	Association for Technology and Structures in Agriculture
LCA	Life cycle assessment
LEITAP	Landbouw Economisch Instituut Trade Analysis Project
LUC	Land-use change
LHV	Lower heating value
LY	Low yield
N	Nitrogen
N_2O	Nitrous oxide
NDF	Net displacement factor (Plevin et al. 2010)
NGO	Non-governmental organization
P	Phosphorus
PE	Partial equilibrium
PEF	Product environmental footprint
RED	Renewable Energy Directive
SAM	Social accounting matrix
SC	Scenario
SEMA	Environmental Protection Agency, State of Pará, Brazil
SVIP	Shire Valley Irrigation Project
SSA	Sub-Saharan Africa
SuC	Sugarcane
UNFCCC	United Nations Framework Convention on Climate Change
UNICA	Sugar and Ethanol Millers Association
USDA	United States Department for Agriculture
VDB	Verband der Deutschen Biokraftstoffindustrie e.V.

Variables

A	Area of land converted to another land use [ha]
A_B	Agricultural reference area in the baseline [ha]
A_C	Agricultural area where compensation measure is implemented [ha]
A_F	Agricultural area freed up by compensation measure [ha]
B_0	Maximum methane production capacity (0.25 kg kg^{-1} COD)
B_{After}	Biomass stock after conversion [t C ha^{-1}]
B_{Before}	Biomass stock before conversion [t C ha^{-1}]
Bf	Additional amount of biofuel feedstock [t]
ΔCO_{2dom}	CO_2 emissions released due to final LUC within the country itself [g CO_2 ha^{-1}]
ΔCO_{2glob}	CO_2 emissions released due to final LUC elsewhere (global average) [g CO_2 ha^{-1}]
$COD_{available,m}$	Chemical oxygen demand available per month for conversion [g L^{-1}]
$E_{CH4, Storage}$	Methane emissions occurring during vinasse storage [kg L^{-1}]
EFF_{GHG}	GHG emissions caused by intensification of agricultural activities [g CO_{2eq} MJ^{-1} of biofuel]
$E^R LUC$	Country-specific LUC CO_2 emissions, Lahl (2010)
F_{all}	Allocation factor
F_{spill}	Share of ILUC that spills across the border in total ILUC
GEA	Gross expansion area for production of biofuel feedstock [ha]
$\%ILUC_{dom}$	Percentage of ILUC occurring within the country itself [%]
$\%ILUC_{glob}$	Percentage of ILUC spilling across the border [%]
$ILUC_{dom\_net}$	Net ILUC occurring within country itself [ha]
$ILUC_{GHG}$	CO_2 emissions related to ILUC [g CO_2 MJ^{-1} of biofuel]
$ILUC_{GHG\_net}$	Net GHG emissions caused by ILUC and EFF_{GHG} [g CO_{2eq} MJ^{-1} of biofuel]
$ILUC_{glob\_net}$	Net ILUC spilling across border and occurring elsewhere [ha]
I_{market}	Indicator for domestic/global market linkage
I_{luc}	LUC indicator for country of interest
MCF	Methane correction factor (0.2; IPCC 2006a)
NEA	Net expansion area for biofuel production [ha]
p	Probability value
R^2	Coefficient of determination

Y_B	Average yield for agricultural area in baseline [t ha^{-1}]
y_B	Average annual growth rate of average yield in baseline [%]
y_{BF}	Biofuel yield per unit of biofuel feedstock [MJ t^{-1}]
y_C	Additional annual growth rate of average yield through compensation measure [%]
y_{SB}	Average annual growth rate of average yield in biofuel scenario [%]
X_B	Amount of biomass produced on A_B [t]

Units

EUR	Euro (European currency unit)
d	Day
g	Gram
ha	Hectare
GJ	Gigajoule
kg	Kilogram
J	Joule
kWh	Kilowatt hour
m^3	Cubic meter
MJ	Megajoule
MW	Megawatt
t	Ton
L	Liter
MKW	Malawian kwacha (Malawian currency unit)
R$	Brazilian real (Brazilian currency unit)
USD	US dollar (currency unit)
yr	Year
%	Percent

1 Introduction

Indirect land-use change (ILUC) has emerged as one of the most heatedly debated aspects of the European Union's (EU) plans to expand biofuel demand. ILUC is defined as a displacement effect that occurs when biofuel feedstock cultivation expands onto existing agricultural land such that new agricultural land is required in order to replace the displaced agricultural goods. CO_2 emissions released as a consequence of such end land-use changes (LUC) are debited to the additional biofuel production.

The EU originally promoted biofuels in order to reduce greenhouse gas (GHG) emissions in the mobility sector. The potential for ILUC to induce even greater GHG emissions than those linked to the production of fossil fuels therefore leads one to question whether such a policy of promoting biofuel consumption still complies with its primary purpose. Numerous studies on ILUC quantification have been published within recent years; the results prove that the existence and relevance of ILUC is no longer questionable. Knowledge gaps, however, still exist concerning the potential impact of regional factors on ILUC. Furthermore, the particular effect of regionally specific ILUC mitigation measures with regard to GHG emissions has not been investigated in detail. Mitigation or compensation measures are defined as measures that are implemented specifically to reduce the ILUC impact of biofuel expansion. Typical examples include measures that increase the agricultural yields; such measures have a positive effect on land demand, but they may also have a negative impact with respect to GHG emissions, e.g. in cases of additional fertilizer applications. Specific knowledge of the net effect of such compensation measures is lacking.

The goal of this dissertation is to contribute to our knowledge of ILUC quantification and mitigation by adopting a case-study approach and applying it to specific regions of the world. This dissertation is a part of the interdisciplinary junior research group “Fair Fuels”, which is generously funded by the German Federal Ministry of Education and Research (BMBF). In the course of this project, studies on the sustainability of biofuel production were conducted in South America, Sub-Saharan Africa, and Europe. Included are three specific case studies that were conducted as a part of this dissertation in order to demonstrate application of the new ILUC case-study approach: additional sugarcane ethanol production in Malawi and in Brazil and additional wheat ethanol production in Germany. In order to address the objectives presented here, the case studies focus on the relevance of regional factors concerning the extent of ILUC, on identifying regionally specific measures to reduce ILUC, and on calculating the resulting net GHG emissions.

1.1 Background information

The goal of reducing GHG emissions in the mobility sector has been an important motivating factor for the worldwide expansion of biofuel production. In the EU this has led to a 10% renewable energies quota for final energy consumption in the mobility sector to be achieved by 2020, as mandated in the Renewable Energy Directive (RED) (2009/28/EC). In 2012, the European Commission (EC) published a proposal to amend the original 2009 RED to limit the amount of biofuels produced from oleaginous, starch- and sugar-containing plants to 5% of final energy consumption in the mobility sector (COM 2012); this proposal was the result of a long-term debate about how to best avoid ILUC effects induced by EU promotion of biofuels expansion.

To ensure that biofuels achieve a significant reduction in GHG emissions, the 2009 RED mandated that biofuel's carbon footprint (CF) must be 35% lower than that of fossil fuels – increasing to 60% by 2018; otherwise, biofuels will not be counted towards attainment of the quota (2009/28/EC). Most of the biofuels produced worldwide currently meet the 35% objective, and potentially even 60%, compared to fossil fuels – if LUC are not considered (Fritsche et al. 2010a).

The CF of biofuels, however, worsens significantly if emissions induced by direct land-use change (DLUC) and ILUC are taken into account (Fargione et al. 2008; Fritsche et al. 2010b). DLUC is defined as the conversion of land not previously used for crop production into land cultivated for biofuel feedstock. ILUC, as already mentioned, is merely a displacement effect. The hypothesis behind ILUC is that when a specific crop is displaced, its market price will increase and farmers will then opportunistically react by placing new land areas into agricultural production. Because of the global nature of such markets, ILUC can occur anywhere in the world, not only in those countries where biofuels are being produced (Plevin et al. 2010).

While there is a recognized method for the calculation of GHG emissions from DLUC, the quantification of ILUC is controversial. In 2007 and 2008, in a context of increasing food prices, ILUC linked to biofuel expansion became a topic of public discussion.

In 2009 the RED mandated that the EC “develop a concrete methodology to minimize greenhouse gas emissions caused by indirect land-use change” (2009/28/EC, 25) and investigate “the inclusion of a factor for indirect land-use changes in the calculation of greenhouse gas emissions” (2009/28/EC, 25). As a consequence of such political pressures, but also of a growing interest in research into LUC issues, a number of ILUC studies have been published in recent years (e.g. Searchinger et al. 2008; Al-Riffai et al. 2010; Laborde 2011; Wicke et al. 2012; Finkbeiner 2013).

To quantify ILUC-induced GHG emissions is a highly complex matter, given that such effects are tied to global market dynamics. Two basic approaches to quantifying ILUC have been developed in recent years: economic models, i.e. partial or general equilibrium models adjusted for the calculation of ILUC (e.g. Searchinger et al. 2008; Al-Riffai et al. 2010; Laborde 2011), and deterministic or descriptive-causal models, which attempt to estimate ILUC based on a set of simplified assumptions (e.g. Bauen et al. 2010; Fritsche et al. 2010a). Furthermore, regional models, which can be either economic or deterministic models, focus on specific local conditions and attempt to take into account regional influences on ILUC (Lahl 2010). Although output variability has decreased in recent years, the results of these models, expressed as ILUC CO_2 emission factors for specific types of biofuels, still vary considerably between studies.

Despite this variability, the proposal to amend the EC’s 2009 RED does introduce a reporting requirement for ILUC factors using estimates based on the economic modeling of grains and other starch-containing feedstocks (12 g CO_2 MJ^{-1} of biofuel), sugar-containing feedstocks (13 g CO_2 MJ^{-1} of biofuel), and oleaginous feedstocks (55 g CO_2 MJ^{-1} of biofuel). The EU member states are obligated to include these when reporting their GHG savings (COM 2012); however, the factors do not have to be included in the mandated biofuel CF reduction as compared to fossil fuels.

By limiting the application of ILUC factors to reporting, the EC avoids mixing attributional and consequential life cycle assessments. The attributional life cycle assessment (ALCA) is a method to calculate the environmental impact of a product based on “business-as-usual” scenarios, meaning that current practices are used to describe the life cycle inventory. Consequential life cycle assessment (CLCA) makes it possible to calculate potential changes in a system, such as an expansion of biofuel feedstock cultivation, making it possible to also account for indirect effects such as

ILUC in the assessment. The CF of biofuels is usually calculated by means of an ALCA, whereas ILUC is integrated in the CLCA, mostly by means of economic modeling. ILUC, however, is in every case the DLUC of another agricultural activity. Since DLUC is already part of the normal CF, calculating CO_2 emissions due to DLUC for all agricultural products and ILUC for biofuel feedstock expansion will result in double counting of LUC-induced emissions. This poses the question of how to avoid double counting of LUC-induced emissions when broadening the scope of the CF – a question that has not yet been properly addressed in the scientific debate.

1.2 Knowledge gaps and research focus

Despite intensive research activities over the past five years, there still remain substantial gaps in our knowledge of how to best quantify and reduce ILUC:

1. Although the EC has acknowledged economic models to be the most sophisticated approach to ILUC calculation, the modelers themselves have regularly noted the limitations of such approaches; at the same time, deterministic models are often criticized for not exhibiting the necessary complexity. A globally accepted and standardized method for ILUC calculation does not yet exist.

2. Existing ILUC-quantification approaches vary in the degree to which detailed regional information is considered (if at all). A question that has not been answered yet is whether regional ILUC factors for specific biofuels can be derived and whether these values would substantially differ.

3. Our knowledge about regional factors or characteristics that influence ILUC and regionally specific measures for ILUC mitigation is still limited, the reason being that until now only a few studies have used case studies to analyze ILUC factors, identify the regional characteristics that influence those factors, or identify current or potential activities for avoiding ILUC.

4. There is also a lack of knowledge about the specific consequences of ILUC mitigation measures with regard to GHG emissions. An increase in productivity is one way to reduce ILUC, but this measure is often accompanied by an application of greater amounts of fertilizer. Thus it is necessary to consider the extent to which

an intensification of farming leads to additional GHG emissions and how net ILUC factors would change as a consequence.

5. Emissions from ILUC are presently fully allocated to the expanding biofuel, thus disburdening the agricultural activities that directly displace natural ecosystems; however, such an approach may lead to a free-rider effect or to double counting (if DLUC was calculated for every product). In order to avoid both, the CO_2 emissions from the final LUC could be allocated to those agricultural activities responsible for the final LUC – be it directly or indirectly. Studies on ILUC have not yet addressed whether and how environmental impacts from LUC could be allocated to the expanding biofuel crop and to the crop directly displacing the natural ecosystem.

This dissertation addresses all five of these aspects. Until now, assessments of ILUC have been limited to GHG emissions and their impact on the CF of biofuels. LUC, however, can considerably influence biodiversity and other environmental impact categories. Whenever a new methodology for ILUC quantification is being developed, as is the case here, it is preferable to focus on the least complex environmental impact; therefore, the focus of the dissertation is on GHG emissions. Broadening the scope of ILUC assessment to include other impact categories should be the next step. The dissertation furthermore addresses feedstock cultivation, which is where ILUC effects are incurred, and industrial biofuel production. Given the focus on ILUC, biofuel end use (in the engine) is considered to be beyond the scope of this study.

1.3 Objectives and hypotheses

In an effort to address the above-mentioned knowledge gaps, this dissertation is guided by the following overall objectives:

1. To develop a case-study approach to quantifying regional and biofuels-specific ILUC factors, i.e. ILUC-induced GHG emissions per MJ of biofuel (chapter 4)

2. To estimate ILUC-induced GHG emissions from additional sugarcane ethanol production at specific sites in Malawi and Brazil and from additional wheat ethanol production in Germany (chapter 5)

3. To identify regionally specific ILUC mitigation measures for the three case studies and quantify their potential to reduce ILUC *as well as* quantify the GHG emissions caused by their implementation (chapter 5)

4. To calculate the CF of sugarcane ethanol production at specific sites in Malawi and Brazil and of wheat ethanol produced in Germany and to identify optimization measures (chapter 5)

5. To analyze input-parameter uncertainty and the sensitivity of the results on ILUC factors to the variability of specific input parameters and to calculate the potential ranges of ILUC-induced GHG emissions in order to assess the degree to which regional ILUC factors significantly differ (chapter 6)

6. To address the questions of whether and how LUC-induced emissions can be allocated between expanding agricultural activities and those which directly displace natural ecosystems, and to analyze the consequential effect on ILUC factors (chapter 6)

These objectives are intended to particularly contribute to our knowledge of ILUC caused by additional biofuel production at specific sites as well as the development of potential compensation measures for reducing ILUC. Behind these objectives looms the overall question of whether a regionalization of ILUC quantification is reasonable and can provide useful results. The following five hypotheses are tested:

Hypothesis 1: Sugarcane area expansion in the case-study regions in Malawi and Brazil and wheat area expansion in the case-study region in Germany, for the purpose of additional ethanol production, lead to ILUC and thus to additional GHG emissions that can be detected by means of the ILUC case-study approach.

Hypothesis 2: If regionally specific factors are considered in the quantification of ILUC and the related GHG emissions, as in the ILUC case-study approach, these regional factors will significantly influence biofuel-specific ILUC factors.

Hypothesis 3: GHG emissions due to ILUC occurring as a consequence of sugarcane expansion in Malawi and Brazil and wheat expansion in Germany, for the purpose of additional ethanol production, are lower than the default value for the

CF of fossil fuels (83.8 g CO_{2eq} MJ^{-1} of fuel); biofuels thus potentially can still yield lower GHG emissions as compared to fossil fuels.

Hypothesis 4: Regionally specific ILUC compensation measures reduce the overall demand for agricultural land; however, they produce additional GHG emissions at the same time. If both effects are considered, the specific compensation measures identified in the case studies will still lead to a net GHG reduction.

Hypothesis 5: If CO_2 emissions from the final natural ecosystem conversion are allocated between indirect and direct drivers of the final LUC, ILUC-induced CO_2 emissions will be significantly lower than if CO_2 emissions are, as is commonly done, entirely debited to the indirect driver biofuel feedstock expansion.

1.4 Dissertation structure

The objectives and hypotheses mentioned in the previous chapter are addressed in the subsequent eight chapters as follows:

Chapter 2 provides general background information and a literature review of relevant topics; these include, in particular, methodological issues with carbon footprinting, ILUC as it relates to biofuels production, existing knowledge on ILUC mitigation measures, and existing approaches to determining GHG emissions linked to ILUC.

Chapter 3 introduces a set of criteria that ILUC-quantification models should fulfill. Existing ILUC-quantification approaches are analyzed as to whether they meet these criteria, thus revealing still existing knowledge gaps. Using these results, a new case-study approach that overcomes some of these weaknesses is derived (chapter 4).

Chapter 4 introduces the methodologies used to achieve the objectives cited above. The methodologies include a newly developed bottom-up case-study approach to quantifying ILUC induced by biofuel feedstock expansion in specific case studies, a specification for product carbon footprinting to be applied as a part of the case studies, further specifications for choosing appropriate case-study countries, and the procedural methodologies of the case studies themselves.

Chapter 5 presents the results of three case studies on additional ethanol production in Malawi, Brazil and Germany. The case studies each include a characterization of the respective country, containing information about biofuel production, LUC, and economic parameters; a quantification of ILUC-induced GHG emissions (best estimate); an analysis of potential ILUC mitigation measures; and a CF calculation for ethanol. The results are compared to and contrasted with existing research studies.

Chapter 6 provides a sensitivity analysis with regard to the ILUC factors calculated by means of the case-study approach. It also deals with how to account for compensation measures and how to allocate LUC-induced CO_2 emissions between expansion of agricultural activities and those involving the direct conversion of natural ecosystems. Finally, the limitations and strengths of the case-study approach with regard to the criteria presented in chapter 3 and the potential for combining this approach with top-down approaches, in particular economic models, are discussed.

Chapter 7 compares the case-study results on ILUC due to ethanol production at specific sites in Malawi, Brazil and Germany, and includes consideration of the CF of ethanol and existing optimization potentials. The knowledge gained through the sensitivity and uncertainty analyses allows an evaluation of the robustness of the results. In this chapter the hypotheses are evaluated and the findings discussed and reviewed in the context of the current relevant literature.

Chapter 8 concludes with a summary of the findings and limitations in this work as well as the proposal of further research questions concerning ILUC quantification and mitigation.

2 Literature review

2.1 The CF of biofuels and indirect effects

2.1.1 Methodological issues with carbon footprinting and LCA

The topic of climate change mitigation has drawn ever greater attention over the last two decades. Governments wanting to establish mitigation policies require GHG emission figures that are linked to products, corporations, and countries' overall economic activities. This need has led to the concept of carbon footprinting – a simplified LCA method focused on the global warming potential (GWP) (Finkbeiner 2009).

Several guidelines have been published in recent years in order to standardize carbon footprinting and LCA in general. One of the earliest efforts to standardize carbon footprinting, PAS 2050, was introduced by the British Standards Institution in 2008 and later revised in 2011 (BSI 2011). The GHG Protocol, a multi-stakeholder partnership, similarly aims to develop internationally accepted GHG accounting standards. As a part of the GHG Protocol, the World Resources Institute and the World Business Council for Sustainable Development published the "Product Life Cycle Accounting and Reporting Standard" (WRI and WBCSD 2011). The working group TC 207 of the International Organization for Standardization (ISO) is currently developing a method ("Carbon Footprint of Products") in order to further the international standardization of carbon footprinting. Finally, the International Reference Life Cycle Data System (ILCD) Handbook published by the Joint Research Centre of the EC (JRC 2010) and the "product environmental footprint (PEF) guide" from the EC contain information on whether and how to include ILUC in LCA and in the PEF (COM 2013a). The PEF guide was only available as a consolidated draft at the time this dissertation was completed; the final PEF guide may therefore deviate slightly from the information reported here.

In order to calculate the carbon footprint (CF), all GHG emissions are converted using gas-specific conversion factors to an aggregated value of CO_2-equivalents (CO_{2eq}), which represent the total GWP (Baldo et al. 2009). The GHG Protocol calls for the inclusion of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and the fluorinated GHGs in CF calculations. In addition to these GHGs, regulated by the Kyoto Protocol (UN 1998), other synthetic halocarbons such as halons and chlorofluorocarbons are identified as relevant GHGs in the Intergovernmental Panel on Climate Change (IPCC) report from 2007 (Le Treut et al. 2007). As established in the GHG Protocol, these gases can but do not necessarily have to be accounted for (WRI and WBCSD 2011).

While the product CF already is popular in product labeling, various criticisms and concerns about open methodological issues have been raised within the scientific community (Finkbeiner 2009; Schmidt 2009). Although the process of CF standardization has made significant advances in recent years, some of these concerns are still valid today, with the major criticism referring to the distinctive character of the CF – the reduction to a single impact category. This reduction makes the CF less expensive, easier to understand and work with than a comprehensive LCA. While there is no question that the CF is not intended to achieve the LCA principle of comprehensiveness, it bears the risk that consumers relying upon it will prefer products with a low footprint without being aware of other environmental burdens (Finkbeiner 2009).

According to ISO 14040/44 (2006), the ILCD Handbook (JRC 2010), the GHG Protocol (WRI and WBCSD 2011), and the PEF guide (COM 2013a), all life cycle stages, including extraction of raw materials, production, distribution, usage and end of life are to be included in LCA and CF calculations. However, the definition of usage profiles is rather complicated given that emissions in the usage stage depend on how and where a product is used. Inasmuch as countries or even individual regions, for example, will have divergent electricity mixes, GHG emissions related to the usage phase necessarily differ from country to country or even region (Schmidt 2009).

Another criticism relates to the wide range of results that are possible; a possibility that is obscured by the labeling of the product with a specific value (Schmidt 2009), or, as is the case with the RED, the default value provided for a specific biofuel. The high degree of variability originates with the varying assumptions made regarding the choice of technology and end-of-life management. In a scientific context, it is therefore recommended that various scenarios be calculated in order to cover various possible results (Schmidt 2009). According to the GHG Protocol, companies must report on uncertainty and methodological choices in order to allow robustness checks of their CF numbers (WRI and WBCSD 2011). The PEF guide even requires robustness checks, including a sensitivity analysis to be conducted in order to assess the extent to which methodological choices influence the final results (COM 2013a).

The CFs of products that include a cultivation stage are generally characterized by a comparatively high uncertainty given that direct GHG emissions from land use show a high variability (Hirschfeld et al. 2008). This high variability is mainly due to the fact that soil emissions, for instance N_2O emissions due to nitrogen (N) fertilizer application, are strongly dependent on parameters such as temperature, humidity, and type of soil (UBA 2007). The IPCC (2006b) assumes that on average 1% of the overall applied N is released as N_2O emissions. According to Hoffmann et al. (2001), on permanent pastures N_2O emissions average between 0.06% and 1.1 % of the applied N fertilizer. Smith and Dobbie (2002, quoted from Leick 2003), however, found much higher N_2O emissions on pastures, between 0.3% and 7.1% of the applied N fertilizer. Because of the high GWP of N_2O, such variability in the input parameters significantly influences the CF of agricultural products.

A typical challenge in both LCA and CF analyses is the setting of appropriate system boundaries. Whether DLUC and ILUC should be included within the scope of CFs and LCAs is a controversial question with regard to system boundaries. GHG emissions arising from DLUC are explicitly to be included in CF and LCA calculations according to the PAS 2050 (BSI 2011) and the PEF guide (COM 2013a), and may be included in the CF according to the GHG Protocol (WRI and WBCSD 2011). The ISO 14040/44 (2006) and the ILCD Handbook (JRC 2010) do not explicitly address the topic of DLUC, but its assessment is generally in line with their provisions.

The question of whether the ILUC impact may or even should be assessed as a part of the CF and LCA is even more difficult to answer with any assurance. ISO 14040/44 does not include a provision or recommendation with regard to the assessment of indirect effects; however, implicit in the standard is the request that if any one indirect effect is to be assessed that all indirect effects be included, as well as the request that the same concept be applied to all products (Finkbeiner 2013).

The ILCD Handbook identifies ILUC as being a topic of CLCA; therefore, if ILUC is considered, the provision on consequential modeling is to be applied (JRC 2010). CLCA in general deals with the prospective environmental consequences of changes in a product system. A CLCA looks at the market effects a product unit provokes within its own and other sectors and the environmental impact that accompanies these changes. Given that the CLCA considers consequences in other sectors, the methodology requires information about economic or market mechanisms such as elasticities of supply and demand. Models that can be used for analyzing market effects include computable general equilibrium (CGE) models and partial equilibrium (PE) models (Lundie et al. 2007). Typical application areas for CLCA are product development and public policy-making (Weidema 2003).

In contrast, ALCA, which is the standard LCA practice, uses average market data that is measureable and fact-based. ALCA is not concerned with market mechanisms or changes over time. As the available data is often generated in previous years, ALCA frequently is also referred to as a descriptive or retrospective LCA (Weidema 2003; Lundie et al. 2007). Typical application areas for ALCA are hot-spot identification, product declaration, and generic consumer information (Weidema 2003). Simply adding ILUC factors to the CF of biofuels would mix ALCA and CLCA.

According to the GHG Protocol, the ILUC impact may also be assessed when a consequential approach is applied (WRI and WBCSD 2011); however, the impact is to be reported separately from the inventory results. The PEF guide correspondingly asks that if ILUC is considered it be reported separately as additional information and explicitly notes that “it shall not be included in the calculation of the greenhouse gas impact category” (COM 2013a, 36). The assessment of ILUC is not included in PAS 2050; the standard in its current version only notes that “the methods and data requirements for calculating these emissions are not fully developed” (BSI 2011, 11) and that ILUC "will be considered in future revisions of this PAS" (BSI 2011, 11).

One general criticism of including only ILUC in the CF of biofuels deals with product comparability: If ILUC is to be added to the assessment of biofuels for regulatory purposes, indirect GHG emissions linked to the provision of fossil fuels should also be considered when determining the fossil fuel benchmark values (Finkbeiner 2013).

Another general methodological issue refers to the data used for CF and LCA calculations. Early on there was an agreement that process-based data linked to technical processes should be used for carbon footprinting (Finkbeiner 2009). Correspondingly, the GHG Protocol (WRI and WBCSD 2011), the PAS 2050 (BSI 2011), and the PEF guide (COM 2013a) all require the use of primary data as far as possible and only rely on secondary data for background processes. The ILCD Handbook, however, recommends identifying the most appropriate data sets for a given case; secondary data may thus be more appropriate for some foreground processes (JRC 2010).

The data sets available and generally used for ILUC assessment are a relevant concern, as it is usually generic data that is being used for ILUC quantification, and the available data sets used in economic modeling are often out-of-date. Finkbeiner concludes that the “quality, the specificity, the level of transparency and the reproducibility of the existing iLUC data […] fail to comply with the requirements of ISO 14044 – unless the scope definition of a particular case study would accept such simplistic and error-prone data quality” (2013, 36).

Finally, allocation of all inputs and outputs is always relevant when a process outputs more than one product or service. Given that allocation has already been an issue in the standardization process of LCA and the issue has not definitively been resolved yet in the scientific context, it does not come as a surprise that there also is debate about proper allocation in carbon footprinting. According to ISO 14044 (ISO 14044 2006), the ILCD Handbook (JRC 2010), the PAS 2050 (BSI 2011), the GHG Protocol (WRI and WBCSD 2011), and the PEF guide (COM 2013a) allocation should be avoided whenever possible, whereby various approaches for avoidance exist.

Use of by-products in the manufacturing process is one possibility, e.g. when heat can be used in the production process. Other possibilities for avoiding allocation are to divide the unit processes into subprocesses that have only one functional output or to extend the system boundaries; however, the identification of a representative alternative production process for each by-product is rather challenging (see Flysjö et al. 2011). When avoidance is not possible, allocation is preferably to be done based on the physical properties of all accruing products (ISO 14044 2006). The lower heating value (LHV) and the mass represent suitable properties for physical allocation. Brankatschk and Finkbeiner (2012), moreover, introduced the cereal unit (CU) allocation as a method particularly suitable for agricultural products. The CU represents the net energy content of agricultural products in relation to feed barley (the CU for animals is based on the net energy of the fodder needed for their breeding) (TLL 2006).Economic allocation based on market values is another approach that can be used, if there are no clear physical relationships applicable (ISO 14044 2006).

Thus, it is clear that much like LCA various methodological issues pertaining to carbon footprinting still remain unresolved. Given that this dissertation focuses on indirect effects currently not included systematically in LCA, it makes sense to use the CF as a reduced form of LCA. Once the inclusion of these effects in the CF is successful and has been accepted, the scientific community should make a greater effort to solve the problem of including indirect effects in the more comprehensive LCA.

2.1.2 The RED methodology for carbon footprinting of biofuels

The EU's 2009 RED includes a 10% target for renewable energies in the overall final energy consumption in the mobility sector to be achieved by 2020 (2009/28/EC). In order to guarantee a sustainable biofuel production, various environmental criteria were established. The main criterion is an obligatory GHG savings vs. fossil fuels of at least 35%, increasing to 60% in 2018. In order to establish a basis for comparability, the RED includes a standardized methodology for how CFs are to be calculated in the scope of certification. The following paragraphs briefly describe the RED methodology, as it partly includes more specific provisions and instructions than the standards presented in the previous chapter.

The methodology refers to direct emissions from feedstock cultivation, extraction of raw materials, industrial processing (including emissions from waste), transportation, distribution, and fuel use. Emissions from fuel use, however, are set to zero (2009/28/EC), although blending fossil gasoline with ethanol can affect an engine's performance and the emissions released during combustion. Information and data about this topic can be found in Wang et al. (1999) and Al-Hasan (2003).

The overall emissions are expressed in g CO_{2eq} MJ^{-1} of biofuel. In order to calculate the CO_2 equivalence, the following specific characterization factors are used: CO_2 = 1, N_2O = 296, CH_4 = 23 (2009/28/EC). The IPCC, in contrast, recommends using slightly higher values (N_2O: 298, CH_4: 25) (Forster et al. 2007).

Emission savings from carbon capture and geological storage, carbon capture and replacement, and from excess electricity from cogeneration are to be included according to the RED 2009. While emissions released by the production of chemicals that are used in the cultivation stage are to be considered, emissions from the manufacture of machinery and equipment are not included (2009/28/EC).

The methodology also includes emissions from DLUC that occurred subsequent to the reference year 2008. Emissions from carbon stock changes caused by DLUC are to be calculated by distributing the overall emissions over 20 years. A specific bonus of 29 g CO_{2eq} MJ^{-1} of biofuel is applied when feedstock cultivation takes place on severely degraded or heavily contaminated land. Emissions from ILUC are currently not being included in the RED methodology. The RED 2009, however, mandated that the EC investigate the inclusion of an ILUC factor in the calculation of greenhouse gas emissions (2009/28/EC, 25).

In the case of by-products, emissions are to be allocated on the basis of the products' energy content. The reference value for fossil fuels (the fossil fuel comparator) is drawn from the latest available average emissions from the fossil part of petrol and diesel marketed in the EU; a default value of 83.8 g CO_{2eq} MJ^{-1} of fossil fuel can be used if no data is available (2009/28/EC).

Studies conducted within recent years show that most biofuels will meet the objectives to reduce GHG emissions by 35% or 50% vs. fossil fuels if LUC are not considered (Menichetti and Otto 2009; Fritsche et al. 2010a). Several studies, however, have already proven the sensitivity of the results with regard to methodological decisions (Gnansounou et al. 2009; Cherubini 2010). Gnansounou et al. (2009) and Cherubini (2010) particularly underscore the relevance of LUC for the CF by citing studies from Fargione et al. (2008) and Searchinger et al. (2008). These authors demonstrated for the first time that both DLUC and ILUC are crucial for the CF of biofuels and can lead to even greater GHG emissions than those released by the supply of fossil fuels. Searchinger et al. (2008) initiated – by pointing out the crucial impact of ILUC – a heated scientific and political debate about whether and how indirect effects should be integrated in carbon footprinting.

2.1.3 Indirect effects related to biofuels production

Although there have been many discussions, reports, and scientific papers on indirect effects with regard to biofuels (Dale 2008; Gnansounou et al. 2008; Searchinger et al. 2008; Blanco Fonseca et al. 2010; Edwards et al. 2010; Fritsche et al. 2010a; Lahl 2010; Bowyer 2011; Laborde 2011; Djomo and Ceulemans 2012; Broch et al. 2013), the term "indirect effects" has not yet been officially defined.

Within the context of the LCA, emissions generated in the upstream product chain are sometimes referred to as indirect environmental impacts (Fritsche et al. 2006). Such emissions are generally included in LCA and CF as they are directly linked to materials or processes that are required for the manufacturing of the product of interest (Fritsche et al. 2006). According to the RED, some of the emissions generated in the upstream chain are to be integrated (e.g. those linked to agrochemicals) and some excluded (e.g. those linked to the manufacture of buildings) (2009/28/EC).

Within the context of bioenergy, Ros et al. (2010) defined indirect effects as "effects that are caused by the introduction of a bio-energy product, but cannot be directly linked to the production chain" (Ros et al. 2010, 5). This definition, however, allows for several interpretations and various system boundaries.

Delzeit et al. (2011) emphasized changes in market prices of various products as the link between biofuel feedstock cultivation and ILUC, which by this definition then becomes a market effect. Originally applied solely to ILUC, this definition could also be extended to indirect effects in general, given that alongside ILUC other indirect effects can and do occur related to changing market prices, as the examples in the following paragraphs show. However, although most of the ILUC models refer to the price effect of biofuel feedstock expansion, the reality is that ILUC can occur without this price effect occurring: for instance, when displaced farmers generate new agricultural land in order to cultivate the food crops for their own sustenance.

ILUC: Most scientists accordingly characterize and define ILUC in the following terms: The conversion of agricultural fields to biofuel crops leads to a displacement of existing food or fodder crops, resulting in an overall decrease in production. The reduced availability of these displaced crops thus leads to increased market prices (e.g. Searchinger et al. 2008; Fritsche et al. 2010a; Delzeit et al. 2011), and the resulting higher prices act as an incentive for farmers or companies to convert additional land area to agricultural production (see Figure 2.1). ILUC can thus be defined as DLUC "for food production incentivized by the cross-price effects of an increased production of biofuel feedstock which then translate into additional demand for unused land areas" (Delzeit et al. 2011, 2). When natural ecosystems such as primary forest, peat bogs, or grassland are converted to arable land, the resulting LUC is accompanied by considerable GHG emissions (Fargione et al. 2008); a consideration of ILUC effects is thus crucial for the biofuels CF (Searchinger et al. 2008; Laborde 2011; Djomo and Ceulemans 2012).

Efficiency gains: Biofuel feedstock production can also result in efficiency gains. Indeed, another way that agribusiness or farmers might react to higher market prices is by increasing productivity, e.g. by applying more fertilizer or by implementing irriga-

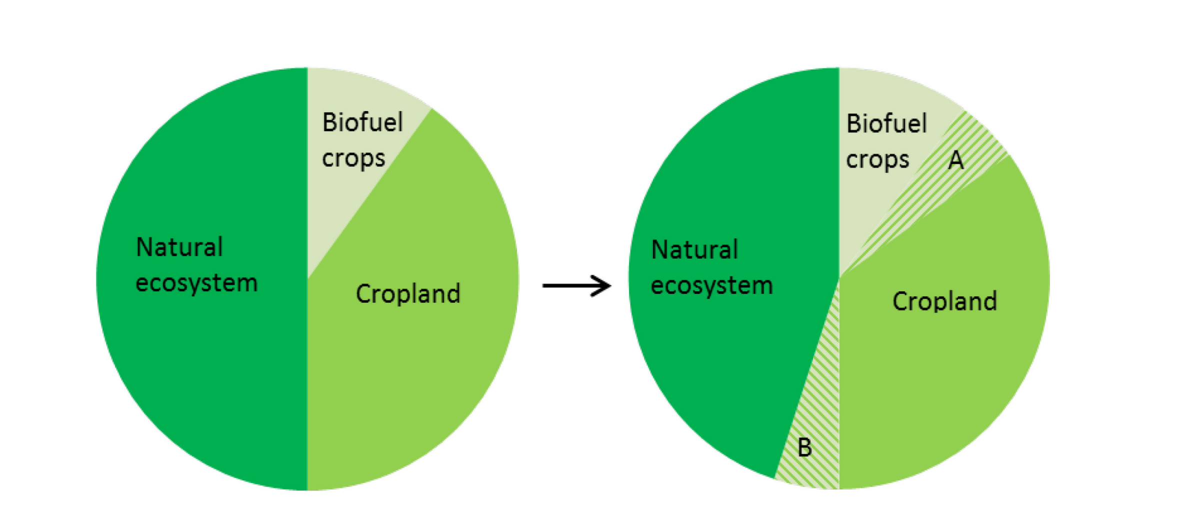

Figure 2.1: Schematic diagram describing ILUC
A represents the amount of additional land required due to expansion of biofuel crops; B represents the natural ecosystem portion converted to cropland as a result of the conversion of cropland to biofuel crops.
Source: Diagram derived, in slightly modified form, from Djomo et al. (2012)

tion systems (cf. Edwards et al. 2010; Fritsche et al. 2010a). In the case of increasing productivity, the net impact on the CF has to be calculated carefully as various effects are simultaneously involved and sometimes working in opposite directions. The application of additional fertilizer, for example, as well as the implementation of irrigation systems in fields previously irrigated by natural precipitation, lead to increased yields and thus avoid ILUC. The production and application of N fertilizer, however, is accompanied by additional GHG emissions; N_2O from soil emissions are especially relevant for the biofuels CF (Crutzen et al. 2007), given the particularly high GWP of N_2O of 298 (Forster et al. 2007, 212). Irrigation can also lead to additional GHG emissions, especially when electrical pumps are used for the water application (Jackson 2009; Najim et al. 2010). The actual amount of GHG emissions obviously depends on the source of electricity used for irrigation (Jackson 2010).

Changing diets: Another potential impact of increasing food or fodder prices occurs when such price changes lead to changes in food consumption patterns (e.g. Plevin et al. 2010; Laborde 2011). The following example readily demonstrates the causal link: The displacement of fodder crops by biofuel may lead to increases in feed prices, with the subsequent result that meat prices begin to rise. Given the particularly high price elasticity of meat (e.g. Thiele 2008 for Germany; Wirsenius et al. 2011 for Sweden), meat consumption is thus likely to decrease. The decrease in meat consumption subsequently reduces the need for fodder crops, potentially freeing up agricultural fields for other purposes, which would indeed be a positive impact on the overall land demand; this positive impact could (in part) compensate the additional land use necessary for biofuel feedstock cultivation and thus reduce ILUC.

Changing demand for fodder crops: Another adverse effect of ILUC can appear with the provision of the by-products that often accrue within the biofuels production chain. Typical by-products include dried distillers grains with solubles (DDGS), which accrue as a by-product of wheat ethanol production (e.g. Kim et al. 2008), and rape or soybean cake, which accrue from rapeseed and soybean biodiesel production (e.g. Lehuger et al. 2009). These by-products can be used as substitutes for other high-protein animal feeds (Taheripour et al. 2010). Once again, a market effect is possible given the increased availability of animal feed on the global market resulting from biofuel production – if demand remains unchanged, feed prices should drop; the result may be a reduction in fodder crop production, thus freeing up agricultural land for other purposes (Lywood et al. 2009a). Taheripour et al. (2010) proved that considering by-products in modeling exercises decreases the LUC effect of increased biofuel production. Djomo and Ceulemans (2012) noted that the potential use of by-products needs to be further addressed in order to improve the understanding of biofuel LUC and ILUC.

Changing total fuel consumption: Rajagopal (2011) identified a linkage between the introduction of biofuels and total fuel consumption. Contrary to what is commonly assumed, biofuels do not simply replace an energy-equivalent amount of fossil fuel. Instead, the adoption of biofuels and other renewable energy sources affects fuel prices and thus total fuel consumption, which may either increase or decrease, depending on the policy regime and specific market conditions (Rajagopal et al. 2011). Measures by which to influence energy prices include subsidies, for example, within the scope of the German Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG), or tariffs that occur in biofuel, agriculture, land use, or trade, as well as in energy policy. Rajagopal et al. (2011) call this type of indirect effect an indirect fuel-use change (IFUC).

2.1.4 Measures to mitigate ILUC

Some of the effects described above can function as mitigation or compensation measures for unintended ILUC in cases where the measures are being promoted with the goal of decreasing the ILUC effect of expanded biofuel production. Examples of potential effects linked to biofuel expansion that can be put to good use include, in particular, efficiency gains and changing diets.

In almost every country opportunities exist for avoiding or at least minimizing ILUC. Measures that increase agricultural productivity may decrease the overall demand for land; such measures can be applicable to all crops, not only a specific biofuel crop (Dehue et al. 2009). Thus, measures that increase overall agricultural productivity in a region, or even a specific plantation, can compensate for ILUC if the implementation is linked to biofuel production. A review of the literature turns up several measures designed either to increase agricultural productivity or decrease the demand for land. Compensation measures intended to increase yields include:

- investments in improved agricultural practices, such as:
  - investing in irrigation systems (Brander et al. 2010)
  - optimizing fertilizer and pesticides inputs (Brander et al. 2010)
  - increasing the stocking rate for grazing animals (Fritsche et al. 2010a)
  - integrating non-bioenergy and bioenergy production (Dehue et al. 2009)
- cultivation of improved seeds and high-yield varieties (Brander et al. 2010) through:
  - breeding of high-yield varieties and improved seeds
  - genetic modification of high-yield varieties.

Compensation measures that decrease the demand for land include, for instance:

- reducing demand for land-use intensive products (Brander et al. 2010), such as meat and dairy, e.g. through implementation of a “meat tax”.

An additional measure for preventing the occurrence of ILUC is the biofuel feedstock cultivation of degraded, marginal or unused land (Wicke et al. 2012). One potential risk here involves land right conflicts, e.g. informal or non-codified property rights

(Dehue et al. 2009). Another obstacle may be a lack of economic feasibility, as can be the case when necessary infrastructure such as access roads is lacking.

Several of the indirect effects described above overlap, as may be the case with the implementation of mitigation measures; thus the calculation of ILUC and the consideration of compensation measures remains a challenging task. The most well-known approaches to quantifying ILUC factors will be described in the following section.

2.2 Approaches to quantifying ILUC factors

The common value for ILUC-induced GHG emissions caused by expanding biofuels production is g CO_2 MJ^{-1} of biofuel. This value can be compared to the “normal” CF of biofuels (without ILUC) and to the CF of fossil fuels; the comparison helps to ascertain whether biofuels still reduce GHG emissions in comparison to fossil fuels when ILUC is considered. However, for a proper comparison with fossil fuels, GHG emissions due to indirect effects from the provision of fossil fuel must be calculated as well. In order to arrive at the target value, one has to quantify ILUC in terms of additionally required area, the related CO_2 emissions, and the amount of biofuel being associated with ILUC. According to the EU biofuels policy, ILUC refers to the additional amount of biofuel (cf. Al-Riffai et al. 2010), as it is assumed that existing biofuel production does not lead to prospective ILUC. The existing extent of biofuel production is thus assumed to be ILUC free, while each MJ of additional biofuel produced on already existing agricultural land is assumed to lead to ILUC.

As indicated in section 2.1.3, ILUC is incurred as a result of fluctuating market prices and global trade flows that are triggered by increasing biofuel feedstock cultivation. Given the mostly global nature of agricultural trade today, the actual location where a natural ecosystem is converted to agricultural land can be far removed from the biofuel feedstock cultivation site (Delzeit et al. 2011); this makes it very challenging to link specific biofuel feedstock cultivation measures to specific LUC.

Along with the adaption and use of economic equilibrium models, several simplified models have been developed in order to calculate ILUC. Simplified modeling is often referred to as deterministic or causal-descriptive modeling. The determination of ILUC can in general include regional information and data to varying extents; some authors refer to this as regional modeling when the spatial resolution is high (e.g. Lahl 2010). Regional models are generally either economic or simplified models.

2.2.1 Economic models

Economic modeling generally works with margin change in a mathematically modeled economic system. Economic equilibrium models consist of equations that define the quantitative relation between supply, demand, and price and a broad database (cf. Di Lucia et al. 2012); they are generally complex and data-intense. The basic assumption is that equilibrium in the economy being studied is achieved when demand equals supply. Markets are normally assumed to be characterized by perfect competition, an idea already formulated by Arrow and Debrue (1954). One can distinguish between two kinds of economic models: CGE models study the entire global economy, while PE models focus on a specific sector such as agriculture. Both types of models are based on linear and nonlinear relations between prices, demand, and production; these relations are characterized by supply and demand elasticities that can be derived from statistic data and historical trends (Nassar et al. 2011).

Economic models, both PE and CGE, have been around for some time, and researchers from various disciplines have constantly been improving and adapting them to new contexts. Such models are typically applied in trade policy, but they are also used in development policy (e.g. Shoven and Whalley 1984; Cardenete et al. 2012) and, as has lately been the case, in bioenergy policy. Beginning around 2007, as concerns about conflicts between increasing biofuel production and the food supply began to increase, researchers in the field of economic modeling started to adapt and develop existing economic models in order to calculate ILUC effects. The first scientific paper on ILUC quantification based on economic modeling was published by Searchinger et al. (2008), who used a PE model to calculate the ILUC effect caused by maize-ethanol production in the USA.

Both PE models (e.g. FAPRI[1], AGLINK[2], IMPACT[2], and CAPRI[2]) and CGE models (e.g. GTAP[2] and LEITAP[2]) have meanwhile been used to project ILUC (Edwards et al. 2010). One of the most important research institutes with regard to ILUC determi-

[1] These acronyms are spelled out in the list of abbreviations on pages x, xi and xii.

nation based on economic modeling is the International Food Policy Research Institute (IFPRI); IFPRI published two studies, in 2010 and 2011, respectively; in the 2010 study CGE models were used for the first time to ascertain LUC impact of the EU's biofuels policy (Al-Riffai et al. 2010; Laborde 2011). Other authors who have applied economic modeling to biofuels LUC quantification are Melillo et al. (2009), Hertel et al. (2010), Kløvepris et al. (2010), Taheripour et al. (2010), Dumortier et al. (2011) (all CGE modeling), Lapola et al. (2010), Havlik et al. (2011) (PE modeling), and Britz et al. (2011) (integrated CGE and PE modeling) (see also Broch et al. 2013).

In order to assess ILUC, CGE and PE models generally take a marginal approach. Initially a baseline scenario is calculated with the model; then in a second step a scenario with a marginal extra demand for a specific biofuel is run (Edwards et al. 2010). Modelers often call the step of calculating the effect of a marginal extra demand for biofuels "giving the model a biofuel shock or policy shock"; this results in a projection of the effects of nationally increased biofuel demand on global commodity markets and on additional land requirements (Edwards et al. 2010).

Given that economic models do not distinguish between feedstocks grown on "new" and those grown on "old" land (Edwards et al. 2010, 13), the results refer only to total LUC, including both DLUC and ILUC (Edwards et al. 2010; Delzeit et al. 2011). In a subsequent step, LUC are mapped to specific land-cover types (e.g. grassland, forest, etc.), based on historical patterns of LUC. Finally, biophysical models are used to project the GHG emissions from land-use conversion (Nassar et al. 2011). A comparison of the two scenarios allows GHG emissions to be attributed to a specific quantity of biofuels, so that the results can be expressed in g CO_{2eq} MJ^{-1} of biofuel. As this value includes emissions from both ILUC and DLUC, adding this directly to the biofuels CF would cause double counting of DLUC (Delzeit et al. 2011). Modelers therefore separate DLUC and ILUC in the qualitative interpretation of the model's results.

The assumptions made in setting up the baseline are crucial for the LUC results from economic modeling. One important assumption refers to the elasticities, especially the so-called transformation elasticity, which characterizes the ease by which land is converted to another type of land use when the prices for agricultural commodities change, and the price elasticities, which indicate how sensitive prices are to supply and demand changes (Broch et al. 2013). Key input parameters, furthermore, are the current and the projected future crops yields, as they determine how much agricultural land will additionally be required (Broch et al. 2013). The manner by which by-products are accounted for also has a crucial impact on the model results. Given that the models differ in how they take into account by-products, the results they provide in terms of LUC differ, as well; in GTAP, for instance, by-products are accounted for by substitution based on relative prices; CAPRI accounts for them by means of physical replacement ratios (Edwards et al. 2010).

A challenge in CGE modeling is creating a consistent dataset. The dataset normally used in CGE modeling is the social accounting matrix (SAM), which describes the transactions and inter-industry value flows between all economic agents within an economy and during a specific accounting period. Given that biofuel sectors are not part of the currently existing SAM and biofuel feedstock are often aggregated, one has to single out these feedstock for LUC calculations (Delzeit et al. 2011).

Economic models can be applied in order to calculate ILUC linked to specific bioenergy feedstock and to specific regional contexts. PE models, for example, have already been used to project ILUC related to maize-ethanol production in the USA (Searchinger et al. 2008) and sugarcane ethanol production in Brazil (Lapola et al. 2010). Britz et al. (2011) found another promising approach by linking a CGE model (GTAP) with a PE model of EU agricultural production (CAPRI).

2.2.2 Deterministic models

Deterministic models are simplified calculations based on explicit assumptions. In contrast to economic models, deterministic models do not model prices, but use assumptions about how the agricultural systems respond to an increase in biofuel feedstock production. In the process, they use cause-and-effect logic to describe system behavior (Bauen et al. 2010). This means an additional biofuel demand has an impact on the broader agricultural system, which has an impact on LUC, which leads to GHG emissions. Assumptions used to describe the market reactions and LUC are mainly based on an analysis of historical data on trade, land use, and LUC (Nassar et al. 2011). Deterministic models are usually realized with a spreadsheet calculator (e.g. Bauen et al. 2010; Fritsche et al. 2010a; Plevin et al. 2010).

A well-known example of a deterministic model is the ILUC factor developed by the Institute for Applied Ecology (Öko-Institut), in Germany. The objective behind their approach was to present a methodology for including potential GHG emissions from

ILUC in regulatory policies for biofuels. The model draws on statistical trade data as well as various assumptions. A crucial assumption in this model is that ILUC can be estimated by looking at the exported products relevant for the bioenergy sector, e.g. soy and palm oil. Calculations are based on 2005 product exports, but for the purpose of simplification, the authors only consider the key regions Argentina, Brazil, the EU, Indonesia, Malaysia, and the USA (Fritsche et al. 2010a).

The authors calculate the area needed to produce these products by using the mass of traded commodities divided by the respective country-specific yields. From the sum of all land use for agricultural exports, each country's proportionate share is derived – the "world mix." Next, additionally needed areas are combined with country-specific assumptions about the specific DLUC associated with the production of the export commodities. Following the application of conversion factors from IPCC, the interim results are then weighted according to each country's share in the "world mix," resulting in an ILUC factor of 270 t CO_2 ha^{-1} or 13.5 t CO_2 ha^{-1} yr^{-1} when allocating the LUC emissions over 20 years (Fritsche et al. 2010a).

These calculations suggest that one hectare of bioenergy feedstock production displaces one hectare of previous production; however, the displacement is assumed to be lower because of further yield increases and the use of so-far unused areas. Assuming average yield increases of 1% per year until 2030, the maximum ILUC factor will only be 75% of the theoretical ILUC factor. The authors suggest three different levels of 25%, 50%, and 75%, as they anticipate that even higher increases in efficiency are possible and assume that a share of the expansion occurs on degraded lands. Figure 2.2 breaks down the level of CO_2 emissions by type of biofuel, country of production, and prior land use. The inclusion of the high level of ILUC emissions means most of the biofuels will not achieve the GHG reductions called for in the RED (Fritsche et al. 2010a).

Plevin et al. (2010) introduced another deterministic model in order to characterize a robust range of ILUC. For this purpose, the authors include four main parameters in a reduced-form model: net displacement factor (NDF – ha of converted land per ha of biofuels), average emission factor (t CO_2 ha^{-1}), production period (yr), and fuel yield (MJ ha^{-1} yr^{-1}). The objective behind this approach was not to determine the most realistic ILUC factors for specific biofuels, but rather to characterize plausible boundaries for ILUC emissions by considering various probability distributions using Monte

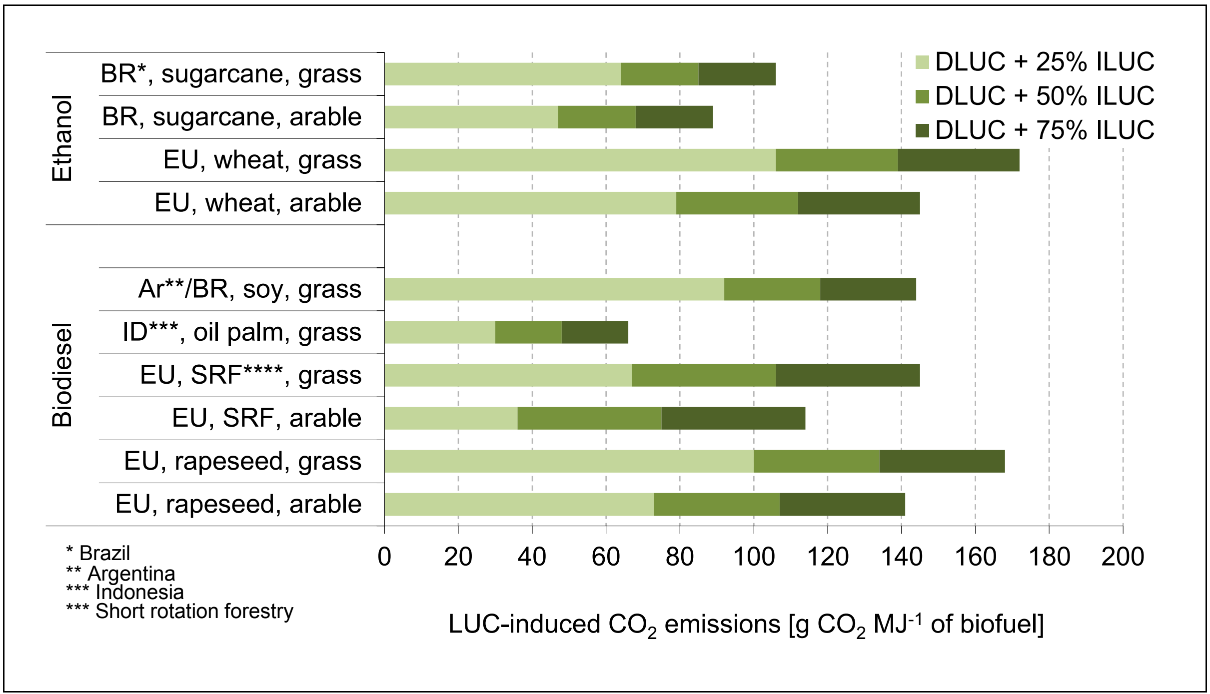

Figure 2.2: DLUC- and ILUC-induced CO_2 emissions (on the basis of a deterministic model)
Source: Figures from Fritsche et al. (2010a)

Carlo simulations. The authors conclude that existing uncertainties will not be reduced any time soon, and an accurate prediction of ILUC emission thus will not be possible. Still, the potential results, in light of the full range of uncertainties, indicate ILUC emissions are likely to be large (Plevin et al. 2010).

Lahl (2010) developed a simplified method on behalf of two German biofuel associations; the work was conducted in response to criticism that other models do not properly consider the effects of state regulation on the global agricultural market, which can take the form of subsidies, customs duties, and trade restrictions such as bans on import and export. The target thus was to include ILUC effects due to domestic trade, which, according to Lahl (2010), is quantitatively more important than global trade and had not been previously considered.

Lahl (2010) suggested the following method for regional modeling: first, the ascertainment of all LUC within a specific country and for a specific period. Country-specific CO_2 emissions ($E^R LUC$) are then calculated for the respective carbon stocks in vegetation and soil, before and after conversion. In order to calculate the share of the various biofuels in total emissions, the change in biofuel production is divided by the change in agricultural production in total and multiplied by $E^{R}LUC$. Next, the portion of total emissions due to DLUC is subtracted, and, the remaining emissions are allocated to the "originator," which can be separate farms or regions. In some cases a correction factor for by-products or transnational effects must be included. To determine whether transnational effects are relevant for a specific country, one looks for a drop in agricultural import levels for recent years and an absolute value of the reduction in agricultural imports higher than the absolute value of the increase of agricultural exports (Lahl 2010). An application of this model is not yet known.

Another deterministic model has been developed by the consulting company E4tech on behalf of the United Kingdom Department of Transport (Bauen et al. 2010). The methodology was tested with five different biofuel feedstocks: sugarcane, palm oil, rapeseed oil, soy oil, and wheat. For each feedstock Bauen et al. (2010) calculated various ILUC factors based on different scenarios and assumptions. The target thus was not to present a central ILUC factor, but to find differences in the ILUC risk between various feedstocks, and to learn more about the uncertainties linked to ILUC. In order to estimate appropriate market responses to a higher demand for biofuels, Bauen et al. (2010) used a statistical analysis of historical trends, a market analysis, expert inputs, and a literature review. The authors concentrated their analysis on the market responses to product substitution (substitution of biofuel feedstock in other markets by other suitable products), area expansion, and yield increase.

Where product substitution was found to occur, a substitution ratio between the biofuel feedstock and the substituting product was determined based on the literature and expert interviews; the additional demand for the substituting product and its land-use impact were calculated based on this ratio. A typical substitution effect is the substitution of palm oil when soy oil is being used for biofuel production. Area expansion and yield increase generally occur simultaneously. In order to calculate the area needed for additional feedstock production it is necessary to estimate what portion of the feedstock will be covered by increased yields and what portion will be covered by expansion of agricultural area. Drawing on Lywood et al. (2009b), Bauen et al. (2010) calculated the shares based on the relationship between historic changes in yield and land use for various regions and crops. In order to determine the final displacement, the authors base their calculations on average yields and not marginal yields[2]. This means they assume that the production of a specific non-biofuel crop will require the same area with the additional biofuel production as without it (Bauen et al. 2010).

Overmars et al. (2011) introduced another simplified model based on historical data and explicit assumptions; the model was applied to the biofuel consumption of the EU. Initially, one has to identify which part of the additional biofuel consumption originates from which crop (expressed in TJ); in order to do so for the case of the EU figures on total EU biofuel consumption, the share of EU-produced and EU-imported biofuels, and the feedstock and origin of the feedstock are needed. With the help of the energy yields per hectare (TJ ha^{-1}) for the feedstocks and the respective by-products the net amount of hectares needed for the provision of these crops can be calculated. After the yield increase has been considered, ILUC associated with the biofuel feedstock production is determined by making assumptions on how the displaced crops are cultivated elsewhere; modeled data on the actual land use conversions to agricultural land that took place between 1995 and 2005 are being used in order to describe the final LUC. CO_2 emissions from ILUC are then related to the additional biofuel consumption (g CO_2 MJ^{-1} of biofuel) (Overmars et al. 2011).

2.2.3 Range of results from ILUC modeling

Following presentation of the various approaches to quantifying ILUC and deriving ILUC factors, this section provides an overview of the range of results the different models produce. Djomo et al. (2012) already depicted the range of ILUC-induced CO_2 emissions for ethanol and biodiesel respectively by comparing several studies. Table 2.1 shows the results of Djomo et al. (2012) along with the results of the additional studies presented in the sections 2.2.1 and 2.2.2. Figure 2.3 illustrates the ranges of ILUC for ethanol only as the dissertation focuses specifically on ethanol. The values presented in the comparison vary significantly, from −53 to 327 g CO_2 MJ^{-1} of ethanol and from zero to 1434 g CO_2 MJ^{-1} of biodiesel. Excluding the noticeably high values presented by Lapola et al. (2010) still leaves a range of −53 to 190 g CO_2 MJ^{-1} of ethanol and zero to 204 g CO_2 MJ^{-1} of biodiesel.

[2] The question of whether average or marginal yields should be the basis of the analysis has not been solved yet. Marginal yield, for example, can be lower than average yields based on the assumption that land with high fertility is already in production. In this case the ILUC effect would be higher compared to a calculation with average yields (Edwards et al. 2010).

Table 2.1: Range of ILUC factors of ethanol and biodiesel calculated using various models (in g CO_2 MJ^{-1} of biofuel)
Source: Djomo and Ceulemans (2012, 395), Britz et al.(2011, 106), Laborde (2011, 78)

Publication	Ethanol		Biodiesel		Biofuel		Reference
	Min	Max	Min	Max	Min	Max	
Economic modeling							
Searchinger et al. (2008)	104	111					Djomo and Ceulemans (2012)
Dumortier et al. (2009)	21	118					Djomo and Ceulemans (2012)
Melillo et al. (2009)	181	190					Djomo and Ceulemans (2012)
Al Riffai et al. (2010)	16	79	46	67	16	79	Djomo and Ceulemans (2012)
Hertel et al. (2010)		27					Djomo and Ceulemans (2012)
Lapola et al. (2010)		327	626	1434		1434	Djomo and Ceulemans (2012)
Britz et al. (2011)						42	Britz et al. (2011)
Havlik et al. (2011)	32	34					Djomo and Ceulemans (2012)
Laborde (2011)	4	40	53	92	4	92	Laborde (2011)
Deterministic modeling							
Fritsche et al. (2010a)	0	136	0	164	0	164	Djomo and Ceulemans (2012)
Bauen et al. (2010)	−53	27	6	81	−53	81	Bauen et al. (2010)
Plevin et al. (2010)	21	142					Djomo and Ceulemans (2012)
Overmars et al. (2011)	26	154	30	204	26	204	Djomo and Ceulemans (2012)
Total Range	**−53**	**327**	**0**	**1434**	**−53**	**1434**	

The variability in the results is due to inherent uncertainty in ILUC modeling. As already indicated in previous chapters, uncertainty mainly refers to price elasticities, transformation elasticities, and assumptions with regard to crop yields in the case of economic modeling (Broch et al. 2013). Uncertainty is particularly high as ILUC effects are generally projected into the future; the actual development of these key parameters thus cannot be known. Furthermore, databases used in economic modeling mostly refer to a pre-2010 time frame; it is thus not clear whether conclusions drawn from this data allow for proper description of future situations. In the case of deterministic modeling, uncertainties mainly deal with the validity or true nature of the presumed cause-and-effect relationships. Plevin et al. (2010, 8019) found it unlikely "that modelers will be able to greatly reduce the uncertainty" on how much land has to be brought into agricultural usage in order to produce a specific amount of biofuel

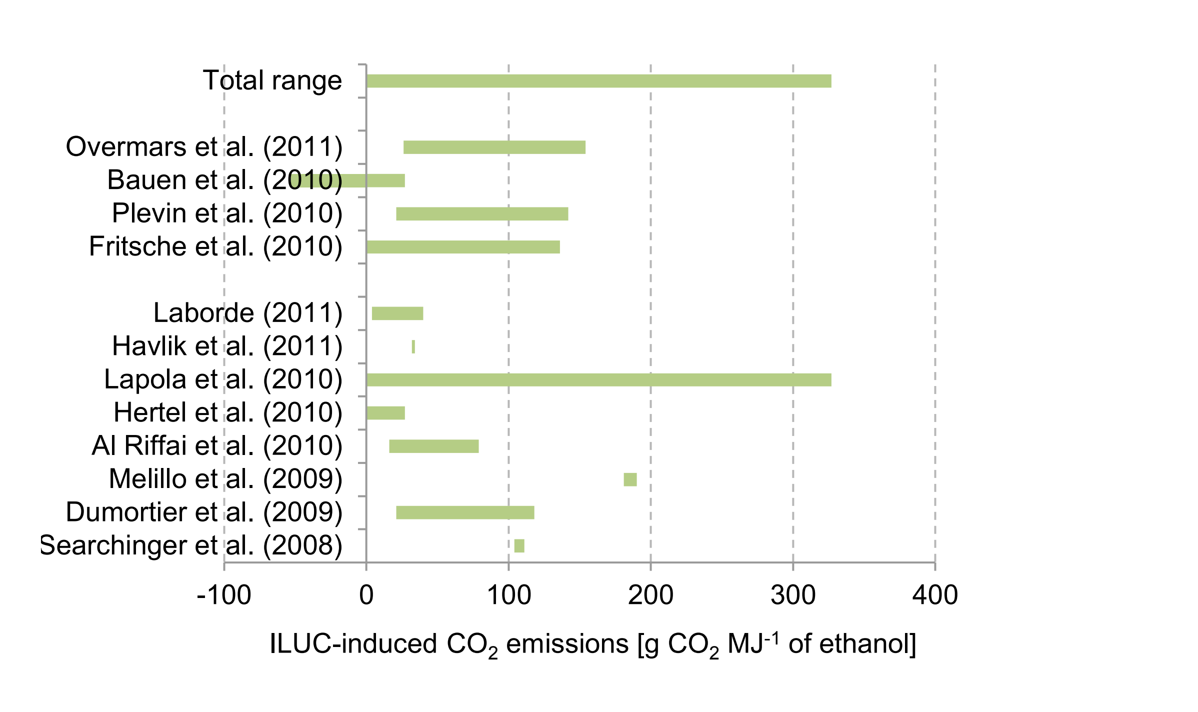

Figure 2.3: Range of ILUC factors of ethanol calculated using various models
Source: Partly based on (Djomo and Ceulemans 2012) (see Table 2.1)

feedstock. Finally the CO_2 emission factors resulting from the final LUC are highly uncertain (Bauen et al. 2010; Plevin et al. 2010).

Plevin et al. (2010) and Overmars et al. (2011) both pointed out that peer-reviewed studies with negative ILUC values, i.e. a positive impact on climate, are not known. Overmars et al. (2011), however, alluded to the possibility of negative ILUC values. Bauen et al. (2010) are the only authors considered here who have actually identified negative ILUC factors; negative values were specifically found for wheat ethanol and occur because of a GHG credit given to DDGS. The models presented here, however, do not allow for consideration of specific mitigation or compensation measures that may be implemented in combination with the biofuel (feedstock) production.

The variations noted here as well as the information provided in the previous chapters make clear that the existing models and approaches and the results gained with them differ significantly. In the following chapter the models presented in sections 2.2.1 and 2.2.2 will be further analyzed with regard to their strengths and weaknesses and the degree to which they fulfill several quality criteria.

3 Analysis of ILUC-quantification models

In this chapter existing approaches to quantifying ILUC will be analyzed with regard to their strengths and weaknesses; the results are used to guide the preparation of a new case-study approach that overcomes some of these weaknesses.

In preparation for the analysis, a set of criteria that each ILUC-quantification method should fulfill were established; the choice of these criteria was based on a review of the literature and the author's own conceptual considerations. The question of which criteria such models should fulfill was further addressed during a scientific workshop on "Quantifying indirect land use change" that was held in the course of the "Fair Fuels" project on April 25, 2012. A total of 28 representatives, representing research institutes, biofuel associations, certification bodies, and environmental non-governmental organizations (NGOs), participated in the workshop. The workshop results further contributed to the development of a comprehensive set of criteria, which were then sorted into three categories: general requirements, ability to account for various indirect effects, and ability to account for regional heterogeneity.

General requirements:

- Level of detail (e.g. in the characterization of the agricultural sector)
- Ability to provide for a sensitivity analysis
- Timeliness of data
- Applicability with regard to data availability
- Applicability with regard to time required for data collection
- Transparency and traceability
- Avoidance of double counting (separation of DLUC and ILUC)

Attention given to various indirect effects:

- Supply of by-products (e.g. fodder crops)
- Efficiency gains (e.g. increase in productivity and in emissions from fertilization)
- Changing diets (e.g. due to changed prices)
- Changing total fuel and energy demand (e.g. due to changed prices)

- Changes in household incomes (e.g. causing a change in product consumption)

Attention given to regional heterogeneity (regionalization):

- Biophysical aspects:
  - Carbon fluxes (above and below ground soil carbon contents)
  - Current and expected productivity (yields)
  - Expected productivity due to the implementation of compensation measures
- Aspects of land use:
  - Amount of unused area in specific regions
  - Regional specification of LUC: Land-cover monitoring or use of statistical data on historic and current land use
  - Regionally available measures to reduce the land demand
- Political, economic and cultural aspects:
  - National legislation with regard to land use (natural ecosystem protection, land use policy) and its enforcement
  - Land tenure and ownership
  - Regional specific management practices
  - Societal preferences (e.g. regarding willingness to cultivate specific crops)
  - Trade incentives and trade barriers

It is useful to analyze the degree to which the various types of approaches fulfill these criteria. Two types of approaches are considered: economic models, CGE as well as PE, and deterministic models. Within the group of CGE and PE models, specific models such as GTAP, LEITAP, FAPRI and IMPACT are not differentiated here as this would require more detailed knowledge and deeper insight into economic modeling. Both groups, however, exhibit characteristic advantages and disadvantages with regard to the set of criteria, and they differ significantly from all deterministic models (see Table 3.1).

A general disadvantage of CGE models is that they do not capture the agricultural sector in the same detail as PE models (Delzeit et al. 2011). Laborde (2011) concedes, for example, that the IFPRI model MIRAGE does not yet capture either multicropping or crop rotation; both, however, can influence land-use patterns significantly. This is precisely the advantage of PE models – that they represent the agricultural sector in greater detail; however, they are not linked to other sectors, thus unlike the case with CGE modeling, interactions with energy prices or fertilizer and chemicals cannot be taken into account.

The level of detail in deterministic modeling strongly depends on the specific approach and the purpose of its development. Fritsche et al. (2010a), for instance, aim to provide a simplified approach that could help to include potential GHG emissions from ILUC in regulatory policies for biofuels. Thus they focused on presenting a readily available, transparent and easy-to-carry-out methodology. By concentrating only on exported biomass products, however, the model is not characterized by a high level of detail. The simplified model of Plevin et al. (2010) also does not aim to capture the agricultural sector in great detail – its purpose was to show the impact of uncertainty on ILUC factors in general. Bauen et al. (2010) and Lahl (2010), however, both aspire to describe market relations as well as regional conditions in greater detail. Lahl's model, however, has not yet been applied to an actual case study.

In principle, all existing models, both economic and deterministic approaches, allow for sensitivity analyses by varying input parameters, or elasticities, in the scope of economic modeling. However, in many studies, sensitivity analyses have not been undertaken or documented. Laborde (2011) reports on the robustness of the IFPRI study's results. He carried out Monte Carlo simulations with several parameters, e.g. the ratio between yield on new cropland and average yields, elasticity of substitution between land and other factors (intensification), and change in intermediate demand price elasticities of agricultural inputs (see Delzeit et al. 2011). However, the author has considered neither the uncertainty in carbon stocks of different land cover types nor the uncertainty of the proportion of different land types converted to cropland; therefore, the real range of results is expected to be significantly higher than documented in the study. Fritsche et al. (2010a) did not present results from sensitivity analyses, but estimated biofuel-specific ILUC factors and their potential range based on rather rough assumptions. Bauen et al. (2010) calculated several scenarios, considering, for instance, differing economic conditions, LUCs, and average LUC CO_2 emission factors. Overmars et al. (2011) also varied several assumptions made in their calculations in order to analyze the variability and to identify the key parameters.

With regard to timeliness of data, the databases used in economic models are often not up-to-date. All CGE models up to 2012 that have used the GTAP database have worked with data for the years 2004/2005; in 2012 the GTAP 8 database was published using the reference years of 2004 and 2007[3]. Given that biofuels production, along with biofuel and feedstock trade, has developed very dynamically, particularly within the last couple of years, there may be market reactions that are not covered within these models. In deterministic models, in which statistical data on LUC is used, the timeliness of data also depends on which data is available. The model of Fritsche et al. (2010a) uses data of the United Nations Food and Agriculture Organization (FAO) for trade of agricultural products in 2005; here, too, a more recent look would be desirable. Bauen et al. (2010) used more up-to-date data. An application of Lahl's model (2010) has not been published; however, it is clear that the timeliness of date would depend greatly on data availability in the specific country.

Nassar et al. (2011) proved the strong influence that the choice of reference year has on the results. Given that deterministic models mainly use statistical data on LUC from previous years in order to forecast the prospective LUC, the extent and type of forecasted LUC depends strongly on the chosen reference years (Nassar et al. 2011). This effect accounts mainly for countries with rather variable LUC rates. Nassar et al. (2011) give Brazil as an example, where the deforestation rate was much higher between 2004 and 2007 than between 2007 and 2009. Depending on the period chosen for the ILUC calculation, ILUC in Brazil would thus be high or low (Nassar et al. 2011). This influence of the choice of reference year on the average CO_2 emission factor is valid for every model that predicts prospective LUC using historical data.

[3] See https://www.gtap.agecon.purdue.edu/databases/v8/default.asp.

Table 3.1: Analysis and comparison of several approaches to quantifying ILUC
+ Model or type of model fulfills the criteria; – model or type does not fulfill criteria.

	CGE	PE	Fritsche et al. (2010a)	Bauen et al. (2010)	Lahl et al. (2010)
General requirements					
Level of detail	low	high	low	high	high
Provision for sensitivity analysis	+	+	+	+	+
Timeliness of data	low	depends	low	high	depends
Data availability	medium	medium	high	medium	medium
Time required for data collection	high	high	low	high	high
Transparency and traceability	–	–	+	+	+
Separation of DLUC and ILUC	–	–	+	+	+
Ability to consider various indirect effects					
By-products	generally possible	generally possible	allocation	system expansion	allocation
Efficiency gains	generally possible	generally possible	+	+	indirectly
Changing diets	generally possible	generally possible	–	–	–
Changing fuel / energy demand	generally possible	generally possible	–	–	–
Changing household income	generally possible	generally possible	–	–	–
Ability to consider regional heterogeneity					

	CGE	PE	Fritsche et al. (2010a)	Bauen et al. (2010)	Lahl et al. (2010)
Carbon fluxes	generally possible	generally possible	IPCC	Winrock	IPCC
Current productivity	generally possible	generally possible	FAOSTAT	FAOSTAT	best available data
Expected productivity	generally possible	generally possible	vague estimation	more precise estimation	indirectly
Potential productivity	generally possible	generally possible	vague estimation	partly	–
Unused area	generally possible	generally possible	vague estimation	partly	possible
Specification of LUC	CET	price elasticities for land demand	statistical data	statistical data	statistical data
Land-cover monitoring	generally possible	generally possible	–	–	possible
Statistical data on LUC	generally possible	generally possible	+	+	possible
Measures to reduce land demand	–	–	–	–	–
Legislation towards land use	–	–	–	–	–
Land tenure and ownership	–	–	–	–	–
Specific management practices	–	–	–	–	–
Societal preferences	–	–	–	–	–
Trade incentives and barriers	+	+	–	+	+

The time required for data collection and preparation is assumed to be substantial for all types of models. For CGE modeling much time is devoted to data disaggregation and preparation. When applying deterministic approaches, more time is needed for data collection. The model of Fritsche et al. (2010a) represents an exception, given that it largely draws on export data provided by FAOSTAT. As a matter of course, all models that aim to account for regionally specific data require more time in situations when several case studies are to be carried out.

Low traceability and transparency for those not familiar with economic modeling in general, and the specific model in particular, are disadvantages of PE and CGE models; Wing (2004) characterizes economic models as black boxes with output values that cannot be “meaningfully traced to any particular features of their database or input parameters, algebraic structure, or method of solution” (Wing 2004, 2). Deterministic models show advantages with regard to transparency and traceability; however, this gain is as a matter of course accompanied by losses in complexity.

Another disadvantage of economic modeling is that DLUC and ILUC cannot be differentiated (Delzeit et al. 2011); this has to be done through interpretation of the results. Adding the ILUC factors gained by economic modeling for the CF of biofuels without separating DLUC and ILUC beforehand leads to double counting and should thus be avoided. Deterministic models, on the contrary, usually allow for a distinction between DLUC and ILUC.

The main advantage of CGE models is that they are able to cover several types of indirect effects at the same time, e.g. changes in other sectors such as the food sector. Although this is generally possible with most of the economic models, scenarios with changing demands for food, intermediates, or fuel are not always conducted. Laborde (2011) notes, for instance, that in the most recent ILUC calculation of the IFPRI, the analyses of the impact of changing food demands have been very limited and that further research is needed on this topic. As a contrast to economic models, deterministic models usually do not offer the possibility to model different kinds of indirect effects at the same time. Such effects can be partially considered by applying rather rough assumptions or by calculating scenarios with deterministic models. However, these effects are then considered by applying external parameters provided by other models or based on rough assumptions.

One difference between CGE and PE models is the way they predict LUC. CGE models mainly work with the constant elasticity of transformation (CET); the key parameter is the elasticity of land transformation that describes how easily land is converted to another type of land use when agricultural commodity prices change (Delzeit et al. 2011). GTAP, for instance, distinguishes between three types of land use: cropland, pasture land, and accessible forests. The elasticity of land transformation finally depends on the share of total returns on these land types. A criticism of CGE modeling is the broadness of the land-use groups (Delzeit et al. 2011).

LUC modeling in PE models normally relies on own- and cross-price elasticities for land demand used for specific crop cultivations. These individual land demands compete with each other so the displacement of agricultural uses can be singled out. Deterministic models draw on rather rough assumptions to describe how the agricultural system is going to respond to an increase in biofuel feedstock production.

Most of the existing models, economic and deterministic, only partially consider regionally specific characteristics such as local LUC, specific carbon stocks, land tenure and ownership systems, management practices, societal preferences, and trade incentives and barriers. In comparison to CGE models, PE models generally allow a greater degree of regionalization given that they refer to the agricultural sector in a specific country. Thus regional economic links and regional data, for example, expected yield developments, can be considered in more detail than in CGE modeling. CGE modeling only allows incorporating regional data such as CO_2 emission factors for regional LUC.

Whether regional conditions are considered in deterministic models depends again largely on the specific model and its aim. While Lahl (2010) and Bauen et al. (2010) explicitly aim to consider regional data and information, Fritsche et al. (2010a) prefer to provide an easily implementable and universally valid methodology. Approaches utilizing case studies such as these of Lahl (2010) and Bauen et al. (2010) theoretically allow using data from land-cover monitoring by satellite images in order to capture previous LUC more precisely; however, the evaluation of such images is an elaborate and time-consuming task so that in most cases statistical data is used.

The models analyzed here do not provide any possibility for identifying or considering specific mitigation or compensation measures that may be implemented in combination with the biofuel (feedstock) production. Wicke et al. (2012, 87) mentioned that "analyzing how overall LUC and its effects can be minimized is an important topic for further research". Bauen et al. (2010) explicitly pointed out that more knowledge is needed on regionally specific mitigation measures and on their net effect concerning GHG emissions.

Regionally relevant economic, political and cultural factors were emphasized as being of particular importance for the occurrence of ILUC by the participants of the "Fair Fuels?" workshop as well as by Lahl (2010) and Delzeit et al. (2011). The presence or absence of effective regulations protecting natural ecosystems, for example, has a strong influence on the extent of ILUC (Lahl 2010).

Thus, as the case-study approach was further developed, the goal became to specifically fill in the knowledge gaps regarding the influence of regional factors as well as the net effect of ILUC mitigation measures, while at the same time fulfilling as many of the above mentioned criteria as possible.

4 Methodological approach

The key objectives of this dissertation were the development of a case-study approach for calculating ILUC effects of specific biofuels and the completion of three case studies in different world regions in order to test this approach. The countries were chosen in accordance with the various characteristics expected to influence the occurrence of ILUC. The intent with the case studies was thus to identify regional factors that influence ILUC, to quantify ILUC and related CO_2 emissions, to identify country-specific measures for avoiding ILUC, and to calculate the net GHG effect and assess the CF for the chosen biofuels. The following methodological approach was pursued:

1. Development of a case-study approach to calculate ILUC-induced GHG emissions (section 4.1).

2. Specification of the general RED methodology for CF calculation with reference to system boundaries and allocation method (section 4.2).

3. Identification of relevant country characteristics influencing the extent of ILUC and selection of the specific case-study countries (section 4.3).

4. Execution of the case studies including a search of the secondary research literature and field research in the selected countries (section 4.4).

4.1 Case-study approach to quantifying ILUC

In order to quantify ILUC-induced GHG emissions, a case-study approach was developed that takes into account regionally specific data and information. This new approach is based in part on ideas found in existing methodologies, such as the deterministic models of Bauen et al. (2010), Fritsche et al. (2010a), and Lahl (2010). However, most of these existing models are top-down approaches, which start with the EU-mandated increase in biofuel demand (e.g. Bauen et al. 2010; Fritsche et al. 2010a); the case-study approach works as a bottom-up approach, starting with the biofuel feedstock production in a specific region.

The simple reason for this decision is that biofuel feedstock production is the direct trigger for ILUC. The biofuel feedstock production relationship also facilitates developing an approach suitable for use in sustainability certification, and allows us to consider the specific efforts of companies or other actors to reduce ILUC. The main actors addressed with the case-study approach thus are the biofuel feedstock producers, who often are also the biofuel producers, as well as the government officials and policy makers able to initiate implementation of specific compensation measures on a broader level.

The case-study approach can roughly be separated into five steps, which are described in the following and illustrated in Figure 2.1.

Step 1: Quantifying the gross expansion area (GEA)

According to Bauen et al. (2010), three options for increasing biofuel production can be distinguished: area expansion, yield increase, and substitution. First of all, the area allotted to a specific feedstock can be expanded in order to produce more biofuel; this is the standard situation considered here. Alternately, increasing the biofuel crop yield produces more feedstock and thus more biofuel; this option is also considered in the case-study approach. The third option, substitution, addresses the transfer of a feedstock such as rapeseed oil from other markets (e.g. the food sector) to the biofuel sector, such that cultivation of a substitute feedstock (e.g. palm oil) then has to be increased to replace the loss within the original sector (Bauen et al. 2010). While yield increases alone do not lead to ILUC, the other market reactions trigger DLUC and/or ILUC.

In cases where a specific feedstock area expansion takes place, the gross expansion area (GEA) for the production of a specific biofuel feedstock can be directly detected and quantified. GEA can be accounted for at the country, regional, or company level. The idea of distinguishing between different organizational levels was already formulated by Lahl (2010); the author, however, begins by evaluating LUC data in a country and then proceeds to allocate the LUC to various agricultural commodities; such a course of action proved to be difficult due to a lack of data in the case studies.

The option yield increase occurs when the biofuel feedstock producer achieves an increase in feedstock yields. In this case the amount of additional biofuel feedstock is greater than the amount gained only through the GEA (see formula (4.1)). In order to ascertain the specific market reactions to yield increase vs. area expansion, Lywood et al. (2009b) provide data for specific regions and feedstocks at the national level, breaking them down according to the share of additional agricultural output provided by yield increases vs. that provided by area expansions (Yield%, Area%)[4]. These values were taken into account in the analysis of Bauen et al. (2010). As the case-study approach focuses on the company level (feedstock producer) the values provided by Lywood et al. (2009b) may not properly describe the situation, as the yield growth rate and the ratio of area expansion to the already existing area might differ from those at the national level. Even so, when more precise information for the company level was not available, these values were used as an approximation.

$$B_f = \frac{GEA * Y_f}{Area\%} \tag{4.1}$$

B_f	Additional amount of biofuel feedstock [t]
GEA	Gross expansion area for the production of biofuel feedstock [ha]
Y_f	Average yield of biofuel feedstock for the GEA [t]
Area%	Percentage of incremental output met through additional area growth

The value B_f, the additional amount of biofuel feedstock, is required in step 5 when the GHG emissions from ILUC are related to the additional amount of biofuel.

Substitution comes into play when the biofuel feedstock producer does not change its cultivation patterns but instead provides the feedstock for another purpose than before. Substitution, for instance, is relevant in the case of oilseeds, given that relatively inexpensive palm oil could substitute for vegetable oil taken over by biofuel production. In the case of ethanol production, substitution is not anticipated. Given the focus here solely on case studies involving ethanol, the problem of substitution is not addressed in detail. In general, market analyses are helpful in estimating whether substitution is expected to occur. If substitution is found to be a realistic option, the specific substitution will have to be analyzed on the basis of statistical and/or historical data or by relying on expert opinion (Bauen et al. 2010). If the specific substitution, the substitution ratio, and the final LUC are known, the case-study approach can easily be applied.

[4] Lywood et al. (2009b, 363) called these parameters Yield%_incremental and Area%_incremental: "'Yield%_incremental' and 'Area%_incremental' are the percentages of incremental output met through additional yield and area growth." Here these are referred to simply as Yield% and Area%.

Step 2: Quantifying the net expansion area (NEA)

GEA represents the gross expansion area within which biofuel feedstock cultivation takes place. Parts of the plants, however, enter food or fodder production as by-products; therefore, it is necessary to calculate the net expansion area (NEA) with the help of a formula (4.2). Allocation of the gross area should be done with the same allocation method chosen in carbon footprinting – in general one might chose energy allocation, given that the RED methodology requires energy allocation (2009/28/EC).

$$NEA = GEA * F_{all} \quad (4.2)$$

NEA	Net expansion area for biofuel production [ha]
GEA	Gross expansion area for the production of biofuel feedstock [ha]
F_{all}	Allocation factor

Step 3: Identifying where ILUC occurs

The additional agricultural area needed for the production of the displaced crop can be provided within the country or elsewhere. The location is relevant, as it determines the type of LUC and thus the average LUC CO_2 emission factor. Subsequently, it is necessary to consider where ILUC induced by NEA will occur. Given that each country functions as a closed unit, the spillover – the percentage of ILUC that occurs across border – needs to be determined. The factor F_{spill} accounts for this spillover effect with respect to the case-study country (see formulas (4.3) and (4.4)).

$$\%ILUC_{dom} = (1 - F_{spill}) * 100\% \quad (4.3)$$

$$\%ILUC_{glob} = F_{spill} * 100\% \quad (4.4)$$

$\%ILUC_{dom}$	Percentage of ILUC occurring within the country itself [%]
$\%ILUC_{glob}$	Percentage of ILUC spilling across the border [%]
F_{spill}	Factor that reflects the probability that ILUC will spill across the border ($0 \leq F_{spill} \geq 1$)

Identifying an appropriate value for F_{spill} is a practical challenge in the application of the methodology. Various data and information, however, can help in reaching an approximation.

A potential indicator for the cross-border effect of ILUC is the occurrence of LUC in the biofuel-producing country (I_{luc}). It is necessary to determine whether natural ecosystems in the country are being converted to agriculture. If there is no conversion of natural ecosystems to agricultural land, F_{spill} will be 1, meaning that 100% of ILUC is cross-border spillover. Policy-related issues strongly influence such conversions: If such natural ecosystems are legally protected and the protection is successfully enforced, ILUC will not take place within the country; thus to estimate I_{luc} it is necessary to take into account the specific country of interest; this should include data collection for LUC and a review of the most important natural resource policies, especially laws addressing forest habitation and management in the country of interest.

Another indicator for the cross-border effect of ILUC is the intensity of the linkage between domestic and global markets (I_{market}). There are various possible parameters that characterize the intensity of this linkage; most can be derived from quantities or values for export, import, and consumption of agricultural products for a specific country. Lahl (2010), for example, suggests looking to see whether imports have dropped over time and then checking whether the absolute decrease of agricultural imports is greater than or equal to the absolute increase in agricultural exports; if this is the case, international ILUC effects might play a significant role. The case-study approach developed here utilizes the ratio of import quantities of agricultural products to the supply of agricultural products and the ratio of export quantities of agricultural products to the supply of agricultural products. It is assumed that the greater the ratio, the more likely the probability of ILUC spilling over the border because it is likely that products formerly produced within a country will be imported when an area is taken over for biofuel feedstock cultivation. Another economic indicator for the intensity of the linkage between domestic and global market is the trade balance. Time series for both relations were generated using FAOSTAT data.

Overall, the factor F_{spill} is a function of the above mentioned indicators I_{luc}, and I_{market}.

$$F_{spill} = f(I_{market}, I_{luc}) \qquad (4.5)$$

F_{spill}	Factor that reflects the probability that ILUC will spill across the border
I_{market}	Indicator for domestic / global market linkage
I_{luc}	LUC indicator for the country of interest

A specific function to calculate F_{spill} is not known. It is only possible to conclude that F_{spill} is high when I_{luc} and I_{market} are high, but it is important to keep in mind that this is a rather rough and speculative estimate. The method presented allows estimating whether ILUC is more likely to occur in the country itself or rather spill over the borders. Any fixed value, such as 90%, or rather only 80%, of the ILUC for spillover is after all arbitrary. Deterministic modeling shows clear limits with regard to the question of where ILUC will occur. In order to cope with this uncertainty, a sensitivity analysis with varying values for F_{spill} was conducted.

Step 4: Considering efficiency gains and mitigation measures

Following quantification of $\%ILUC_{dom}$ and $\%ILUC_{glob}$ the next step is to consider efficiency gains. This is important because the extent to which ILUC occurs is dependent on whether and to what extent displacement leads to yield increases for the agricultural area of a respective region or country – or even globally.

In order to properly account for efficiency gains, it is first necessary to establish a baseline reference level. Looking at a suitable reference area, we can establish the rate of yield increase that occurs even without the market incentive of biofuel feedstock expansion. Estimates of expected yield increases in the country itself or globally are thus dependent on the choice of reference area location. Using formula (4.6) the amount of biomass produced in the reference area without biofuel feedstock expansion can be calculated.

$$X_B = A_B * (Y_B + Y_B * y_B) \qquad (4.6)$$

A_B Agricultural reference area in the baseline [ha]

Y_B Average yield for agricultural area in the baseline [t ha^{-1}]

y_B Average annual growth rate of the average yield in the baseline

X_B Amount of biomass produced on A_B [t]

Formula (4.6) only applies to short-term scenarios; in the case studies, calculations were conducted for the time period one year after biofuel production expansion. When long-term scenarios are being investigated, one has to consider that the average annual yield growth rate will decrease over time, approaching zero or even assuming a negative value when soil degradation occurs or new agricultural area at the agricultural frontier exhibits lower yields than for the area already in agricultural use.

Subsequently, the anticipated additional yield increase from the pressure of additional biofuel production in the biofuel expansion scenario must be assessed. Setting the expected growth rate of yield in the baseline and in the biofuel production scenario gives us the net ILUC that is needed to produce the displaced agricultural production ($ILUC_{dom\_net}$ and $ILUC_{glob\_net}$). Formulae (4.7) and (4.8) describe the mathematical link in the case of ILUC occurring within the country itself.

$$ILUC_{dom\_net} = \frac{A_B * (1 + y_B) - ((A_B - NEA) * (1 + y_{SB}))}{(1 + y_{SB})} * \%ILUC_{dom} \qquad (4.7)$$

$ILUC_{dom\_net}$	Net ILUC occurring within the country itself [ha]
A_B	Agricultural reference area in the baseline [ha]
y_B	Average annual growth rate of the average yield (baseline)
y_{SB}	Average annual growth rate of the average yield (biofuel scenario)
NEA	Net expansion area for biofuel production [ha]
$\%ILUC_{dom}$	Percentage of ILUC occurring within the country itself [%]

y_{SB} is calculated with the following formula:

$$y_{SB} = \frac{Yield\% * (1 + y_B)}{(\frac{A_B}{NEA} - 1)} + y_B \qquad (4.8)$$

Yield%	Share of yield increase in the total incremental crop output growth (see Lywood et al. (2009b)) [%]

The formulae for $ILUC_{glob\_net}$ are the same – only the size of the reference area and the average annual growth rate of average yield may be different.

The implementation of specific compensation measures offers a possibility to further decrease net ILUC. This is accounted for by substracting A_F from $ILUC_{dom\_net}$ and or $ILUC_{glob\_net}$, the agricultural area freed up through compensation measures, in formula (4.7). In order to show the potential of specific measures to reduce ILUC, figures for specific biofuels produced together with the implementation of compensation measures were considered. In order to do so, it is necessary to refer to the specific area where the compensation measure takes place; the size of this area can be equal to, bigger, or smaller than $ILUC_{dom\_net}$. The area freed up by the implementation of the compensation measure can be calculated with the help of formula (4.9).

$$A_F = A_C * y_C \qquad (4.9)$$

A_F Agricultural area freed up through compensation measure [ha]

A_C Agricultural area where compensation measure is implemented [ha]

y_C Additional annual growth rate of the average yield through compensation measure

One has to notice that in cases in which a full compensation takes place, the average annual growth rate of the average yield in the biofuel scenario (y_{SB}) equals the average annual growth rate of the average yield in the baseline scenario (y_B). This is because the market effect yield increase will not occur if a measure is being implemented that fully compensates the ILUC.

Step 5: Calculating CO_{2eq} emissions

CO_2 emissions related to ILUC ($ILUC_{GHG}$) depend on where the final LUC occurs. When ILUC spills across the border, global average GHG emissions from LUC calculated by Fritsche et al. (2010a) are considered as a default value. In those situations where ILUC takes place within the case-study country itself one has to gather data on typical LUC and typical carbon stocks in the specific country. CO_2 emissions can then be calculated using IPCC (2006b) (see section 4.2). The overall $ILUC_{GHG}$ is the sum of both CO_2 emissions from $ILUC_{dom\_net}$ and $ILUC_{glob\_net}$.

The final result is called $ILUC_{GHG\_net}$ and includes additional GHG emissions arising from efficiency gains and the implementation of specific compensation measures (EFF_{GHG}). EFF_{GHG} is relevant because yield increases may lead not only to area savings but also to additional GHG emissions. One thus has to estimate the additionally released GHG emissions, e.g. by estimating the additionally needed amounts of fertilizer or the additional electricity demand of irrigation systems, in order to determine these emissions. Finally the overall GHG emissions are related to the additional amount of biofuels produced by the company (see step 1). The unit of $ILUC_{GHG\_net}$ is thus g CO_{2eq} MJ^{-1} of biofuel.

$$ILUC_{GHG\_net} = \frac{\Delta CO_{2\,dom} * (ILUC_{dom\_net}) + \Delta CO_{2\,glob} * ILUC_{glob\_net} + EFF_{GHG}}{B_f * y_{BF}} \qquad (4.10)$$

$ILUC_{GHG\_net}$ GHG emissions per MJ of biofuel induced by ILUC including GHG emissions due to efficiency gains [g CO_{2eq} MJ^{-1} of biofuel]

ΔCO_{2dom} CO_2 emissions released due to final LUC within the country itself

	(allocated over 20 years) [g CO_2 ha^{-1}]
ΔCO_{2glob}	CO_2 emissions released due to final LUC elsewhere (global average, allocated over 20 years) [g CO_2 ha^{-1}]
$ILUC_{dom\_net}$	Net ILUC occurring within the country itself [ha]
$ILUC_{dom\_net}$	Net ILUC occurring outside the country [ha]
EFF_{GHG}	GHG emissions occurring due to efficiency gains [g CO_2]
B_f	Additional amount of biofuel feedstock [t]
y_{BF}	Biofuel yield per unit of biofuel feedstock [MJ t^{-1}]

Step 6: Sensitivity analysis

In order to determine the robustness of the results, a sensitivity analysis was conducted; this involves repeated variations of all input parameters entering the ILUC-quantification approach. Initially, the parameters were varied by plus and minus 10% and sensitivity was calculated; sensitivity refers here to the percentage deviation of $ILUC_{GHG\_net}$ following variation of an input parameter. In a second step, minimum and maximum values for all input parameters were determined in order to calculate the potential range of results. The following input parameters were varied:

- share of area expansion in the total incremental output growth of biofuel feedstock (Area% (feedstock); see Lywood et al. (2009b))
- allocation factor, in order to consider by-products (F_{all})
- location of ILUC within the country itself or elsewhere (F_{spill})
- type of final LUC and related CO_2-emissions (average LUC CO_2 emission factor, ΔCO_{2dom}, ΔCO_{2glob})
- share of yield increase in the total incremental output growth of crops (Yield%)
- additionally applied amount of fertilizer in order to reach the yield increase
- biofuel yield (MJ ha^{-1}).

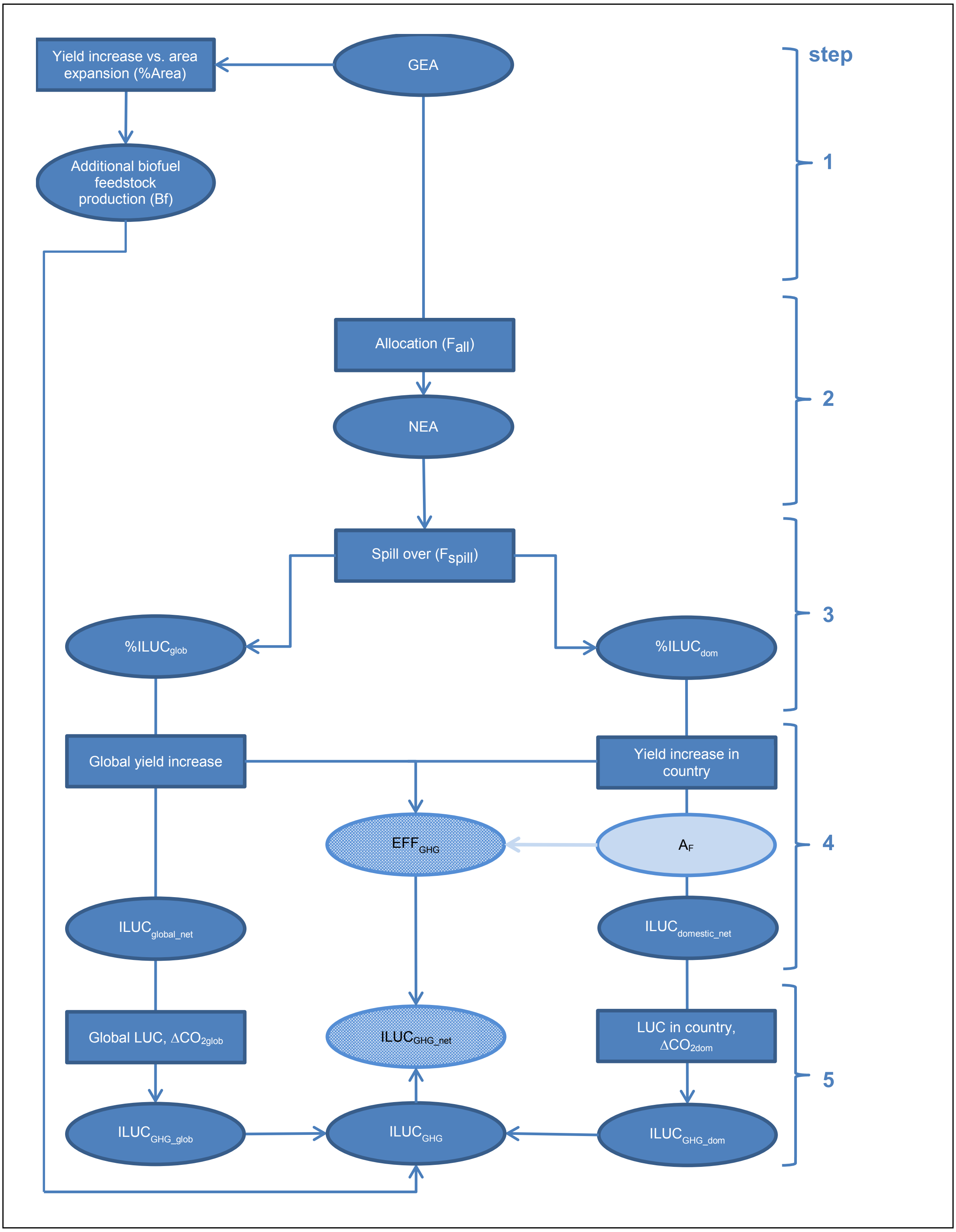

Figure 4.1: Schematic flow diagram describing the ILUC-quantification case-study approach

The ovals represent relevant intermediate results from the steps of the case-study approach; the rectangles stand for input parameters or processes. The lighter color indicates A_F yield from the implementation of compensation measures. EFF_{GHG} and $ILUC_{GHG\_net}$ result from the implementation of compensation measures as well as from the "normal" efficiency gains.

4.2 CF methodology within the case studies

The CF was quantified using the RED methodology presented in section 2.1.2. The functional unit chosen to compare ethanol and conventional gasoline is thus 1 MJ of ethanol or gasoline, respectively. The GWP_{100} is used to calculate the CF, which means that CO_2 equivalents are calculated for a 100-year time span; in accordance with the RED, the study focuses on the GHGs CO_2, CH_4, and N_2O; the specific CO_2 equivalents of the gases for the calculation are: CO_2: 1, CH_4: 23, and N_2O: 296.

System boundaries applied in this study include the cultivation phase and the industrial processes, ending at the ethanol manufacturing gate. Upstream production processes, such as agrochemical manufacturing, are also included. For the cultivation stage, data on fuel, agrochemicals, electricity use for irrigation, emissions regarding pre-harvest burning in the case of sugarcane, and soil N_2O emissions are required. For the assessment of the ethanol production process data on various chemicals, process heat and electricity consumption are needed. Input and output data referring to buildings, machines, or equipment have, in accordance with the RED methodology, not been taken into account. The end use has also not been considered as the emissions released during the usage stage are set to zero according to the RED.

CF calculations are based partly on primary data gathered in field research and partly on secondary data (see section 4.4). In order to consider potentials for technological optimization, various scenarios were developed for each of the three case studies.

Generally more than one product accrues as an output of ethanol production, so the overall GHG emissions must be distributed over all products. The RED methodology calls for application of an energy allocation. Inasmuch as producers often decide how much main product and how much by-product to produce on the basis of the products' current market prices, an economic allocation does seem appropriate. Therefore both allocation procedures, energy and economic, were applied; the outcomes of the two allocation procedures reflects the robustness of the results. In the case of energy allocation, all inputs and outputs are allocated to the by-products according to share of the LHV. The LHV used in this study relates to the products' dry mass. An advantage of energy allocation is the fixed allocation ratio over time. In the case of economic allocation, all inputs and outputs are allocated to the by-products by share of market value. An advantage of economic allocation is that the market price adequately represents the real market value of a product (Klöpffer and Grahl 2009).

The RED methodology requires that emissions related to DLUC be included. It was thus necessary as part of the case studies to consider DLUC that takes place due to sugarcane or wheat expansions. GHG emissions from DLUC were then calculated with the help of the IPCC methodology (IPCC 2006b) including the changes in carbon biomass stocks, the changes in dead wood or litter stock and the change in soil carbon stock. IPCC (2006b) provides default values for most of the required input parameters (including B_{Before} = biomass stock before the conversion, B_{After} = biomass stock after the conversion, and SOC_{ref} = original soil carbon content) for different land use categories, soil types in various world regions, and different management types, but recommends using more specific and accurate values for specific regions whenever available given that these default values are characterized by a relatively high degree of uncertainty. The time period assumed for soil carbon stocks to reach a new equilibrium after the conversion is 20 yr in IPCC (2006b).

In cases where expansion takes place on land already in agricultural use, IPCC (2006b) directs that changes in biomass and dead organic matter (DOM) stocks be calculated for perennial woody crops only – for annual crops the increase in biomass stocks is presumed to be equal to biomass losses from harvest (IPCC 2006b). The changes in soil carbon stocks depend mainly on management practices such as irrigation, fertilization, and organic input and can be calculated if specific information on these practices is known. In this study, GHG emissions linked to cropland remaining cropland are assumed to be zero in accordance with the RED (2009/28/EC). N_2O and CH_4 can also play a significant role, as they have particularly high GWPs. These gases are especially relevant when burning above-ground biomass in the transformation phase (IPCC 2006b); however, in this study it was assumed that natural ecosystem conversion takes place without burning, so these gases were not considered.

4.3 Choice of appropriate case-study countries

In accordance with the dissertation's objectives, it was necessary to select specific case-study countries and specific biofuels being produced in these countries. The idea was to select countries that feature different characteristics expected to affect the occurrence and extent of ILUC. As made clear in section 4.1, such characteristics mainly refer to the relevance of LUC within a country and the trade dynamic of its agricultural products. Other aspects, such as the extent of biofuel production within the country, the intensity of agricultural production, and the population's lifestyles, are relevant in determining the potential of specific compensation measures.

Relevance and type of LUC: The location of ILUC depends on whether natural ecosystem conversion takes place within the case-study country. Moreover, the average LUC CO_2 emissions factor (ΔCO_{2dom}) depends on the type of LUC that occurs.

Trade dynamic of agricultural products: As shown in section 4.1, the location of ILUC depends on the trade dynamic of the agricultural products. A country can be characterized as having a largely regional dynamic if the two agricultural product quantity ratios, export vs. supply and import vs. supply, are both low. If these two ratios are high, the trade dynamic is characterized as global. The dynamic can also be characterized by largely unidirectional trade, which means that only one of these is high.

Relevance of biofuel production: The extent of biofuel production affects the potential for compensation measures. If moderate increases in biofuel production and biofuel feedstock expansions are assumed, then the implementation of compensation measures will likely be a realistic option for reducing ILUC. If biofuel production levels are already high and further significant increases are planned, the potential for compensation measures will sooner or later be exhausted.

Intensity and productivity of agricultural production: The intensity of agricultural production is defined as the sum of all inputs or expenditures on an area unit (Eckert et al. 1999). The extent of this intensity allows us to estimate whether additional agricultural area can be freed up through increases in crop yields or an intensification of livestock farming. However, the quantification of the intensity of agricultural production is a rather difficult issue, as the collection of considerable data and a comparative price analysis are necessary. Therefore, productivity per unit, i.e. the output or yield per hectare (Eckert et al. 1999), has been used as an approximation for the intensity of agricultural production, as productivity is assumed to increase with increasing intensity. In practice, the ratio of the average maize yield in the case-study country to the global average maize yield was used as an indicator for the intensity and productivity of agricultural production in the case-study countries.

Population's lifestyle: A look at population lifestyles in a specific country allows us to estimate whether changes in consumption patterns could be an appropriate measure to free up additional agricultural area. Especially in countries where meat and dairy consumption is high, a decrease in consumption would be a potential measure to free up agricultural land and thereby decrease ILUC.

Given these considerations, Malawi, Brazil and Germany were chosen as the most appropriate case study countries because of the different characteristics they exhibit.

Malawi, as a developing country, was assumed to have a rather regionally oriented agricultural trade (subsistence farming). Although sugarcane ethanol production has a long tradition in Malawi, the relevance of biofuel production, intensity of agricultural production, and consumption of meat and dairy products were all assumed to be low. The relevance of LUC in Malawi was not known prior to the case study, but the topic was found to be relevant.

Brazil, as an emergent country, was presumed to have a high share of agricultural production exports. The relevance of biofuel production is known to be high, as is the case for natural ecosystem conversion (deforestation of the Amazonian rain forest).

Germany, as a developed country, was assumed to already have high-intensity, high-productivity agricultural production. The trade dynamic was assumed to be global, the relevance and extent of LUC was assumed to be low. In contrast, the extent of biofuel production was assumed to be high, and likewise for the consumption of meat and dairy products.

Results on the detailed characterization of the case-study countries can be found in the sections 5.1.1, 5.2.1, and 5.3.1 and a summary can be found in the section 7.1. Sugarcane ethanol was identified as the most relevant biofuel in Malawi and Brazil, and wheat ethanol was selected for the case study on Germany.

4.4 Case-study procedure

The main tasks in conducting the three case studies were to gather the information and data required for a deeper characterization of the selected countries, for the application of the ILUC case-study approach, and for the CF calculations.

Initial information and data were acquired by means of secondary research; thereafter, more detailed data for the ILUC and CF calculations were gathered via field research in the subject countries. An additional aim of the field research was to conduct guideline-based expert interviews with representatives from local authorities, NGOs, relevant companies, and academic institutions in order to identify the regional factors that influence ILUC and to identify auspicious country-specific measures showing potential for avoiding ILUC. The compensation effect was thus calculated based on information and data specifically valid for the respective case-study regions.

The schedule and an overview of the interviews conducted as a part of the field research can be found in the appendix. For the country characterization and the ILUC case-study approach, the following information is required:

- production, export and import, and supply of agricultural products data,
- biofuel production and biofuel feedstock cultivation area data
- planned biofuel feedstock expansions
- LUC, especially deforestation
- average and global crop yields
- meat and dairy consumption data

Most of this data could be acquired through secondary research. FAOSTAT,[5] for instance, provides most of the data required for the country characterization and ILUC quantification; the service is an internationally recognized and established data source for time-series on data relating to agriculture, resources, and trade and was sourced for data on the production, export, import and supply of agricultural products. At the time the case studies were conducted, FAOSTAT only provided data up to 2009/2010. In order to acquire the additional data needed and to gather data directly from companies involved in ethanol production, field research in the case-study countries was conducted over the course of 2011.

Given that a systematic or internationally standardized approach to recording biofuels data in national and supranational statistical databases does not exist, various data

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[5] http://faostat.fao.org/

sources, including the United States Department of Agriculture (USDA) and databases and reports from national ministries and various other agencies had to be considered, and where necessary, integrated into the analyses.

The regularly published GHG National Inventories served as a reliable data source for LUC in the individual countries[6]; data from the national statistical offices or ministries complemented the inventories, as these are often not current and not available for every country.

With regard to data required for the CF calculation, the procedure differed between the three case studies. In *Malawi,* data was collected directly from the companies involved in the sugar and ethanol production in the Southern Region, as no input-output data have previously been published. In *Brazil, a* comprehensive database on sugarcane cultivation and ethanol production already exists for the State of São Paulo (Macedo et al. 2008); however, for other expanding sugarcane regions, e.g. in the states of Minas Gerais, Goiás, and Mato Grosso, English-language publications on CFs are unknown. The CF for sugarcane ethanol was therefore calculated for an exemplary sugar and ethanol mill in Minas Gerais. During field research, data were collected by means of survey questionnaires. Additionally, it was possible to exchange data with a doctorate candidate at the University of Minas Gerais, Juan Carlos Claros Garcia, whose work focuses on the question of how GHG emissions can be reduced through optimization of the sugarcane cultivation and who had gathered data at the same mill. Some of the values used in the analysis, such as sugarcane yield, are typical for Minas Gerais; other values, such as the amount of electricity produced in cogeneration, are not representative for the entire sugarcane sector in Minas Gerais or Brazil but are only valid for the exemplary site. For the case study on *Germany,* secondary data from scientific reports and databases were used in order to calculate the CF, as primary data from the relevant companies were not available. Given that regional differences are not as significant as in Brazil, averaged data were used in order to characterize the cultivation stage.

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[6] Reports are published on the website of the UNFCCC http://unfccc.int/national_reports/items/1408.php.

Following completion of the field research, the remaining data gaps for the CF calculation were filled in using generic data from the databases *ecoinvent database v2.2*[7] and *GEMIS 4.7 (Globales Emissions-Modell Integrierter Systeme)*[8]; this mainly entails emission factors for fertilizers or pesticides. Default emission factors and values for specific process steps (CH_4 emissions from vinasse storage and N_2O emissions from the application of N fertilizer) were additionally taken from the IPCC (IPCC 2006a; IPCC 2006b). The specific data utilized for each of the three case studies is explained in the respective subsections of chapter 5.

[7] Ecoinvent, one of the leading suppliers of life cycle inventory data, is a non-profit association founded by inter alia the ETHZ, EPFL and Empa: http://www.ecoinvent.ch/

[8] GEMIS is a public domain life cycle and material flow analysis model and database provided free of charge by IINAS: http://www.iinas.org/gemis.html

5 Case-study results

This chapter presents the case-study results including the case-study characterization, the application of the ILUC case-study approach, and the CF calculation for ethanol production at specific sites in Malawi, Brazil and Germany. With regard to ILUC, the results represent a so-called “best estimate”; this means that for those input parameters characterized by uncertainty, the figures that seemed most likely were chosen. Chapter 6 then provides a discussion of the methodology, including sensitivity analysis.

5.1 Malawi – sugarcane ethanol

While the scientific body of literature dealing with biofuels in general focuses on GHG emissions, scientific publications about biofuels production in countries of Sub-Saharan Africa (SSA) are dominated by issues of competition between food and bioenergy production (UNECA 2008; Mitchell 2011) and large-scale land acquisitions by internationally operating companies (Matondi et al. 2011). DLUC and ILUC, so far, do not play a visible role in the body of literature on biofuel production in SSA.

The case study on sugarcane ethanol produced in Malawi analyzes whether DLUC and ILUC occur linked to the sugarcane ethanol production in Malawi and ascertains its CF. It also contributes to the knowledge about regionally available ILUC compensation measures in Malawi. The following section provides a country characterization with the information that is needed for the ILUC quantification and helpful for the identification of appropriate ILUC compensation measures.

5.1.1 Country characterization

5.1.1.1 Biofuel production

5.1.1.1.1 Policies regarding biofuel production

In developing countries such as Malawi, the forces driving increased biofuel production differ, at least in part, from those in developed countries. Rising fuel prices and promotion of a secure energy supply are crucial factors for developing countries. The price for gasoline is in Malawi particularly high because of high transportation costs: it almost doubles from 0.35 USD L^{-1} at the harbor in Dar es Salaam to 0.64 USD L^{-1} inbound landed costs in Malawi (Mitchell 2011). Fuel shortages at the country’s filling stations regularly occur as a consequence of the high prices and foreign currency shortages (Lange and Klepper 2011). Objectives of a biofuel policy thus are to reduce expenditures for fossil fuel imports through the use of domestically produced biofuels and to secure a reliable fuel supply. Ethanol exports may play an important long-term role in coastal states such as Mozambique and Tanzania (Mitchell 2011), but in Malawi ethanol exports overseas do not play a significant role because of high transportation costs (pers. comm., L. Chakaniza, 2011).

In general, the reduction of a country's GHG emissions is not considered to be a major policy driver for biofuel production in developing countries. The Clean Development Mechanism (CDM) under the Kyoto Protocol, which allows industrialized countries to purchase reduction credits by financing mitigation projects in developing countries (UNFCCC 2010), however, may encourage companies and institutions in developing countries to contribute to GHG mitigation.

Thus, mainly because of high import costs and regularly arising fuel shortages the Malawian government promotes ethanol production by maintaining a blending rate of currently 20% (pers. comm., L. Chakaniza, 2011). Since this is substantially higher than the previous blending rate of 10% prior to February 2011 (Liaquat et al. 2010), further regional expansions in crop production are to be anticipated. Ethanol is maintained at a price that is on average 5 MKW (Malawian Kwacha) less than the prevailing wholesale price of gasoline – a measure intended to make ethanol production financially attractive to producers. Ethanol pricing, however, is currently under review (Lange and Klepper 2011).

Another policy that may indirectly influence biofuel production is the Land Act of 2002, which regulates land tenure. The Act recognizes public land, private land and customary land. Customary land is the most common form of land tenure in Malawi; however, most of the smallholder farmers that hold land under customary tenure cultivate less than one hectare of land (pers. comm., A. Ilberg 2011). Land tenure can also be an obstacle for investments such as irrigation systems that are intended to increase agricultural productivity, as specific concepts for financing, participation, and management have to be developed. A new land bill and a land reform begun in 2005 should help to distribute land more equally and generate incentives for long-term investments (Chirwa 2008).

5.1.1.1.2 Data on ethanol production

In Malawi, biofuels are exclusively produced from sugarcane molasses, a by-product from sugar production. Investments in Jatropha cultivation for biodiesel production have occurred in the previous years; however, in 2011, at the time the field research was conducted, biodiesel production had not yet been initiated.

Sugarcane, having been cultivated in the country on a large scale since the mid-1960s, represents one of the most important cash crops in the country. Although the sugarcane area represents less than 1% of the total arable land in Malawi, sugar, together with tobacco and tea, has been one of the most important agricultural export products in terms of value from the mid-1970s until the present (FAO 2012).

One might wonder why the sugarcane area is not larger given the sugar's high economic importance; the most likely reasons are that Malawi is a country with a huge rural population living from self-subsistence farming, and that sugarcane cultivation requires high investments that cannot be provided by small-scale farmers.

Fuel ethanol production as a by-product of sugar production was initiated in 1982 in Dwangwa in the Central Region. Malawi is thus one of the first countries worldwide to engage in ethanol production from sugarcane molasses (Liaquat et al. 2010). In 2011 the overall sugarcane area covered approx. 23,000 ha. Roughly 38% of it is located in Dwangwa; the remainder is in Nchalo, in the Southern Region (see Table A.1 in the appendix), where a second, newer ethanol plant has been operating since 2004.

In 2010 both locations together produced roughly 17 million L of ethanol, which is in part used to augment the expensive-to-import fossil fuels. Roughly 500 ha land were used for sugarcane ethanol production when allocating the sugarcane area to sugar and molasses based on the LHV; the allocation factor was calculated to be 7.1% (see section 5.1.3.1). These values are based on values valid for 2010. According to one of the ethanol-producing companies, the molasses sucrose content has decreased over time so that the numbers in Table 5.1 must be seen as an approximation. Despite this limitation in data availability, the time series makes clear that the area allocated to ethanol has only slightly changed over time; thus LUC and ILUC from ethanol production presumably did not occur in the past. However, the area used for ethanol production will enlarge substantially in the near future in order to meet the increasing domestic ethanol demand in Malawi. One already planned expansion of about 9,000 ha is to take place in Shire Valley, in the Southern Region. The planned expansion in the valley is linked to a large-scale government-driven irrigation scheme, the Shire Valley Irrigation Project (SVIP), which will likely be financed by a public-private partnership.

Table 5.1: Ethanol production and area allocated to fuel ethanol in Malawi (1990 to 2010)
Source: Data on ethanol (fuel) production (ETHCO 2011; Presscane 2011); data on sugarcane area (FAO 2012)

Year	Total fuel ethanol	Total ethanol	Sugarcane area	Sugarcane area allocated to fuel ethanol*
	[1000 L]	[1000 L]	[ha]	[ha]
1990	12,039	12,367	17,000	1,179
1991	12,175	12,759	18,000	1,224
1992	11,196	11,556	18,000	1,243
1993	13,111	14,911	14,000	877
1994	12,461	14,177	18,000	1,127
1995	12,124	13,125	18,000	1,185
1996	9,906	13,704	17,650	909
1997	6,147	9,842	17,500	779
1998	11,463	12,679	18,000	1,160
1999	11,615	12,178	19,000	1,291
2000	11,168	11,836	20,000	1,345
2001	7,050	7,462	20,500	1,380
2002	8,962	9,749	24,000	1,572
2003	9,382	10,223	20,500	1,341
2004	10,770	12,523	20,000	1,226
2005	3,783	7,900	22,000	751
2006	3,431	15,795	22,500	348
2007	4,578	13,902	23,000	540
2008	6,612	18,762	23,000	578
2009	6,320	16,718	23,000	620
2010	5,079	16,671	23,000	499

* The area used for ethanol production was calculated by energy allocation (allocation factor = 7.1%); it was also considered that only a share in the overall ethanol production is used as a fuel.

5.1.1.2 Land-use changes

5.1.1.2.1 Policies regarding land-use changes

Because deforestation has been a topic of interest in Malawi for some time the Forest Act of 1964 already focused on forest protection and afforestation. One important afforestation initiative involved the distribution of subsidized seedlings to those farmers who were willing to plant them. Another measure was the initiation of large-scale fuel wood plantations. Both measures were criticized as not being successful in the effort to avoid forest loss in Malawi (Kerr 2005).

The new Forestry Act of 1997 now emphasizes the role of local communities through the management of so-called Village Forestry Areas. These are maintained according to a set of rules agreed to by the community and the village headman. The forestry act promotes agroforestry, plantations, nurseries, and small-scale forest product industries. The declaration of forest reserves is another means for preventing deforestation (Kerr 2005). The overall success of the current forestry act, however, is limited, according to local experts, because of a lack of sufficient enforcement, monitoring and control (pers. comm., J. Ngalande, 2011).

5.1.1.2.2 Data on land-use changes

Malawi lost 15% of its former forest area between 1990 and 2008 according to FAOSTAT data (see Table A.2 in the appendix). According to the available national statistics (GoM 2009), forest loss accounted for 7% between 1991 and 2008, and woodland loss 29% (altogether 28%; see Table 5.2).

Table 5.2: Land cover in Malawi in 1991 and 2008
Source: Based on (GoM 2009)

Land cover	1991 [1000 ha]	2008 [1000 ha]	Difference [1000 ha]
Forest	83	77	–6
Woodland	2419	1727	–692
Plantation	156	183	29
Extensive agriculture	2669	2852	183
Intensive agriculture	3091	3721	630
Open land	766	614	–152
Other	216	223	8

Differences between the two databases (FAOSTAT and GoM) are due to differing definitions. In GoM (2009), forest is defined as “evergreen forest having green leaves throughout the year with the land containing less than 20% open land" (GoM 2009, xix); woodland is defined as "non-evergreen forest with the land containing less than 20% open land" (GoM 2009, xix). The FAO, by contrast, does not distinguish between evergreen and non-evergreen forest but defines forest as an area "spanning more than 0.5 ha with trees higher than 5 meters and a canopy cover of more than 10%, or trees able to reach these thresholds in situ" (FAO 2010). In accordance with this definition Malawi lost roughly 600 thousand ha forest between 1990 and 2008; in both 2009 and 2010, an additional 33 thousand ha were deforested (FAO 2012).

An important driver for deforestation in Malawi is a high fuel-wood demand (pers. comm., J. Ngalande, 2011). In 2008, more than 88% of Malawi's total energy consumption was supplied by biomass, mainly fuel wood and charcoal (GoM 2009). Fuel wood represents the primary source of energy for heating and cooking, as only 5% of the country's population has access to electricity (Jumbe and Angelsen 2010). Other relevant purchasers for fuel wood include smoke houses for fish (Abbot and Homewood 1999). The local population also uses forest resources for food, and income-generating activities such as brick making (USAID 2010). Fuel wood collection and charcoal production generally degrade a forest's qualities (GoM 2009). Given that farmers often move into cleared areas and begin permanent farming there, fuel wood gathering or charcoal production can be seen as a preliminary phase in the conversion to arable land and therefore deforestation. Expansion of agricultural land is thus another driver for deforestation. Between 2000 and 2010, the increase in cropland (sum of arable land and permanent crops) has been characterized by an average annual growth rate of 2.7% (FAO 2012). Kerr (2005) identified agricultural area expansion caused by population growth combined with difficulties in intensifying agricultural production as being the most important driver for deforestation.

5.1.1.3 Economic data, agricultural production, and trade

The global demand for agricultural products, in particular the demand of neighboring countries, is, in addition to biofuel production, another potential driver for cropland generation. Malawi has had a positive trade balance during most of the period from 2000 to 2010 (see Figure 5.1; (FAO 2012)). In 2002 and 2005 the import quantities of agricultural products were, as an exception and in the first instance obviously a consequence of the 2002 harvest failure (Stevens et al. 2002), higher than the export quantities; in 2007 one can observe a short-term upturn in the trade balance.

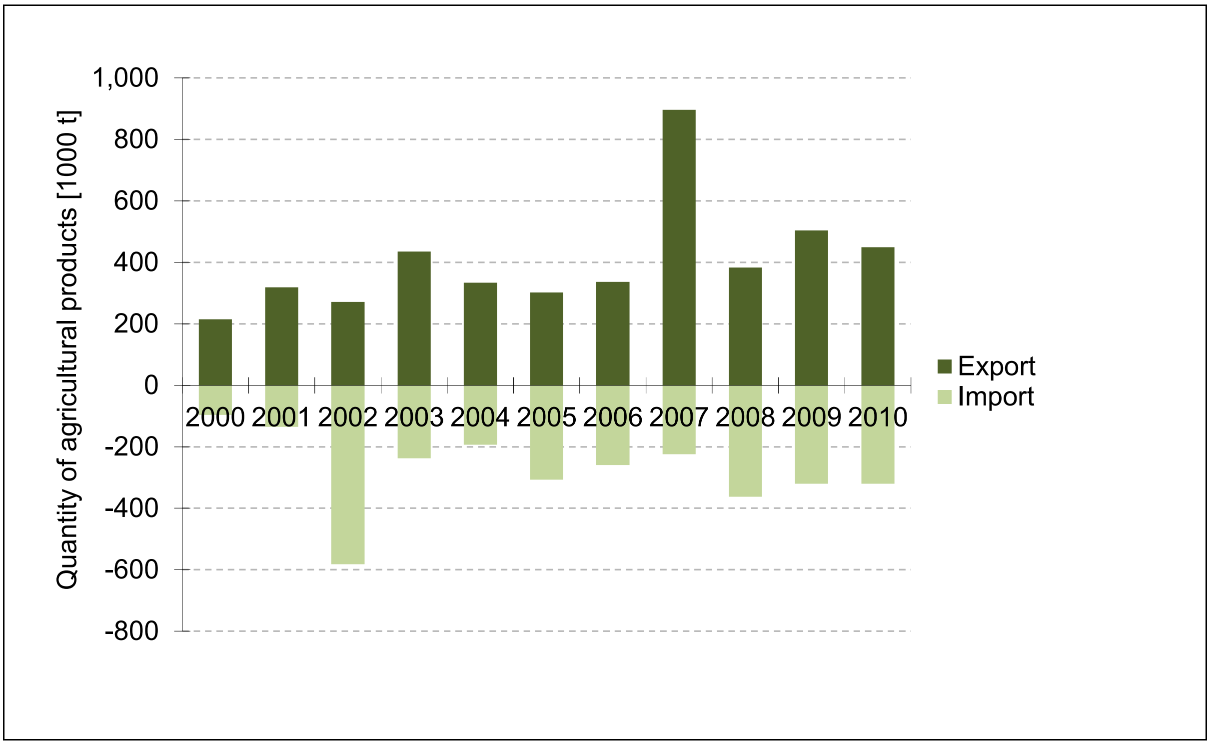

Figure 5.1: Import and export of agricultural products (Malawi)
Source: Based on (FAO 2012); data can be found in Table A.3 in the appendix.

In order to assess the degree to which the domestic market is linked to the global market, the ratios of agricultural imports to food supply and agricultural exports to food supply were calculated. The results show that the ratio between import of agricultural products and food supply ranged from 1.5 to 9.0% in the period 2000 to 2009. The ratio between export of agricultural products and food supply ranged from 3.4 to 11.1% in the same period (FAO 2012). These comparatively low values indicate a low linkage between the domestic and global markets and indicate a particularly strong tendency to self-sufficiency.

In comparison to average meat consumption globally, the annual meat consumption per capita in Malawi is very low; it has risen slightly, from 5.5 kg capita^{-1} yr^{-1} in 2000 to 8.3 kg capita^{-1} yr^{-1} in 2009 (FAO 2012), this represents only 14 and 20% of the average global meat consumption per capita. Milk consumption increased from 3.7 to 5.0 kg capita^{-1} yr^{-1} during this period (FAO 2012), corresponding to 5 and 6% of the average global milk consumption per capita (see Table A.4 in the appendix).

The intensity and productivity of agricultural production in Malawi are also comparatively low. This is readily apparent in the low average maize yield as compared to the global average; between 2000 and 2010 average maize yields ranged from 17 to 43% of the global average (see Table A.5 in the appendix). Based on this data and on the assessments of actors on the ground (pers. comm., G. Mwepa 2011, I. Gruenewald 2011) it was assumed that crop yields in Malawi can be significantly increased by investing in measures to intensify agricultural production.

5.1.1.4 Overview of country characterization

Table 5.3 summarizes the information and data given in the previous chapters.

Table 5.3: Key characteristics of Malawi

Characteristic	Description
Relevance of biofuel production	Amount of biofuel production is low; however, expansion is expected
Relevance of LUC	High, especially deforestation
Trade dynamic of agricultural products	Regional dynamic, self-sufficiency
Intensity of agricultural production	Low
Meat and dairy consumption	Very low

The amount of biofuel produced in Malawi is still low; however, the role of biofuels in the mobility sector is very relevant as fossil fuels are extremely expensive. A significant expansion of biofuel production is thus assumed to occur in the future.

LUC is a relevant topic in Malawi, particularly deforestation, which is regularly occurring; thus, there is the risk of ILUC as a consequence of biofuel feedstock expansion.

Trade in agricultural products mainly takes place at the regional level: the ratios of import and export quantities to supply for agricultural products are very low. The intensity of agricultural production is also assumed to be low as the average maize yield in Malawi is significantly lower than the global average maize yield. Meat and dairy consumption are likewise very low compared to the global average.

Measures that increase crops yields thus represent promising ILUC compensation measures. In contrast, those compensation measures that decrease meat or dairy consumption will be inadequate, because of the existing low consumption level.

5.1.2 ILUC due to sugarcane ethanol production

This section provides an analysis of the anticipated ILUC effect due to the planned sugarcane area expansion in the Southern Region in Malawi. Both the sugar and the ethanol factories at Nchalo have additional production capacity available; therefore current plans call for the expansion of the sugarcane area as close as possible to the already existing sugar plantation. The area chosen is presently in cultivation with other crops, with the small-scale farmers mainly cultivating maize, so that ILUC may occur in order to provide for the displaced maize cultivation.

As was made clear in the previous section, there are many other potential drivers for LUC and especially deforestation in Malawi besides ethanol production. In ILUC-modeling, all CO_2 emissions from the final LUC are generally debited to the expanding biofuel feedstock that indirectly leads to LUC. The direct drivers, such as fuel wood use or agricultural activity directly following the natural ecosystem conversion, do not take over any of the CO_2 emissions; this has been criticized, e.g. by Finkbeiner (2013). In a first step, the ILUC case-study approach also debits all CO_2 emissions from the final LUC to the biofuel feedstock expansion; however, a proposition for further development to additionally include drivers other than the indirect driver "biofuel feedstock expansion" can be found in section 6.1.4.

5.1.2.1 ILUC without the implementation of compensation measures

In the Southern Region of Malawi, the sugar and ethanol companies intend to expand the sugarcane area by 9,000 ha. Area%, the percentage of incremental output met through additional area growth, is assumed to be 100% as sugarcane yields in the Southern Region are already very high (111 t ha^{-1}). The average ethanol yield is 15.7 GJ ha^{-1}, so that the additional amount of biofuels is 141 thousand GJ of ethanol (B_F). Expansion is intended to take place within the SVIP, a large irrigation scheme that is planned to cover roughly 40,000 ha. Initially, it is, however, useful to consider a scenario without implementation of the SVIP, which serves as an ILUC compensation measure, as it is currently not certain whether the project will be realized. If the SVIP is not implemented, the 9,000 ha planned as sugarcane plantation will displace food crop production without compensation. Given that ethanol is a by-product of sugar production, the net expansion area (NEA) only amounts to 639 ha when using energy allocation (F_{all} = 0.071, see section 5.1.3.1).

As described in section 4.1, ILUC could theoretically occur in Malawi itself or beyond its borders; therefore in step 3, estimates are made as to where ILUC will take place. The data and information presented in section 5.1.1 allow us to estimate whether ILUC induced by ethanol production in Malawi will occur within the country or spill over the border. Overall, the following observations could be made for Malawi:

– a constant loss of forest area during the last decades (I_{luc} is high)
– a constant expansion of the agricultural area (I_{luc} is high)
– a low ratio of import quantities to supply of agricultural products (I_{market} is high)
– a low ratio of export quantities to supply of agricultural products (I_{market} is high)

Based on these observations, it is likely that ILUC will mainly or even entirely occur within Malawi itself. Another indicator that a large share of ILUC is likely to take place in Malawi is the fact that small-scale farmers participating in sugarcane outgrower schemes often still cultivate food crops to cover their own food demand. This tendency towards self-sufficiency strongly reduces the likelihood for ILUC to occur across border. In the following analysis it is assumed that ILUC entirely takes place in Malawi (F_{spill} = 0, $\%ILUC_{dom}$ = 100%).

In step 4 efficiency gains are considered. Sugarcane area expansion mainly takes place on already existing arable land, so that the extent of ILUC depends on how the expansion influences average crop yields in Malawi. Between 2000 and 2010 average crop yields increased by annually 1.3% (FAO 2012). One reason for yield increases is improved fertilization as the government initiated a subsidy measure to provide chemical fertilizer to households a few years ago (pers. comm., G. Mwepa, 2011). The relevant set of questions with regard to ILUC is whether and to what extent the average yield in Malawi would change as a consequence of sugarcane area expansion. The idea behind this is that the loss of area for crops other than sugarcane would cause a yield increase so that part of the area loss would be compensated. However, a precise quantification of the influence of the sugarcane area expansion on the average crop yield is impossible, given that the sugarcane plantations have existed for a long time and have only slightly expanded in recent years.

As a simplification it was assumed that the average crop yield will increase by 100% compared to the baseline scenario if the relation between NEA and the reference area is 1. Yield% thus equals 50%, meaning that 50% of the displaced crops would be provided by agricultural area expansion; the other half would be provided by yield increases. The assumption is based on findings of Lywood et al. (2009b), who calculated shares of between 10 and 78% for several biofuel feedstocks to be provided by yield increases. In this case study the relation between NEA and the entire agricultural area in Malawi is 0.0001, resulting in an additional yield increase of 0.005%. The average yield increase is thus 1.300% in the baseline and 1.305% in the biofuel expansion scenario. Overall, an additional 319 ha ($ILUC_{dom\_net}$) will thus be needed in order to maintain the agricultural output.

In step 5 ILUC-induced GHG emissions ($ILUC_{GHG}$) are estimated based on information about previous LUC in Malawi. CO_2 emissions related to the conversion of forest to cropland amount to 19 t CO_2 ha^{-1} yr^{-1} when allocating the emissions over 20 years; conversion of grassland and wetland to cropland leads to emissions of about 4 t CO_2 ha^{-1} yr^{-1}, respectively. The average CO_2 LUC emission factor (ΔCO_{2dom}) thus is 16 t CO_2 ha^{-1} yr^{-1} (see Table 5.4). Emissions due to $ILUC_{dom\_net}$ are then related to the additional amount of ethanol produced on the GEA. Without considering efficiency gains, $ILUC_{GHG}$ would thus account for 74 g CO_{2eq} MJ^{-1} of ethanol.

Table 5.4: LUC in Malawi and CO_2 emissions from LUC
Source: Data on land conversion is taken from (GoM 2009); results in g CO_2 MJ^{-1} of ethanol based on energy allocation; the CO_2 totals are weighted by share.

Land use	Converted 1991-2008 [1000 ha]	Share of converted area [%]	CO_2* [t ha^{-1} yr^{-1}]	$ILUC_{GHG}$ [g CO_2 MJ^{-1} of ethanol]
Forest / woodland	698	82.1	19	
Grassland	20	2.4	4	
O Dambo (wetland)	132	15.5	4	
Total	**850**	**100.0**	**16**	**74**

* The calculation is based on IPCC (2006b); above ground biomass in forest = 140 t dm ha^{-1} and in grassland = 16.6 t dm ha^{-1}; ratio of below-ground biomass to above-ground biomass in forest = 0.28; carbon fraction of dry matter = 0.5; dead wood/litter stock under forest = 2.8 (t C ha^{-1}); SOC_{ref} under forest and grass = 39 t C ha^{-1} and under wetland = 86 t C ha^{-1}; F_{MG} = 1.15; F_I = 1.11; all other final stock-change factors = 1. CO_2 emissions allocated over 20 yr.

When we consider the expected additional yield increase induced by the overall sugarcane area expansion in Malawi, $ILUC_{GHG}$ only accounts for 37 g CO_{2eq} MJ^{-1} of ethanol. The expected yield increase thus halves the ILUC factor.

5.1.2.2 ILUC with the implementation of compensation measures

Specific compensation measures such as the SVIP can further contribute to reducing ILUC emissions. How high the intensification in productivity has to be in order to completely compensate the sugarcane expansion depends on the extent of intensification, and on the relation between the size of the area expansion and the size of the area on which the additional intensification takes place.

The key question is whether the yield increase due to SVIP will compensate for the conversion of food crop plantations to sugarcane area.

The SVIP will cover roughly 40,000 ha, using the water resources of the Shire River, with at least an additional 9,000 ha of this area targeted for sugarcane cultivation. 15,000 ha of the overall 40,000 ha are already being cultivated with sugarcane and also irrigated, so that no yield increase on this share of the area is expected to happen. The rest of the area is mainly used by small-scale farmers for maize cultivation (see Table 5.5); here high-yield increases are to be anticipated.

Table 5.5: Current and projected land use and yields in the area of the SVIP (HY scenario) before and after implementation of the SVIP
Source: SVIP project description

	Current utilization [ha]	Yield [t ha^{-1}]	Yield [t]	Planned utilization [ha]	Expected yield [t ha^{-1}]	Expected yield [t]
Staple crops						
Maize	12,639	0.53	6,640	9,121	8.0	72,971
Sorghum	1,923	0.59	1,142	698	10.0	6,982
Rice	796	1.10	875	3,602	6.0	21,609
Pulses	5,395	0.70	3,984			
Cash crops						
Cotton	5,992	8.10		4,519		
Sugar	15,000			24,200		
Other crops	394					
Total	42,140		12,641	42,140		101,562

According to the current plans, maize, sorghum and rice are to be the major food crops in the SVIP. The crop pattern presented in Table 5.5 serves only as a recommendation from the project planners – the small-scale farmers will continue to be able to choose which crops they cultivate. The results still can help to demonstrate how the limited cultivation area in a country or region could be allocated to different sub-sectors in order to avoid or at least minimize ILUC.

The agricultural area within the SVIP remaining for food-crop cultivation, which represents the area in which the compensation measure occurs, covers 13,421 ha. Considering the entire 13,421 ha area would mean to completely credit the increase in productivity to the additional ethanol production; however, the project will presumably be financed as a public-private partnership, held by the sugar company, the Malawian government, and an international donor. The sugar company makes its profits by sugar manufacturing but also by selling the molasses to the ethanol company, so that ethanol production represents an incentive to expand the sugarcane cultivation and thus to invest in the irrigation system.

However, the main intent of the Malawian government's investment in this project is to increase food security in Malawi (pers. comm., G. Mwepa 2011). Thus, it makes sense not to credit the entire benefit in productivity to the biofuel production, but to allocate it among specific targets; this can be done based on the share of the overall financial volume that each group finally is going to invest. Given that these figures are not yet known, the calculation has to be based on assumptions. If we assume that the sugar company will invest a 10% share of the budget required for the 13,421 ha and that in turn 10% of this investment could be credited for ethanol production, then the reference area would amount to 134 ha.

In order to avoid distortions of the results with regard to switching from lower yielding to higher yielding crops, the same usage (share of crops) was assumed before and after implementation of the SVIP. For the ethanol scenario without compensation it is assumed that crop yields on the SVIP area increase by only 1.3% annually.

In order to estimate the ILUC effect including consideration of compensation measures, two scenarios were considered. The first scenario, "high yield" (HY), is based on the current SVIP planning. As the expected yield increases found in the project description were criticized by Malawian agricultural experts as being too high, a second scenario, "low yield" (LY), with more cautious assumptions regarding the expected yield increase was calculated (see Table 5.6 and Table 5.7).

Table 5.6: Potential yield increases through irrigation in the Southern Region (Malawi)
Source: Yields before and with SVIP in HY are based on the project description; yields with SVIP in LY are derived from Fandika et al. (2008)

	High Yield Scenario (HY)		Low Yield Scenario (LY)	
	Yield before SVIP [t ha^{-1}]	**Yield with SVIP** [t ha^{-1}]	**Yield before SVIP** [t ha^{-1}]	**Yield with SVIP** [t ha^{-1}]
Maize	0.5	8.0	0.5	5.0
Sorghum	0.6	10.0	0.6	5.0
Rice	1.1	6.0	1.1	3.0
Pulses	0.7	-	0.7	-

Table 5.7: Current and recommended land use and yields in the area of the SVIP (LY scenario) before and after implementation of the SVIP
Source: Project description; expected yields from Fandika et al. (2008)

	Assumed utilization [ha]	**Current yield** [t ha^{-1}]	**Current yield** [t]	**Planned utilization** [ha]	**Expected yield** [t ha^{-1}]	**Expected yield** [t]
Maize	91	0.5	48	91	5.0	455
Sorghum	7	0.6	4	7	5.0	35
Rice	36	1.1	40	36	3.0	108
Total	134		92	134		598

Estimates underlying the current planning assume that maize yields will be 15 times higher after the implementation of the SVIP, sorghum yields 17 times higher, and rice yields five times higher. The overall yield increase weighted by share of agricultural area after implementation of the SVIP thus amounts to 1008%. This extremely high yield increase would free up a total area of −1,353 ha (A_F); the net ILUC effect ($ILUC_{dom\_net}$) thus is negative in this case and amounts to −714 ha. $ILUC_{GHG}$ would thus be −83 g CO_{2eq} MJ^{-1} of ethanol in the HY scenario.

According to Fandika et al. (2008), the average maize yield for smallholder winter maize in the Southern Region will increase no more than 4 to 6 t ha^{-1} by means of optimized irrigation and fertilization. The total yield increase in the LY scenario thus is only 553% for the entire area, which would free up an area of totally −742 ha; overall the net ILUC effect ($ILUC_{dom\_net}$) thus is −103 ha and the associated CO_2 emissions −12 g CO_{2eq} MJ^{-1} of ethanol ($ILUC_{GHG}$).

5.1.2.3 GHG emissions from efficiency gains

Measures that enable efficiency gains in agricultural production may lead to the release of additional GHG emissions, as is the case with the application of additional fertilizer. These emissions have to be taken into account in order to determine overall net ILUC emissions ($ILUC_{GHG\_net}$). Given that most of the models do not consider GHG emissions from intensification measures, these are presented here separately.

The irrigation system as planned within the SVIP will work with gravity; GHG emissions due to the technical operation thus are not anticipated. However, the yields documented in the project description suggest an optimized fertilization was also taken into account. Fandika (2008) observed improved yields at N-fertilization rates of 120 kg ha^{-1}. Current fertilization rates are likely to be significantly lower. As a simplification, 60 kg N ha^{-1} are assumed to be additionally needed in order to reach the yields described in HY and LY. Taking into account an emission factor for N fertilizer production of 7.5 kg CO_{2eq} kg^{-1} of N fertilizer and N_2O emissions of 1% of the total amount of applied N, produces additional GHG emissions of less than 1 g CO_{2eq} MJ^{-1} of ethanol (see Table 5.8), so that there would still be a significantly high net GHG savings compared to the same situation without the compensation measure.

Table 5.8: ILUC factors for additional sugarcane ethanol produced in the Southern Region of Malawi with and without the consideration of GHG emissions from efficiency gains

Best estimates	$ILUC_{GHG}$ [g CO_{2eq} MJ^{-1} of ethanol]	EFF_{GHG} [g CO_{2eq} MJ^{-1} of ethanol]	$ILUC_{GHG\_net}$ [g CO_{2eq} MJ^{-1} of ethanol]
Without compensation measures	37	3	40
With compensation measure (LY)	−12	0.6	−11
With compensation measure (HY)	−83	0.6	−82

5.1.2.4 Overview of ILUC-induced GHG emissions

The best estimate considers those input parameters that seem most likely for the case study on sugarcane ethanol production in Malawi. The best estimate without the application of compensation measures amounts to 40 g CO_{2eq} MJ^{-1} of ethanol ($ILUC_{GHG\_net}$). However, if an investment in an irrigation system occurs as a compensation measure and if positive land-use impacts are taken into account, negative ILUC factors are possible, even if GHG emissions from additional fertilizer application are considered; this is due to the strong positive effect of implementing the SVIP on the overall demand on agricultural land. The best estimate with the application of the SVIP amounts to −11 g CO_{2eq} MJ^{-1} of ethanol (LY). In order to compare the results to those of a more general model, the ILUC factor was also calculated according to the deterministic model of Fritsche et al. (2010a), who calculated global mean LUC CO_2 emissions of 13.5 t CO_2 ha^{-1} or 3.4 t CO_2 ha^{-1} with a 25% ILUC risk (see Fritsche et al. 2010b). With an energy yield of 203 GJ of ethanol and sugar in Malawi, the 25% ILUC factor for sugarcane ethanol produced in Malawi would be 17 g CO_{2eq} MJ^{-1} of ethanol (100% ILUC factor = 67 g CO_{2eq} MJ^{-1} of ethanol) (see Figure 5.2).

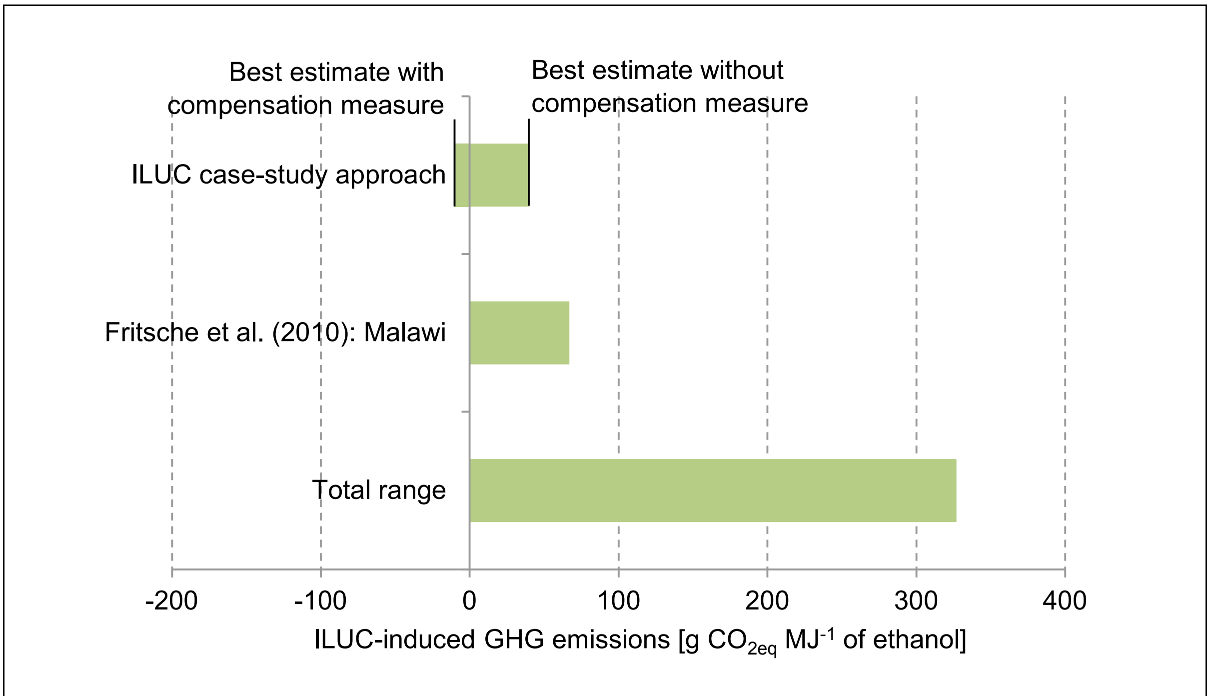

Figure 5.2: Best estimates for ILUC-induced GHG emissions for sugarcane ethanol produced in the Southern Region of Malawi
Source: Author's case-study approach vs. Fritsche et al. (2010b) and vs. the total range of ILUC factors for ethanol in the secondary research literature (see section 2.2.3) but excluding the negative value for wheat ethanol from Bauen et al.(2010)

The best estimate $ILUC_{GHG\_net}$ of 40 g CO_{2eq} MJ^{-1} of ethanol is thus significantly lower than the 100% ILUC factor calculated according to the model of Fritsche et al. (2010b). In comparison to the total range of ILUC factors found in the secondary research literature (see section 2.2.3) the negative value due to the implementation of the SVIP is striking. Negative values are almost unknown in the secondary literature, as most existing approaches do not consider the effect of compensation measures. For sugarcane ethanol, no such values have been documented. Bauen et al. (2010) did find negative values for wheat ethanol, when considering the positive effect of DDGS on the overall agricultural land demand by system expansion.

5.1.3 GHG emissions due to direct effects

5.1.3.1 System boundary, data sources, and allocation procedure

Sugarcane is a perennial crop with a cultivation phase generally of seven to eight years and a harvest every twelve months (Franke 1994). Harvesting can be done manually or mechanically. In Malawi sugarcane is largely harvested manually, with the one exception being a small experimental area. Manual harvesting in Malawi, as elsewhere, is combined with pre-harvest burning, a controlled on-site burning of dead sugarcane leaves that facilitates the harvesting. After the sugarcane has been transported to the mill, the sucrose-containing juice is pressed out of the stalk. Ethanol can be produced directly from the raw juice or from molasses, a liquid by-product from sugar manufacturing. In Malawi ethanol is solely produced from molasses.

The two regions, Dwangwa and Nchalo, each have their own separate sugar mills and ethanol production plants. Input data for sugar milling was only available for Nchalo and thus the subsequent CF calculations are based solely on this location; however, the cultivation and manufacturing conditions are very similar at both sites. The main difference is that the rainfall in Dwangwa, roughly 1400 mm, is almost sufficient for sugarcane cultivation and only minimal additional irrigation is necessary, while in the dryer and hotter Southern Region regular irrigation is essential (Church et al. 2008). Figure 5.3 illustrates the process flow diagram for sugarcane ethanol produced in Nchalo. In addition to ethanol, an essential output from the ethanol plants is the distillation residue, the so-called vinasse, which at both sites is held in evaporation ponds. In Nchalo, roughly one quarter of the vinasse is used as a fertilizer while the main portion, of 80,000 t, is stored in evaporation ponds; vinasse storage accrues in eight ponds, each with a height of 1.5 m, a width of 50 m, and a length of 350 m; the residence time is three months. In accordance with IPCC (2006a), the release of methane during storage of vinasse in open ponds was calculated as:

$$E_{CH4,storage} = COD_{available,m} * B_0 * MCF \qquad (5.1)$$

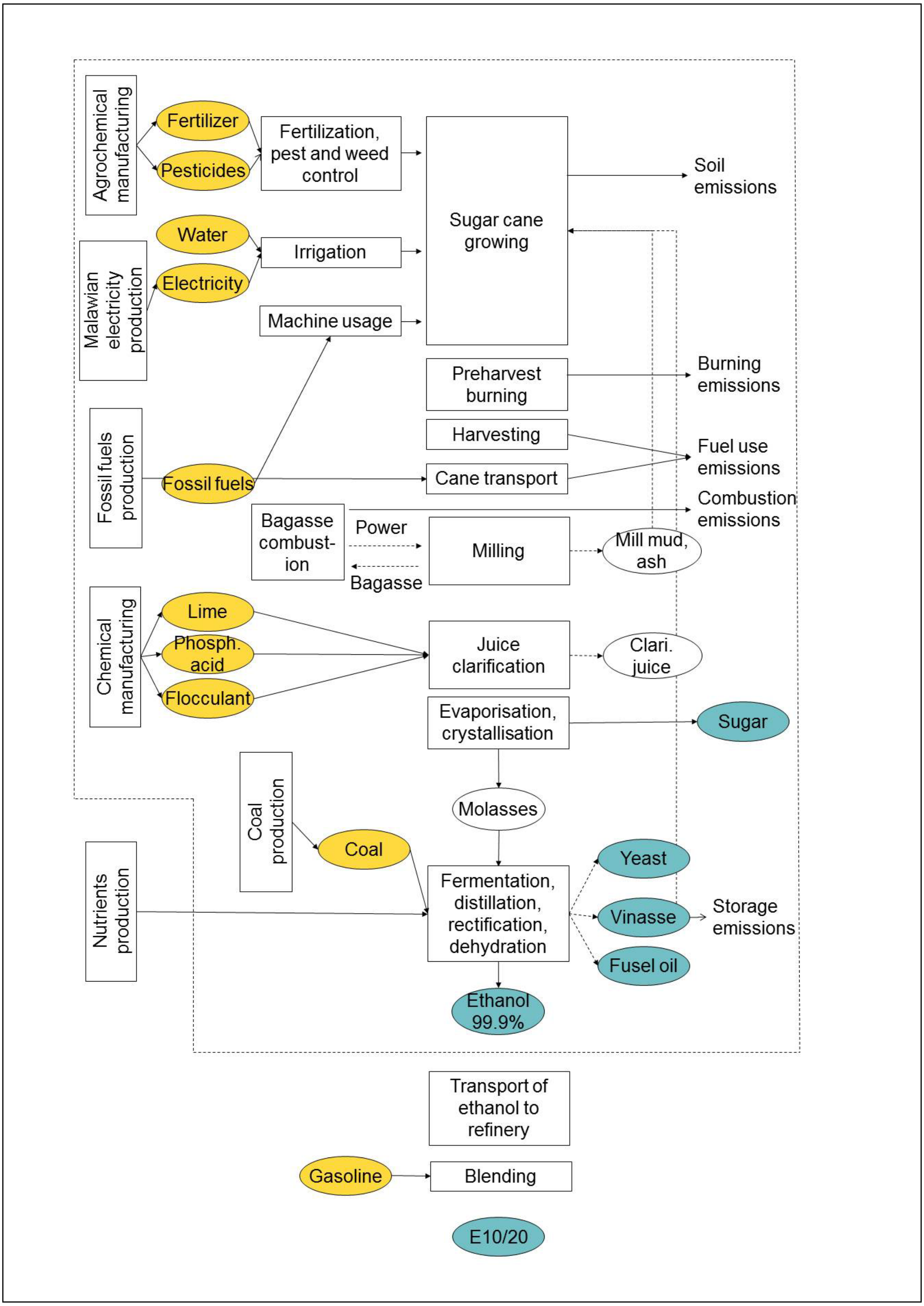

Figure 5.3: Process flow diagram for sugarcane ethanol production from molasses in Malawi

The broken line marks the system boundaries; orange ellipses (light grey) are materials and products that enter the production process; blue ellipses (dark grey) mark outputs.

$E_{CH4, storage}$	Methane emissions occurring during vinasse storage [kg L^{-1}]
$COD_{available,m}$	Chemical oxygen demand available monthly for the conversion[9]
B_0	Maximum methane production capacity (0.25 kg kg^{-1} COD)
MCF	Methane correction factor (0.2)

Given that ethanol is not being produced throughout the whole year, the assumption was made that vinasse accumulation occurred during eight months of the year, with the amount produced in one month being stored for three months in one pond. After evaporation the remaining sludge is disposed of at a landfill. In a pilot project small amounts of the sludge are being used as manure to improve soil quality. Given vinasse's high C content and its biological oxygen demand of >20,000 mg L^{-1} (Lisboa et al. 2011), its storage represents a relevant source of methane; however, vinasse is a potential substrate for biogas production for these same reasons.

The dataset used for CF calculation is based on the practices established in the sugarcane area in the Southern Region. Companies involved in sugarcane ethanol production filled out previously prepared questionnaires during field research in the country (see Table 5.9 and Table 5.10). The amount of cane trash was calculated based on a straw/fresh cane ratio of 0.19 (De Figueiredo and La Scala 2011).

Table 5.9: Basis data: sugarcane cultivation in the Southern Region of Malawi
Source: Average data for the 13,800 ha of sugarcane area in the Southern Region (2010)

Item	Unit	Quantity	Ref.
Cane productivity	t ha^{-1}	111	Questionnaire
Cane trash (dry basis)	t ha^{-1}	21	Own calculation*
Electricity (irrigation)	MWh ha^{-1}	7	Questionnaire
Diesel	MJ ha^{-1}	5,406	Questionnaire
Petrol	MJ ha^{-1}	342	Questionnaire
N-fertilizer	kg ha^{-1}	161	Questionnaire
Pesticides	kg ha^{-1}	15	Questionnaire
Diesel for haulage	MJ t^{-1} of sugarcane	38	Questionnaire

* Based on a straw/fresh cane ratio of 0.19 (De Figueiredo and La Scala 2011).

[9] $COD_{available,m}$ is equal to the COD of vinasse (40 g L^{-1} (Baez-Smith 2006) plus the COD carried over from the previous month. The amount carried over equals that available for conversion minus that consumed ($COD_{available,m}$ multiplied with MCF).

Table 5.10: Basis data: sugarcane ethanol production in the Southern Region of Malawi

Source: Average data for 2010

Item	Unit	Quantity	Ref.
Sugar mill			
Hydrated lime	kg t^{-1} of sugarcane	1.00	Questionnaire
Phosphoric acid	kg t^{-1} of sugarcane	0.03	Questionnaire
Output molasses	kg t^{-1} of sugarcane	30	Questionnaire
Ethanol production			Questionnaire
Coal	MJ t^{-1} of molasses	2,964	Questionnaire
Urea	kg t^{-1} of molasses	0.66	Questionnaire
Sulphuric acid	kg t^{-1} of molasses	0.18	Questionnaire
Caustic soda	kg t^{-1} of molasses	0.02	Questionnaire
Output ethanol	L t^{-1} of molasses	240	Questionnaire
Output vinasse	t t^{-1} of molasses	2.40	Questionnaire

Emission factors used to calculate the CFs of ethanol are shown in Table 5.11. In those cases where specific data for Malawi were not available, generic values from IPCC were used. This accounts, for example, for emissions from pre-harvest burning, soil N_2O emissions from the use of chemical fertilizer, and CH_4 emissions from vinasse storage. Specific emission factors for fossil fuels and fertilizers used in Malawi were also not available; therefore default values from IPCC or factors recorded for South Africa or Europe were used. A specific value valid for electricity production in Malawi was used, however, since 88% of the entire production came from hydropower in 2010 (eia 2012); the emission factor, therefore, is comparatively low. As described in section 4.1, energy and economic allocation were used to allocate the GHG emissions to the products sugar and ethanol.

Table 5.11: Emission factors used to calculate the CFs of ethanol

Item	Region	Unit	Quantity	Reference
Diesel	Default value	g CO_{2eq} MJ^{-1}	88	IPCC (2006c, 3.16ff), Punter et al. (2004, 60)
Gasoline	Default value	g CO_{2eq} MJ^{-1}	82	IPCC (2006c, 3.16ff), Punter et al. (2004, 60)
Coal boiler	South Africa	g CO_{2eq} MJ^{-1}	108	GEMIS 4.7

Item	Region	Unit	Quantity	Reference
Heat from natural gas cogeneration	Germany	g CO_{2eq} MJ^{-1}	37	Own calculation, based on GEMIS 4.7
Electricity from natural gas cogeneration	Germany	g CO_{2eq} MJ^{-1}	105	
Electricity	Malawi	g CO_{2eq} MJ^{-1}	42	
Electricity	Brazil	g CO_{2eq} MJ^{-1}	61	Ecoinvent 2.2
Electricity	Germany	g CO_{2eq} MJ^{-1}	157	Thrän et al. (2011)
N fertilizer	Europe	kg CO_{2eq} kg^{-1}	7.5	GEMIS 4.7
P fertilizer	Europe	kg CO_{2eq} kg^{-1}	1.2	GEMIS 4.7
K fertilizer	Europe	kg CO_{2eq} kg^{-1}	1.2	GEMIS 4.7
Lime	Europe	kg CO_{2eq} kg^{-1}	0.6	GEMIS 4.7
Pesticides	Europe	kg CO_{2eq} kg^{-1}	12	GEMIS 4.7
Phosphoric acid	Europe	kg CO_{2eq} kg^{-1}	3.6	GEMIS 4.7
Sulphuric acid	Europe	kg CO_{2eq} kg^{-1}	1.2	GEMIS 4.7
Caustic soda	Europe	kg CO_{2eq} kg^{-1}	0.5	GEMIS 4.7
Urea	Europe	kg CO_{2eq} kg^{-1}	0.8	GEMIS 4.7
Diammonium phosphate	Europe	kg CO_{2eq} kg^{-1}	0.5	GEMIS 4.7
Calcium chloride	Europe	kg CO_{2eq} kg^{-1}	0.9	GEMIS 4.7
N_2O soil emissions	Default value	%	1.0	IPCC (2006b)
Pre-harvest burning CH_4	Default value	g CO_{2eq} kg^{-1}*	62	IPCC (2006b)
Pre-harvest burning N_2O	Default value	g CO_{2eq} kg^{-1}	21	IPCC (2006b)
Vinasse storage				
Methane correction factor			0.2	IPCC (2006a)
Maximum methane production capacity B_0		kg CH_4 kg COD^{-1}	0.25	IPCC (2006a)
Chemical oxygen demand (COD)		g L^{-1}	40	IPCC (2006a)

* Related to dry mass of cane trash

Energy allocation: Inputs and outputs are allocated to the by-products according to their LHV. Sugar has a LHV of 16,500 MJ t^{-1} (Rein 2010) and an LHV of 3,300 MJ t^{-1} was estimated for molasses. This assumption is based on a sucrose content of molasses of 20% (fresh-weight basis) and an LHV of 16,500 MJ t^{-1} of sucrose. Assuming then that 0.11 t of sugar and 0.04 t of molasses are being produced from 1 t of sugarcane in the Southern Region of Malawi implies a relative contribution of sugar and ethanol of 13:1, and emissions are accordingly allocated between sugar and ethanol at 92.9% and 7.1%, respectively.

Economic allocation: The prices for sugar and molasses in 2010 were 162,200 MKW t^{-1} for sugar and 4,850 MKW t^{-1} for molasses (pers. comm., L. Chakaniza, 2011) (1,053 USD t^{-1} for sugar and 31.5 USD t^{-1} for molasses), respectively. The relative contribution of sugar and molasses is 87:1, and emissions are accordingly allocated between sugar and molasses at 98.9% and 1.1%, respectively.

According to the RED (2009/28/EC), emissions related to DLUC must be included in the CF. Given that the planned expansions in the Southern Region will take place on land already used for agriculture land, GHG emissions are assumed to be zero in accordance with the RED (2009/28/EC).

Three scenarios were calculated in order to point out existing optimization potentials regarding the CF. Scenario 1 (SC 1.1) represents the status quo. Scenario 2 (SC 1.2) suggests using the vinasse as an input for biogas production in order to replace a portion of the coal used currently for heat production. Scenario 3 (SC 1.3) additionally assumes green harvesting is applied instead of pre-harvest burning. Harvesting without burning delivers additional biomass, which can be used as a substitute for coal.

Green harvesting may affect N availability: While De Figueiredo and La Scala (2011) report higher requirements of N fertilizer during the first five years after the switchover, according to Hartemink (2008) small reductions of N fertilizer application may be possible in the long term. Given that the long-term effect is not known for the specific site, in this case study the amount of N fertilizer application was assumed to remain unchanged after the switchover. Green harvesting is often done mechanically instead of manually, so that according to the literature, diesel consumption per hectare would increase by 52% compared to the status quo (De Figueiredo and La Scala 2011); this effect was considered in the calculations, although manual harvesting is likely to continue in Malawi for some time.

5.1.3.2 Carbon footprint (CF) results

Sugarcane yields in Malawi are roughly 55% higher than the global average sugarcane yield of 71 t ha^{-1} (Lisboa et al. 2011). The location in the Southern Region, Nchalo, shows a level of GHG emissions of 46 kg CO_{2eq} t^{-1} of sugarcane (see Table

A.7 in the appendix). GHG emissions, thus, are significantly higher in comparison with sugarcane produced in other countries (38 kg CO_{2eq} t^{-1} of sugarcane in Thailand and 31 kg CO_{2eq} t^{-1} of sugarcane in Brazil (Nguyen and Gheewala 2008)). Higher GHG emissions are the result of a higher N fertilizer input in Malawi, of high diesel consumption as well as the electricity input needed for irrigation.

Processes in the sugar mill do not contribute significantly to the total CF of ethanol (see Figure 5.4). The only energy source used in the sugar mill is bagasse, which is a by-product of sugar production and for which no GHG emissions are accounted for.

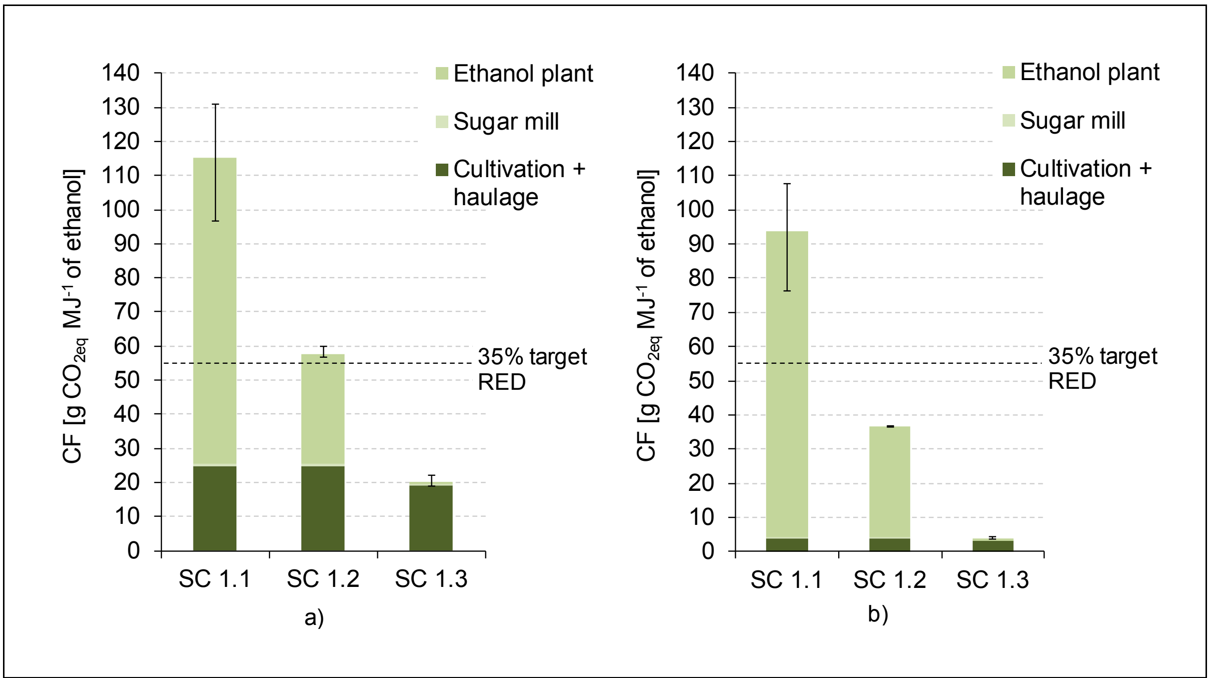

Figure 5.4: CF of sugarcane ethanol produced in the Southern Region (three scenarios)
a) Energy allocation b) Economic allocation
SC 1.1: Vinasse evaporation in open ponds; SC 1.2.: Biogas production from vinasse; SC 1.3. Green harvesting instead of pre-harvest burning. Error bars result from a variation of N_2O emissions from N fertilizer between 0.5–3% and a MCF of 0.1–0.3.

However, in SC 1.1, extremely high GHG emissions arise from the ethanol production. Two processes, in particular, are responsible for these emissions: vinasse storage in open ponds and coal usage to generate process heat. GHG emissions from vinasse storage in open ponds account for 39 g CO_{2eq} MJ^{-1} of ethanol. This value demonstrates that evaporation of vinasse in open ponds is an inacceptable practice with regard to its climate impact. Coal-fired boilers account for another 50 g CO_{2eq} MJ^{-1} of ethanol. In SC 1.1 a total of 115 g CO_{2eq} MJ^{-1} of ethanol is released (energy allocation). Given that the RED default value is 83.8 g MJ^{-1} for gasoline (2009/28/EC), the product would therefore not be accepted for the EU's renewable energies quota.

In SC 1.2, the vinasse was assumed to be used as an input for biogas production. Assuming a biogas recovery rate of 26 m^3 m^{-3} of vinasse and a heating value of 6.64 kWh m^{-3} of biogas, biogas production would amount to 4.6 MJ L^{-1} of ethanol (cf. Nguyen and Gheewala 2008). This represents almost 40% of the entire required energy in the ethanol plant, so the demand for coal could be reduced significantly and would result in a considerably lower CF of 58 g CO_{2eq} MJ^{-1} of ethanol in total.

In SC 1.3, the rest of the coal is replaced by additionally obtained biomass from green harvesting. Cane straw has a LHV of roughly 15 MJ t^{-1} (Dias et al. 2009); 10% of the straw delivered through green harvesting would be more than enough to compensate for the currently overall used coal. Potential negative impacts on soil quality due to the extraction of biomass can thus be avoided because 50% cane trash is usually enough to provide weed and erosion control on the field (Dias et al. 2009).

GHG emissions related to sugarcane cultivation in SC 1.3 are altogether slightly lower compared to SC 1.1 and 1.2. Although emissions from fuel consumption for harvesting are higher, the overall emissions are lower, due to cessation of pre-harvest burning. Fuel consumption data was taken from De Figueiredo and La Scala (2011) and refers to several mills in Brazil. Given that diesel consumption in mechanized harvesting varies widely from mill to mill, it is advisable to establish a country reference point by means of testing sites. With 20 g CO_{2eq} MJ^{-1} of ethanol (energy allocation), SC 1.3 is the scenario offering the lowest CF; this is due primarily to the use of residues as energy sources instead of coal. However, switching from manual to mechanical harvesting would incur substantial employment losses. In developing countries, it might thus be preferable to switch from pre-harvest burning to green harvesting while maintaining manual harvesting during a transitional phase. In this case, GHG emissions related to the cultivation stage in SC 1.3 are even lower and the total emissions in SC 1.3 would reach only 19 g CO_{2eq} MJ^{-1} of ethanol.

The relative effect of the allocation method on the end product's CF corresponds to the relative contribution of the cultivation procedure to the overall CF (cf. Nguyen and Gheewala 2008; see Figure 5.4 a and b). The greater the contribution of the cultivation stage to the overall CF, the greater the effect of switching from energy allocation to economic allocation (SC 1.1: −23%, SC 1.3: −415%).

As became clear, even without consideration of ILUC, sugarcane ethanol produced in the Southern Region of Malawi with the current manufacturing conditions does not fulfill the requirements of the RED. Only through investments in improved technology and adaptations to the harvest will it be possible for the product ethanol to save on GHG emissions as compared to fossil fuels. ILUC, however, can be relatively easily prevented by investing in irrigation systems in order to increase food crop yields.

5.2 Brazil – sugarcane ethanol

Brazil, in contrast to Malawi, plays a prominent role in the ongoing discussion of DLUC and ILUC related to biofuels production; this is due to the country's specific characteristics and its recent developments. Brazil represents one of the countries in the world with major primary forest resources, accounting for 28% of all original forest holdings worldwide in 2007 (Macedo and Seabra 2008). Deforestation and conservation of forest areas are therefore important issues. At the same time, the agricultural sector is characterized by enormous growth and the expansion of the biofuels sector is viewed by some scientists as a relevant driver behind the expansion of total agricultural area and thus deforestation (e.g. Dufey 2007; Andrade de Sá et al. 2013).

5.2.1 Country characterization

5.2.1.1 Biofuel production

5.2.1.1.1 Policies regarding biofuel production

In Brazil, policies promoting biofuel production already enjoy an astonishingly long tradition. Proálcool, the National Alcohol Program, was launched in 1975 as a reaction to high energy costs during the oil crisis. The program includes various measures, such as mandatory blending rates and guaranteed purchases by the state-owned company Petrobras. Proálcool has made ethanol an up-and-coming sector of the economy. The introduction of so-called flexible-fuel vehicles in 2003 has further increased sales of ethanol (Goldemberg et al. 2008).

Biodiesel has not yet achieved the same degree of importance. It was only in 2004 that the government implemented the Brazilian Biodiesel Program, with the intention of establishing biodiesel as a significant fuel in Brazil and diminishing the negative social and environmental effects related to biodiesel production (Gucciardi Garcez and De Souza Vianna 2009; Laabs and Gröteke 2010). While the social and environmental aspects have often been criticized as not being given sufficient attention, the establishment of biodiesel in the fuel market has been successful (Laabs and Gröteke 2010). Annual biodiesel production, however, is still an order of magnitude lower than ethanol production – 2.5 billion vs. 27 billion L, for 2010 (USDA 2010).

Sugarcane represents the main feedstock for ethanol production in Malawi. Unlike in Malawi, where sugarcane cultivation is hardly regulated, various efforts to achieve more sustainability within the ethanol production process exist in Brazil at both the national and regional level. A 1998 federal law mandates reductions in pre-harvest burning through an embargo on burning on flat areas (slope < 12%) to be fully implemented by 2018 (USDA 2010). The State of São Paulo has also established a schedule for completely banning pre-harvest burning by 2031 (USDA 2010). The São Paulo State Secretariat of Environment and Agriculture, the State Secretariat of Supply, and the Sugar and Ethanol Millers Association (UNICA) furthermore signed the so-called Green Protocol in 2008, committing themselves to ending burning on high slope areas by 2017 (Estado de São Paulo 2008).

A regulation regarding the application of vinasse also can be found at the state level: In the States of São Paulo and Minas Gerais the amount of vinasse allowed for application to a specific field depends on the site characteristics, e.g. the soil's potassium (K) content (CETESB 2006; COPAM 2011).

5.2.1.1.2 Data on ethanol production

Ethanol is mainly produced from sugarcane in Brazil. Brazil is the largest sugarcane- and second largest ethanol-producing country (after the USA) worldwide. In 2010 Brazil accounted for 43% of worldwide sugarcane production and 32% of ethanol production worldwide (see Table A.11 in the appendix). The annual production in 2010 comprised 602,193 thousand t of sugarcane, 25,694 million L of ethanol and 32,956 thousand t of sugar (UNICA 2012). Moreover, around 300 cogeneration plants (CONAB 2011), total capacity 6,287 MW (MME 2011), utilized bagasse from sugarcane as a feedstock in 2010. Sugarcane represents a strongly expanding crop. Only a portion of the sugarcane is used as a feedstock for biofuels production; however, the share used for ethanol fuel production is considerable, between 51 and 59% of total sugarcane production during the period 2007 to 2011 (see Table 5.12).

Table 5.12: Feedstock use in ethanol production and area used for cultivation (Brazil)
Source: Data on ethanol production, amount of sugarcane for ethanol production, and harvested area for sugarcane drawn from (USDA 2008; USDA 2009; USDA 2011a)

	2007	2008	2009	2010	2011
Ethanol production [1000 t]	17,820	21,441	20,623	22,092	19,116
SuC* for ethanol [1000 t]	216,140	267,650	330,000	340,700	335,100
SuC [1000 t]	428,000	491,100	555,000	603,000	660,000
SuC for ethanol [%]	51	55	59	57	51
Total SuC area harvested [1000 ha]	5,940	6,500	7,400	8,050	8,950
Net area SuC for ethanol [1000 ha]	3,000	3,543	4,400	4,548	4,544

*SuC = sugarcane

In order to calculate the net agricultural area used to cultivate sugarcane for ethanol production in Brazil, data on feedstock inputs were needed. The USDA regularly documents these data in its annual sugar reports (e.g. USDA 2007; USDA 2008; USDA 2009; USDA 2011a). By-products do not have to be considered, as the USDA reports already distinguish between sugar and ethanol production.

The calculation results prove that the net area used for ethanol production increased by 50% between 2007 and 2011, reaching an area of 4,500 thousand ha in 2011. The area expansion for ethanol production thus contributed to 39% of the overall expansion of agricultural area (data on land use can be found in Table A.12 in the appendix). Moreover, as sugarcane has mainly expanded on already existing agricultural areas, ethanol feedstock expansion has presumably led to ILUC in the past.

5.2.1.2 Land-use changes

5.2.1.2.1 Policies regarding land-use changes

One crucial measure in avoiding land-use changes is the Brazilian forest law, in existence since 1965 (Mueller and Alston 2007). The so-called Código Florestal defines Permanent Protection Areas, including riverbanks, water bodies, steep slopes, and hilltops, from which the vegetation may not be removed. Additionally, the law sets target values for so-called Legal Reserves, areas of natural habitat in private ownership. According to the Código Florestal, landowners are allowed to use a specific share of their total land for agriculture or other uses, but the remainder must be preserved. Within the Amazônia Legal[10], 80% of a private landowner's land should be preserved as these parcels are designated as legally protected reserves; in the Cerrado, 35%, and in the other biomes, only 20% needs to be preserved. The state of Pará, also part of the Amazônia Legal, represents an exception to the 80/20 rule. Here, a higher share of 50% of the total area is allowed be cultivated. The main reason for this exception is that huge areas in the North East had already been deforested decades earlier during the colonization period (Silva de Almeida et al. 2010) and have subsequently been in agricultural use for some time.

The Brazilian government enacted revisions to the forest law in October 2012. These revisions have been criticized by environmentalists for weakening forest protection, mainly because the preservation of riverbanks can now be counted toward the attainment of quotas. The preservation of riverbanks was previously treated separately, so that the revision reduces the total forest area farmers are required to keep intact. The revised law furthermore includes amnesties for small farmers by not requiring the recovery of already deforested area (mongabay 2012).

A general limitation to the forest law is that it is rather commonly disregarded by landowners. Obstacles to enforcement include a lack of incentives for landowners: compliance leads to a loss of potential income from the sale of agricultural products, and there is no provision for financial benefits to offset these losses. Financial penalties certainly reduce violations of the restrictions; however, enforcement by the Environmental Protection Agency in the state of Pará (SEMA) is regarded as random; SEMA employees stress a lack of sufficient staff and money for appropriate enforcement (pers. comm., T. Pompeu de Mello, 2011).

5.2.1.2.2 Data on land-use changes

Despite the long existence of the Código Florestal, Brazil lost almost 10% of its previously forested regions between 1990 and 2010 (see Table A.12 in the appendix). In order to consider data at a regional level, other sources and databases were evaluated in addition to FAOSTAT. INPE, the National Institute for Space Research, is continuously monitoring deforestation rates in the Amazônia Legal and other regions

[10] The Amazônia Legal is a territory defined by the Brazilian government that covers 550 million ha in the north of Brazil and includes the tropical rainforest region (Martino 2007).

of Brazil by analyzing satellite image data (see Figure 5.5). Deforestation rates are especially high in the states of Pará and Mato Grosso, which together were responsible for 69% of the total deforestation in the Amazônia Legal between 1990 and 2010. Figure 5.5 also demonstrates a considerable variation in deforestation rates over time; in particular, one can observe a decrease since 2004.

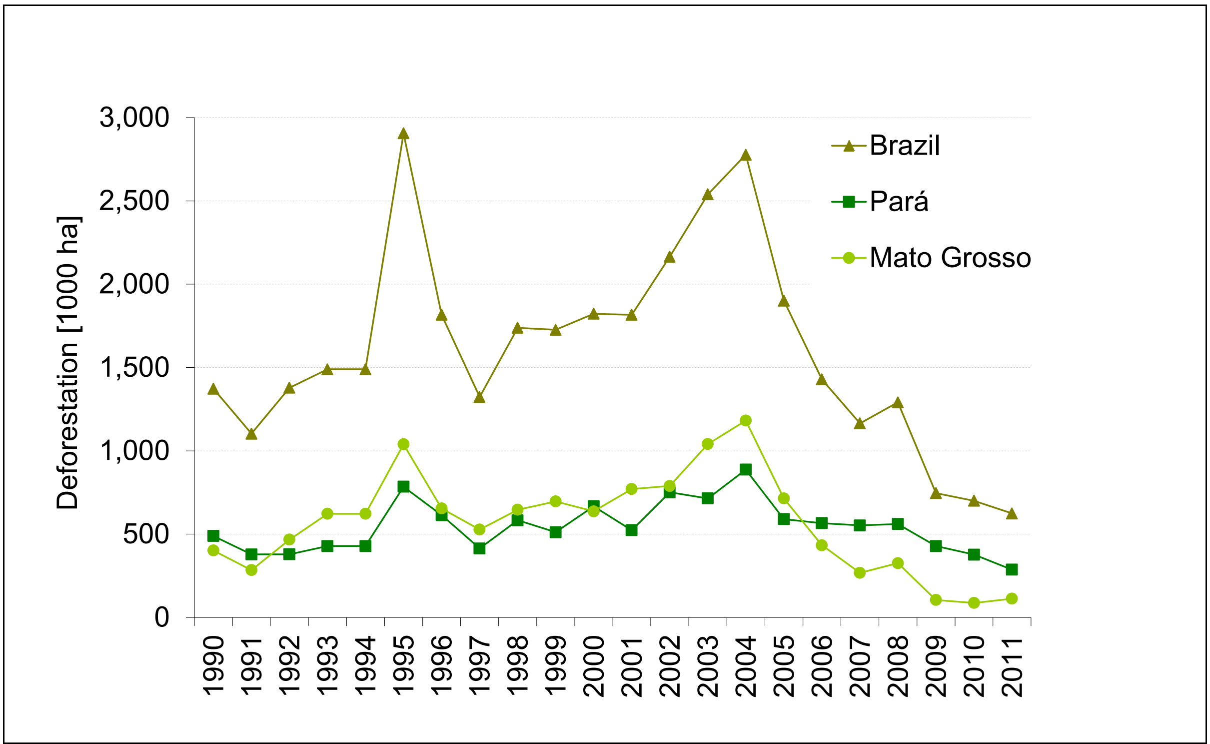

Figure 5.5: Deforestation rates in the States of Pará, Mato Grosso, and in Brazil
Source: (INPE 2011a; data can be found in the appendix)

Deforestation goes hand in hand with agricultural area expansion. Between 1990 and 2010, the area within the FAO categories *arable land, permanent crops, permanent meadows and pastures* as well as *other land*, have increased by roughly 20%, an increase of more than 55 million ha (see Table A.12 in the appendix). FAOSTAT data, however, does not include information about the specific transformations between different land uses. In order to answer questions about the specific LUC that have occurred, the Greenhouse Gas Inventory (GGI; MCTI 2010) for Brazil provides useful information (see Table 5.13); the GGI also provides data on LUC for the various biomes (Amazon, Cerrado, etc.), respectively. The data, however, refer to the period between 1994 and 2002 and do not consider more recent LUC.

Table 5.13: LUC between 1994 and 2002 in Brazil
Source: Based on (MCTI 2010)

Land use in 1994 [1000 ha]	**Land use in 2002 [1000 ha]** Forest	Grassland	Cropland	Settle-ments	Wetland	Other land	**Total 1994**
Forest	517,988	25,213	7,589	230	140	19	**551,180**
Grassland	1,117	171,693	5,052	304	8	5	**178,178**
Cropland	160	3,189	97,556	225	1	1	**101,131**
Settle-ments	0	0	0	2,359	0	0	**2,359**
Wetland	0	0	0	0	15,845	0	**15,845**
Other land	4	791	149	6	1	327	**1,278**
Total 2002	**519,268**	**200,886**	**110,346**	**3,124**	**15,995**	**352**	**849,970**

According to the GGI data, the major LUC activity has been the conversion of forest to agricultural area, occurring between 1994 and 2002. Overall, 25.2 million ha of forest have been converted into grassland and 7.6 ha forest have been converted into cropland (see Table 5.14). Within the same period, conversions between grassland and cropland in both directions have taken place, but overall, roughly 2 million ha more grassland were converted to cropland.

Table 5.14: Share of LUC between 1994 and 2002 in Brazil
Source: Based on (MCTI 2010)

	LUC	**Share in total conversion of natural ecosystems**	**Share in total conversion of natural ecosystems into cropland**
	[1000 ha]	**[%]**	**[%]**
Forest to grassland	25,213	72.7	
Forest to cropland	7,589	21.9	80.3
Grassland to cropland	1,863	5.4	19.7
Total	**34,665**	**100.0**	**100.0**

The data offered in the GGI is more accurate than the aggregated data presented here. It distinguishes between the different types of grassland, such as *unmanaged*, *managed*, *with secondary vegetation*, and *planted pasture* (MCTI 2010). A closer look at the data in MCTI (2010) demonstrates that all forest-to-grassland conversions taking place between 1994 and 2002 have resulted in planted pasture. Expanding pasture land, thus, has been one driver for deforestation in this period. Fearnside

(2005) also stated that the main land use after conversion of forest into agricultural land was historically cattle ranching; only within the last decade has soybean production become another common land use after conversion (Fearnside 2005).

MCTI (2010) also includes more specific data on LUC in the Brazilian biomes; as the data shows, the conversion of forest to grassland has mainly taken place in the Amazon and Cerrado biomes (see Table 5.15). The largest share of the total forest-to-cropland conversion has occurred in the Cerrado biome; additionally, in the Cerrado biome, 11% of the grassland that has remained grassland has been converted from unmanaged to managed grassland or planted pasture.

Table 5.15: LUC between 1994 and 2002 in several biomes in Brazil
Source: Based on (MCTI 2010)

Biome	Forest to grassland [1000 ha]	Forest to cropland [1000 ha]	Grassland to cropland [1000 ha]
Amazon	15,295	2,023	–321
Cerrado	4,693	3,834	2,160
Caatinga	3,000	1,565	39
Atlantic forest	1,633	106	11
Pampa	0	0	0
Pantanal	594	60	–25
Total	**25,213**	**7,589**	**1,863**

Data from FAOSTAT (2012) help to answer the question of which crops have been responsible for cropland expansion at the national level: The area used for cultivating permanent crops expanded from 6.7 million ha in 1990 to 7.1 million ha in 2010, and the area used as arable land expanded from 50.7 million ha to 70.3 million ha (see Table A.12 in the appendix). In particular, soybean and sugarcane areas have increased, while other crops, such as cotton, show decreases during this period. If one considers only expanding crops, the overall increase in the harvested area accounts for 19.6 million ha, with soybeans, sugarcane, and maize representing the most heavily expanded crops (FAOSTAT data on harvested area for crops can be found Table A.15 in the appendix). Given that the net area used for ethanol production has significantly increased within recent years, the expansion of ethanol production would seem to be a relevant driver for LUC.

5.2.1.3 Economic data, agricultural production, and trade

Along with biofuel production, the increasing global demand for agricultural products is a potential driver for cropland expansion. The Brazilian trade balance (export quantity minus import quantity) for agricultural products (biofuels were not included in the referenced data source) increased steadily between 2000 and 2007, by a total factor of 2.9. In 2008 it decreased slightly but increased again in 2009 and 2010 (see Figure 5.6 and Table A.16 in the appendix).

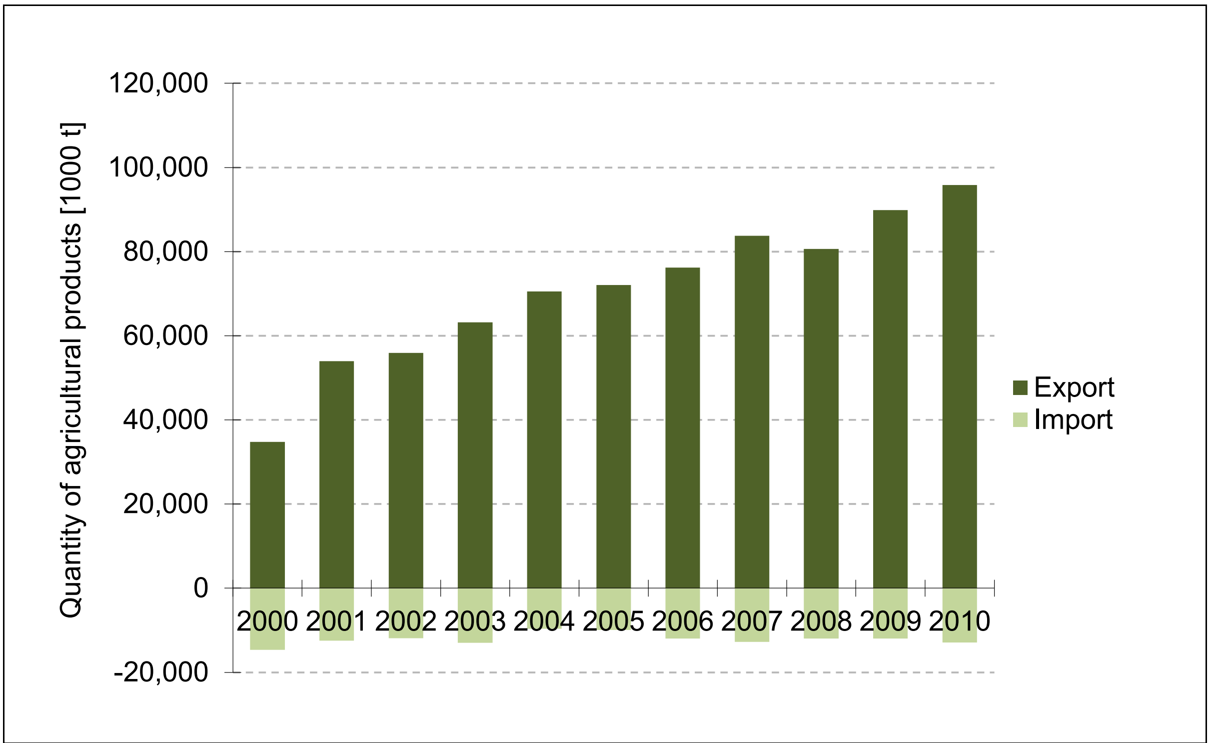

Figure 5.6: Import and export of agricultural products (Brazil)
Source: Based on (FAO 2012); data can be found in Table A.16 in the appendix

Products that show the highest increase in total exports by quantity are soybeans, raw and refined sugar, and maize. The global demand for these products might therefore be an important driver for expanding the agricultural area in Brazil. Between 2000 and 2010, the Brazilian population increased by an average annual growth rate of 1.5% per year, roughly 16% in total (IndexMundi 2011). The increasing domestic food demand is probably another driver for agricultural area expansion.

In order to assess the degree to which the domestic market is linked to the global market, the ratios of agricultural imports to food supply and agricultural exports to food supply were calculated. The results show that the ratio between import of agricultural products and food supply hovered between 5.4 and 9.0% in the period 2000 to 2009 (see Table A.16 in the appendix). The ratio between export of agricultural products and food supply ranged from 21.4 to 44.6%. The domestic and global markets are thus considerably more strongly linked than is the case in Malawi; however, the share of imported agricultural products in the total food supply is rather low. Brazil can thus be characterized as a net exporter of agricultural products.

This data confirms the expert opinion that Brazil itself produces the major share of the agricultural products consumed by the increasing population (cf. Valdes et al. 2009). Valdes et al. (2009) also found that the Brazilian population is changing its food consumption behavior towards a higher level of meat and milk consumption. Data from FAOSTAT (2012) show that meat consumption per capita increased steadily between 2000 and 2009. In comparison to the global average, meat consumption in Brazil is already high, having risen from 79 to 85 kg capita^{-1} yr^{-1} between 2000 and 2009 (see Table A.17 in the appendix); these numbers correspond to 207 and 204%, respectively, of the global average for meat consumption per capita. Milk consumption increased from 113 to 137 kg capita^{-1} yr^{-1} during this period, corresponding to 144 and 157% of the global average for milk consumption.

The intensity and productivity of agricultural production in Brazil are significantly higher than in Malawi. Average maize yields were used as an approximation for the intensity and productivity of agricultural production. Between 2000 and 2010 average maize yields ranged from 63 to 84% of the global average (see Table A.18 in the appendix). Thus, it can be assumed that crop yields in Brazil can still be further increased by investing in measures to intensify agricultural production; in particular, it may be possible to improve cattle farming productivity through increases in the cattle stocking rate (pers. comm., L. Barbosa, 2011; M. E. Chaves Oliveira, 2011).

5.2.1.4 Overview of country characterization

Table 5.16 summarizes the information and data given in the previous sections. The amount of ethanol produced in Brazil is already substantial, with Brazil being the second largest ethanol producer worldwide; moreover, ethanol production is expected to further increase (pers. comm., S. Teixeira Coelho, 2011). LUC is a relevant topic in Brazil; deforestation rates, in particular, are still high because of dysfunctional implementation of forest resource protection laws; thus, there is a risk of ILUC occurring as a consequence of biofuel feedstock expansion.

Table 5.16: Key characteristics of Brazil

Characteristic	Description
Relevance of biofuel production	Amount of biofuel production is high, expansion is expected
Relevance of LUC	High, especially deforestation
Trade dynamic of agricultural products	global dynamic, export-oriented
Intensity of agricultural production	Medium
Meat and dairy consumption	High

The trade dynamic for agricultural products is export-oriented; the import-to-supply ratio for agricultural products is low, the export-to-supply ratio for agricultural products high. The intensity of agricultural production is assumed to be moderate as average maize yields in Brazil are slightly lower than the global average. Measures that increase agricultural yields thus represent promising ILUC compensation measures. Meat and dairy consumption, in contrast, are high compared to the global averages. Compensation measures that decrease meat or dairy consumption will thus also be suitable for reducing ILUC.

5.2.2 ILUC due to sugarcane ethanol production

Sugarcane is the sole feedstock for bioethanol production in Brazil (USDA 2011b). Given that in 2010 more than 4,550 thousand ha of sugarcane were in production for fuel ethanol in Brazil and 436 biorefineries were in operation (USDA 2011b), the specific conditions with regard to sugarcane cultivation and ethanol production naturally vary significantly within the country (Macedo et al. 2008). Brazil, therefore, represents a considerably different case study than Malawi, where the domestic ethanol sector only includes two ethanol manufacturing plants. In Brazil, unlike Malawi, most of the mills are flexible and can easily shift between sugar and ethanol production, depending on the world market prices for sugar and ethanol (Fischer et al. 2008).

Brazilian research institutes offer a remarkably large body of literature regarding LCA on sugarcane ethanol production and land-use impacts of the sugarcane cultivation (Goldemberg et al. 2008; Macedo et al. 2008; Ometto et al. 2009; Crago et al. 2010; De Figueiredo and La Scala 2011; Andrade de Sá et al. 2013); however, some knowledge gaps still exist, e.g. regarding the environmental performance of the mills in specific regions (pers. comm., J. E. A. Seabra, 2011). As a part of this dissertation, a single exemplary site in Minas Gerais, a state for which only a small amount of information on the performance of its mills exists, was chosen for the ILUC assessment and the CF calculation for sugarcane ethanol.

Before the results of the ILUC case-study approach are presented, the following section deals with the question of where specifically the sugarcane area expansion occurred and whether sugarcane cultivation has led to DLUC in the past.

5.2.2.1 Sugarcane area expansion and DLUC

The sugarcane production area has expanded considerably during the last decades; the expansion, though, has not been constant over time (Macedo and Seabra 2008). Pró-Álcool and the resulting national demand for ethanol was clearly the driver for the first expansion phase, which saw a rise beginning in the mid-1970s and then a drop in 1984 (Macedo and Seabra 2008). A significantly lower price of petroleum was presumably the reason for the reduced expansion during 1985 and 2001. A second sharp expansion phase started in 2002 (see Figure 5.7); the major driver was the

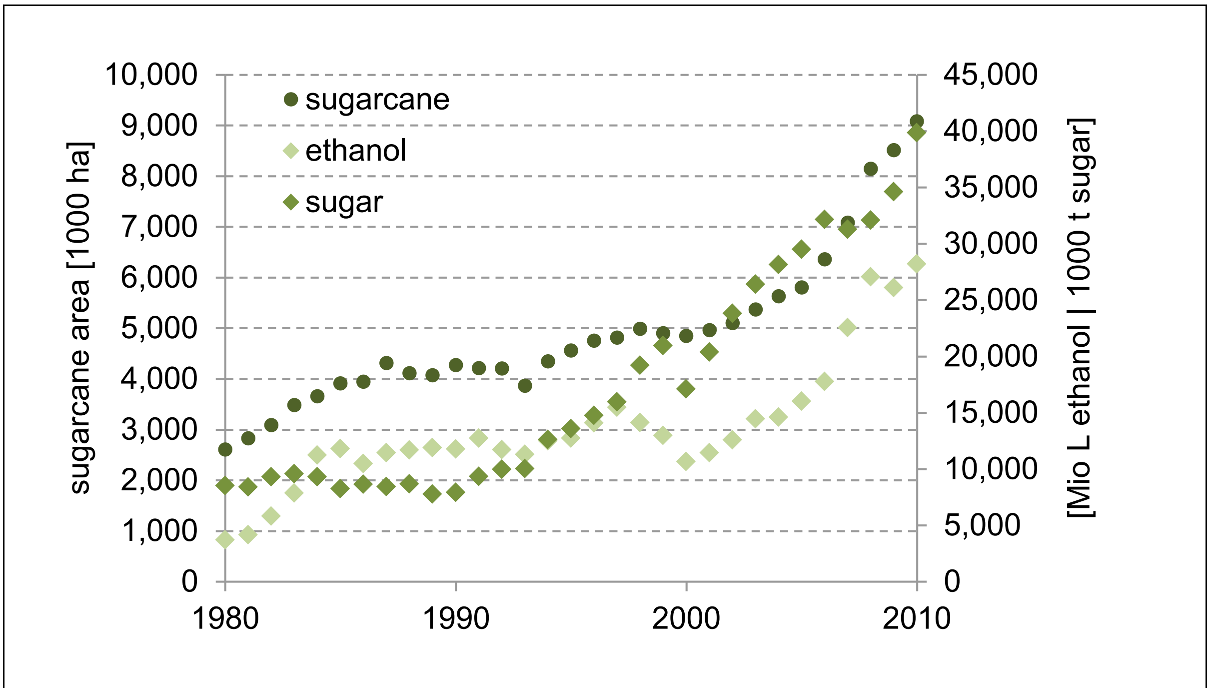

Figure 5.7: Sugarcane area, ethanol and sugar production between 1980 and 2010 in Brazil
Source: Based on data from (FAO 2012; eia 2011)

global demand for ethanol as many countries had developed policy instruments to partially fulfill their national fuel demand with biofuels (Fischer et al. 2008).

During 2002 and 2010 the sugarcane area increased by 78%, from 5,100 thousand ha to 9,077 thousand ha, and ethanol production more than doubled during this period (see Table A.19 in the appendix). The huge expansion in area since 2002 is very likely the main reason why DLUC and ILUC related to biofuel production have received considerable attention from Brazilian researchers (see Teixeira Coelho et al. 2007; Macedo and Seabra 2008; Lapola et al. 2010; De Souza Ferreira Filho and Horridge 2011; Nassar et al. 2011; Andrade de Sá et al. 2013).

Sugarcane cultivation is concentrated in the South-Central Region,[11] especially in the State of São Paulo, which accounts for 60% of the total sugarcane area and ethanol production in Brazil (see Table A.20 in the appendix). Other, noticeably smaller, sugarcane areas are located in Goiás, Minas Gerais, Mato Grosso, Mato Grosso do Sul, Paraná, and in the Northeast Region (see Table A.21 in the appendix). The major portion of the recent expansion took place in the State of São Paulo; between 2003[12] and 2010 the sugarcane area expanded there by 77%, from 3,009 thousand ha to 5,309 thousand ha, in 2010 (see Table A.20 in the appendix).

DLUC related to sugarcane cultivation obviously takes place mainly in the South-Central Region, where the sugarcane expansion is occurring. Given that the stock of convertible land has run out in most of the states in this region, it is predominantly already existing agricultural land that is being converted to sugarcane plantations (De Souza Ferreira Filho and Horridge 2011). According to CONAB (2010), 78% of the sugarcane area expansion in the 2008/2009 growing season took place on pasture land; in the 2009/2010 season the share was slightly lower (see Table 5.17). The large share of pasture land is probably due to its representation in the total agricultural land in Brazil, as well as its spatial proximity to existing sugarcane estates (Fischer et al. 2008). Nassar et al. (2008) presented data on DLUC for selected states in the South-Central Region. Their results are based on an analysis of remote

[11] The South-Central Region includes the states Goiás, Espírito Santo, Minas Gerais, Mato Grosso do Sul, Mato Grosso, Paraná, Rio de Janeiro, and São Paulo (INPE 2011b).

[12] Earlier data at the state level is not available in INPE (2011b).

sensing images to identify LUC and differ significantly from CONAB as they indicate that, depending on the respective state, only 21 to 55% of the expansion area was former pasture land with most of the area having been cropland.

Table 5.17: Former land use of the expansion sugarcane areas in Brazil (2008/2009 and 2009/2010 seasons)
Source: CONAB (2010, 52), CONAB (2012, 43)

Land use before conversion	2008/2009		2009/2010	
	Area [ha]	Share [%]	Area [ha]	Share [%]
Maize	11,639	2.6	9,570	3.0
Soy	37,566	8.4	49,585	15.8
Coffey	636	0.1	820	0.3
Orange	9,478	2.1	4,607	1.5
Pasture land	349,248	77.9	226,340	72.0
Natural ecosystems	4,047	0.9	No information	No information
Others	35,828	8.0	23,439	7.5
Total	**448,442**	**100.0**	**314,360**	**100.0**

Experiences with newly developed mills offer an explanation for these deviations: Many project planners mentioned the necessity of cultivating crops other than sugarcane following the conversion of pasture land as pasture land soils often suffer from low productivity. Sugarcane fields, furthermore, have to be renovated after roughly six harvests, so that normally 15 to 20% of the total sugarcane area is cultivated with another crop in order to improve soil quality (Nassar et al. 2008). The authors also provided results regarding the direct influence of sugarcane expansion on deforestation: While in most of the states the share of former forest in the total expansion area was small (< 2%), in Mato Grosso former forests represented a significant share of 8% of the expansion area in 2007 and 2008 (Nassar et al. 2008).

Scientists project that sugarcane area expansion will mainly occur in the State of São Paulo, but significant expansion is also expected to occur further west and north in Goiás, Mato Grosso, Minas Gerais, and Mato Grosso do Sul (Macedo and Seabra 2008). A model by Nassar et al. (2008) further predicts that pasture land will be the predominantly displaced land use.

5.2.2.2 ILUC without implementation of compensation measures

This section provides an analysis of the anticipated ILUC effect due to the planned sugarcane area expansion at the exemplary mill in Minas Gerais without implementation of specific compensation measures. The sugar and ethanol company interviewed in Minas Gerais is planning to expand the cultivation area through pasture land conversions, so that ILUC will presumably take place in order to provide land for the displaced cattle farming.

The size of the GEA is 5,000 ha. According to Lywood et al. (2009b), in Brazil 23% of the additional output of sugarcane could be accounted for through yield increases, and 77% is expected to result from area expansion. The current ethanol yield is 147 GJ ha^{-1} of sugarcane, if only ethanol is being produced; relying on the assumptions made by Lywood et al. (2009b), the yield will increase to 192 GJ ha^{-1}.

It is assumed that half of the expansion area is used for ethanol production and the other half for sugar production. The GEA is therefore allocated to the products sugar and ethanol according to their LHVs, with sugar having an LHV of 16,500 MJ t^{-1} (Rein 2010) and ethanol 21 MJ L^{-1} (ANL 2008). The allocation factor (F_{all}) is thus 0.5, so that NEA amounts to 2,500 ha, and the ethanol yield is thus reduced to 74 and 96 GJ ha^{-1} of sugarcane, respectively.

As described in section 4.1, ILUC could theoretically occur in Brazil itself or beyond its borders; therefore in step 3, estimates are made as to where ILUC will take place. The data and information provided in section 5.2.1 are useful for estimating whether ILUC induced by sugarcane ethanol production in Brazil will occur in the country itself or spill across the border. Overall, one could observe in Brazil:

- a constant loss of forest area during the last decades (I_{luc} is high)
- a constant expansion of the agricultural area (I_{luc} is high)
- a comparatively low ratio between import quantities of agricultural products and food supply (I_{market} is high)
- a comparatively high ratio between export quantities of agricultural products and food supply (I_{market} is low)

In light of these observations, it is likely that most or even all of the ILUC will occur within the country. The high ratio between export quantities and food supply indicates that Brazil could also export less in order to compensate the increasing biofuel feedstock cultivation. In this case ILUC would more likely spill over the border; however, this seems not to happen because the overall export quantities of agricultural products have steadily increased from 35 million tons in 2000 to 96 million tons in 2010. Therefore, in the following analysis it is assumed that ILUC occurs entirely within Brazil itself (F_{spill} = 0), so that $\%ILUC_{dom}$ is 100%.

In step 4, efficiency gains are considered. Since sugarcane area expansion largely involves pasture land, the extent of related ILUC largely depends on how cattle farming will develop. Nassar et al. (2008) assumed an increase of the stocking density and argued that the reduction of pasture land would not lead to a reduction of the supply of meat and dairy (Nassar et al. 2008). Other studies conducted by Brazilian scientists accordingly indicate a low ILUC risk for sugarcane expansion due to a high potential for intensification of agricultural activities (Teixeira Coelho et al. 2007; De Souza Ferreira Filho and Horridge 2011). If this is true, then the amount of ILUC could be significantly decreased or even fully compensated.

To prove the validity of these statements and to investigate the recent development of the livestock sector, the stocking rate of bovine animals (head per ha) was analyzed for the most important sugarcane states, for the South-Central Region as a whole, and for the country as a whole. The data presented in Table 5.18 demonstrates the variability in stocking rate development in the various regions in Brazil.

Table 5.18: Development of the intensity of cattle farming in Brazil, the amount of pasture land, the number of cattle, and the stocking rate for several regions in Brazil.
Source: IBGE (2006) and IBGE (2010), see Table A.22 in the appendix

	Annual change between 1996 and 2006			
	Minas Gerais	**São Paulo**	**South-Central Region**	**Brazil**
Pasture land [ha]	–479,354	–46,815	–1,163,248	–533,209
Number of cattle	94,706	–209,759	202,424	1,689,535
Annual growth in stocking rate [%]	2.6	–1.3	1.5	1.4

Various factors were probably responsible for the differences between the values calculated for the various regions. With regard to the characterization of the baseline, i.e. the development of the stocking rate without additional sugarcane cultivation, it is important to estimate how increases or decreases in the stocking rate are connected to sugarcane area expansion.

In order to investigate the possible relationship between sugarcane expansion onto pasture land and livestock intensification, a statistical analysis was conducted. The rationale behind this was that as soon as pasture land area begins to shrink due to increased sugarcane expansion and thus loss of pasture, there would be an incentive to increase the stocking rate in order to maintain the overall number of cattle.

Given that data on sugarcane area, pasture land, and stocking rates were not available at the state level for the same period, it was only possible to look for an indication of such a cause-and-effect relationship by analyzing the statistical correlation between pasture land growth rate and rate of increase in the stocking rate. Given that pasture land decreases as a consequence of sugarcane expansion, the rate of sugarcane cultivation, if such a dependency exists, should influence the stocking rate.

The agricultural censuses conducted in 1996 and 2006 by the Brazilian government provide data regarding the size of pasture lands and cattle stocking rates at the state level; more recent data will not be available until 2016. Based on the data at hand, a test was conducted to determine whether the annual rate of growth in pasture land negatively influences annual changes in the stocking rate. The hypothesis was that the greater the annual decrease (i.e. the lower the annual growth rate for pastureland area), the greater the annual rate of increase in the stocking rate. Thus, the annual growth rate of pastureland area represents the independent variable, while the annual rate of change in the stocking rate represents the dependent variable. Linear regression analysis was conducted with the help of the software IBM SPSS 18.

The analysis yielded a coefficient of determination (R^2) of about 0.44, which is significant to a level of $p \leq 0.0001$. Thus, 44% of the variability of the dependent variable can be explained by the annual growth in pasture land (see Figure 5.8). The coefficient of the independent variable (–0.8) is negative, as expected, and highly significant, at a level of $p \leq 0.0001$. The annual rate of change in the stocking rate thus decreases by 0.8 when the annual pasture land growth rate increases by 1.

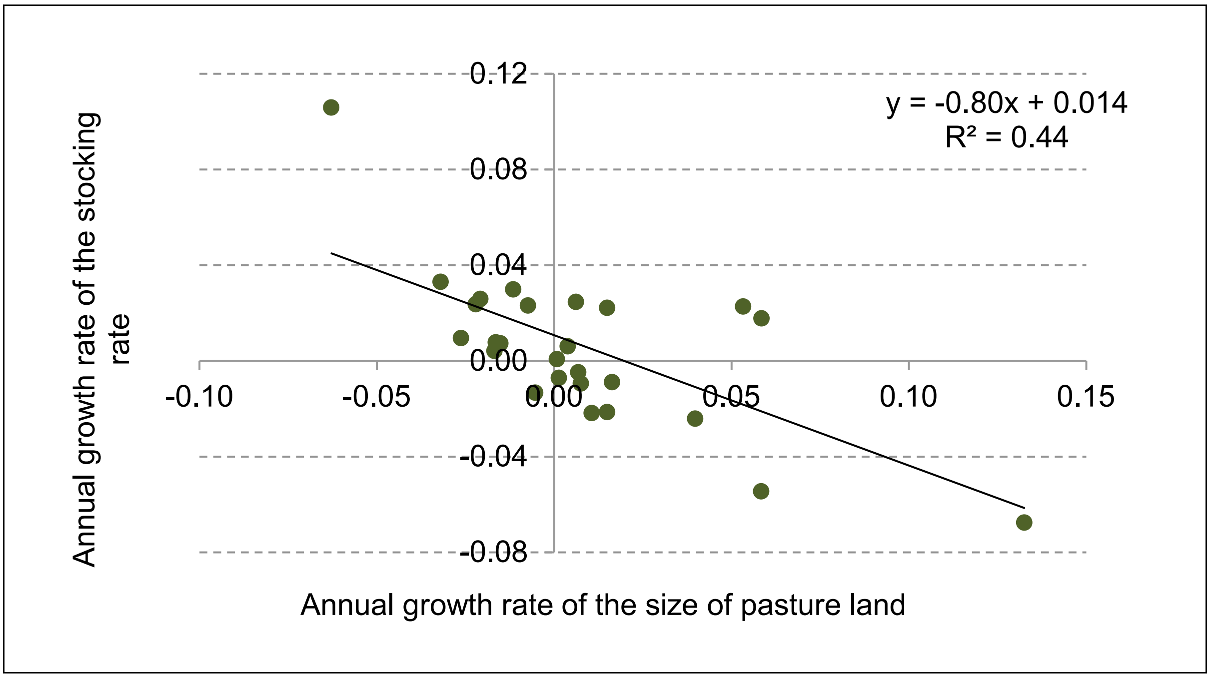

Figure 5.8: Correlation analysis of stocking rate and size of pasture land in Brazil
The figure shows a linear correlation between the annual growth rate of the stocking rate and the annual growth of the size of pasture land in Brazil. Each data point refers to the data for a state in Brazil. Original data on the number of cattle and size of pasture land taken from IBGE (2006) and IBGE (2010); see Table A.22 in the appendix.

As indicated, several other variables also influence stocking rates. According to Chomitz and Thomas (2001), relevant factors that influence the stocking rate include agro-climatic conditions, farm size, and access to roads. Given that these factors are not static over time, they might also influence annual changes in stocking rates at the state level. Thus, although the regression analysis shows a correlation between the annual growth rate of pasture land size and stocking rates, the extent of the influence might change if additional variables of influence are considered in the linear regression analysis.

Overall, the analysis suggests that sugarcane expansion, by decreasing the amount of available pasture land in Brazil, has – among other factors – very likely influenced past stocking rates. However, data on annual stocking rates in São Paulo State shows that sugarcane expansion does not automatically lead to increases in the stocking rate. In the seasons 2007/2008 and 2008/2009, sugarcane expansion over pasture land was greater in São Paulo State than in Minas Gerais. Thus, one might have expected a stronger increase in the stocking rate in São Paulo than in Minas Gerais. So far, this has not been the case. On the contrary, the stocking rate increased annually by 2.6% between 1996 and 2006 in Minas Gerais, while decreasing by 1.3% during the same period in São Paulo State (see Table 5.18).

What should also be noted is that it is not only stocking rates that have gone up – the average slaughter weight of bovine animals has also increased. Nassar et al. (2010) provided data for the slaughter weight of bovine animals between 2002 and 2008, broken out by region but not by state. A statistical analysis as carried out for the stocking rate thus was not possible; however, the aggregate data shows that slaughter weight increased annually by 1.5% between 2002 and 2008 (cf. Nassar 2010).

What can be concluded from the data analyses presented? First, sugarcane expansion has likely influenced the development of stocking rates and slaughter weight in the past; second, the effect varies and is dependent on regional conditions; and third, we cannot precisely quantify the reaction of future stocking rates to further sugarcane expansion over pasture land. For the following calculations these assumptions must therefore inevitably be viewed in a context of high uncertainty.

In order to quantify the expected increases in the stocking rate and slaughter weight due to sugarcane expansion, data available from previous years were used and extrapolated to 2009. The basis for the rate of increase in stocking rates is the level observed between 1996 and 2006 for Brazil as a whole (1.4%); the growth rate in annual slaughter weight (1.5%) is from Nassar et al. (2010). Taken together, the increase per hectare thus adds up to 2.9%.

For the biofuel expansion scenario, it was assumed as a simplification that average beef production per hectare will increase by 400% compared to the baseline scenario if the relation between NEA and the reference area is 1. This means that roughly 20% of the crop displacement will come from agricultural area expansion – a value significantly lower than the one chosen for the Malawian case study (50%). A higher share of yield increase and thus lower share of area expansion in the (overall increasing) output was chosen, because in the case of cattle farming in Brazil there are several options for increasing productivity, i.e. stocking rate and slaughter weight. The potential to increase the productivity was thus assumed to be higher.

In this case study the relation between NEA and the reference area is 0.000015 (reference area = overall pastureland area in Brazil, 172 Mio ha (IBGE 2010)), so that the additional yield increase is 0.0012%. If we take this productivity increase into consideration, $ILUC_{dom\_net}$ for the sugarcane area expansion is 500 ha in total, meaning that 0.2 ha ha^{-1} of sugarcane (by reference to NEA) will additionally be needed in order to maintain the same level of beef production.

In step 5, GHG emissions induced by ILUC were calculated. Given that the generation of new pasture land mainly occurs in the north and northeast regions of Brazil (see Table 5.19), new pasture land was assumed to emerge from the conversion of Amazonian rain forest and Cerrado savannah, accounting for 75 and 25% of the total conversion, respectively (see Table 5.20).

Table 5.19: Development of pasture land area in the five macroregions of Brazil
Source: IBGE (2006) and IBGE (2010)

	1995/96 [ha]	2006 [ha]	Annual Change [ha]
Central-West	62,763,869	56,836,903	–592,697
South	20,696,548	18,145,572	–255,098
Southeast	37,777,044	32,071,529	–570,552
Northeast	32,076,137	32,648,537	57,240
North	24,351,567	32,630,533	827,897

Table 5.20: LUC due to the generation of pasture land from forest and unmanaged grassland in Brazil and related CO_2 emissions (allocated over 20 years)
Source: Share of converted area was estimated, based on IBGE (2006), IBGE (2010), CO_2 calculation bases on IPCC (2006b), Macedo and Seabra (2008) and MCTI (2010)

Land use	Share of converted area [%]	CO_2* [t ha^{-1} yr^{-1}]	$ILUC_{GHG}$** [g CO_2 MJ^{-1} of ethanol]
Amazonian rainforest converted to cultivated pasture land	75	30	159
Cerrado savannah converted to cultivated pasture land	25	1	3
Total	**100**	**23**	**120**

*The calculation is based on IPCC (2006b); above-ground biomass in forest = 300 t dm ha^{-1}; carbon fraction of dry matter = 0.5; dead wood/litter stock under forest = 2.1 (t C ha^{-1}); above-ground biomass in Cerrado = 25.5 t dm (Macedo and Seabra 2008, 105); $SOC_{Ref\ (Forest)}$ = 66 t C ha^{-1}; $SOC_{Ref\ (cultivated\ pasture\ land)}$ = 52 t C $ha^{-}1$ (Macedo and Seabra 2008, 105); $SOC_{Ref\ (Cerrado)}$ = 46 t C $ha^{-}1$ (Macedo and Seabra 2008, 105); all final stock-change factors = 1 (IPCC 2006b).
**The calculation is based on an ethanol yield of 192 GJ ha^{-1} of ethanol.

According to calculations based on data provided by the IPCC (2006b) and Macedo and Seabra (2008), CO_2 emissions related to the conversion of tropical rain forest to pasture land account for 30 t CO_2 ha^{-1} yr^{-1} when the emissions are allocated over 20 years; conversion of Cerrado savannah leads to emissions of about 1 t CO_2 ha^{-1} yr^{-1}. The average CO_2 LUC emission factor (ΔCO_{2dom}) is thus 23 t CO_2 ha^{-1} yr^{-1}.

CO_2 emissions due to ILUC ($ILUC_{GHG}$) account for 120 g CO_2 MJ^{-1} of ethanol if no increases of the cattle stocking rate and the slaughter weight are considered. When we consider the increase in stocking rates and slaughter weight induced by the sugarcane area expansion as explained above, CO_2 emissions account for only 24 g CO_2 MJ^{-1} of ethanol in the best estimate ($ILUC_{GHG}$).

5.2.2.3 ILUC with the implementation of compensation measures

As shown above, part of the cattle farming displacement is compensated for by an increase in the stocking rate. Compensation measures can further contribute to reducing ILUC emissions. To increase the stocking rate is an appropriate compensation measure in Brazil and specifically Minas Gerais because sugarcane expansion mainly occurs on pasture land and the actual average stocking rate is rather low (1.103 head ha^{-1} in Minas Gerais in 2009).

An additional increase in the stocking rate can thus contribute to reducing ILUC emissions. The level of intensification in productivity necessary to completely compensate for expansion depends on the extent of intensification and on the relation between size of the area expansion and size of the pasture land on which the additional intensification takes place. Whereas in the Malawian case study these values were defined by the spatial limitation of the irrigation project SVIP, in the Brazilian case study the spatial references are not self-evident and must be determined. Therefore, the analysis of compensation measures was conducted based on two points of view – once from that of the sugarcane-cultivating and ethanol-producing company and once from that of an administrative unit (the administrative units responsible for the states in the South-Central Region are considered collectively).

Company point of view

Starting from a planned expansion of 5,000 ha at the mill in Minas Gerais, it is necessary to determine the size of the pasture land for which we are accounting for intensification that is in addition to that intensification that will anyway occur for all pasture land in Brazil. On the point of view from the sugarcane-cultivating and ethanol-producing company the reference area used for the implementation of compensation measures is assumed to be equal to NEA, i.e. 2,500 ha. The sugar and ethanol company currently does not plan to increase stocking rates, so the ILUC factor $ILUC_{GHG}$ would actually be 24 g CO_2 MJ^{-1} of ethanol. However, a single (but lasting) 100% increase in the stocking rate on the reference area would be enough to completely compensate ILUC induced by the sugarcane area expansion.

Administrative unit point of view

As it is also possible that the government of an administrative unit would take measures to intensify cattle farming, it is worthwhile to refer to a larger scope – the whole South-Central Region. Such calculations help in drawing conclusions about how strong intensification would have to be in order to compensate the total expected sugarcane area expansion within the region.

Sugarcane expansion in the South-Central Region accounted for 270,000 ha yr^{-1} between 2008 and 2010 (CONAB 2010), and pasture land in the South-Central Region covered 89 million ha in 2006. These values were used as an approximation for the size of the sugarcane area expansion and of the pasture land as the area on which the compensation takes place. Using the assumptions mentioned above, NEA is 135,000 ha, and $ILUC_{dom\_net}$ amounts to 27,000 ha. In this case, an additional increase in the stocking rate of 0.16% for the entire compensation area would be enough to compensate ILUC induced by the sugarcane area expansion.

5.2.2.4 GHG emissions from efficiency gains

As described above, the increase in the stocking rate could help reduce the ILUC effect of sugarcane expansion; however, pasture intensification may require changes in agricultural management, e.g. the application of fertilizers and herbicides, the planting of better varieties, genetic improvements to the cattle stock, and improved rotation schedules (Fearnside 1999). Application of P fertilizer, in particular, might be necessary in order to maintain the productivity of the pasture land and to avoid degradation (Fearnside 1980), especially when the stocking rate increases.

According to Fearnside (1980), the recommended amount of phosphorus (P) fertilizer in order to maintain pasture land productivity is 50 kg P_2O_5 ha^{-1}. In the present work 50 kg P_2O_5 ha^{-1} was thus assumed to be additionally necessary to realize the intensification in the biofuel expansion scenario when the relation between NEA and the agricultural reference area equals 1. When taking into account an emission factor of 1.2 kg CO_{2eq} kg^{-1}, the additional GHG emissions (EFF_{GHG}) amount to 0.4 g CO_{2eq} MJ^{-1} of ethanol (see Table 5.21).

Table 5.21: ILUC factors for additional sugarcane ethanol produced in Minas Gerais with and without consideration of GHG emissions from efficiency gains

Best estimates	$ILUC_{GHG}$ [g CO_{2eq} MJ^{-1} of ethanol]	EFF_{GHG} [g CO_{2eq} MJ^{-1} of ethanol]	$ILUC_{GHG\_net}$ [g CO_{2eq} MJ^{-1} of ethanol]
Without compensation measure	24.0	0.4	24.4
With compensation measure			
At company level	0.0	0.0	0.0
At administrative unit	0.0	0.4	0.4

In the case of the additional compensation measure, from the company and the administrative points of view, additional GHG emissions would account for less than 0.1 and 0.4 g CO_{2eq} MJ^{-1} of ethanol, respectively. The benefit from avoided land use would thus still clearly outweigh the GHG emissions released through an additional increase in the stocking rate. Moreover, an integration of sugarcane (cropping) and pasture in Brazil could help to minimize the additional fertilizer demand given that cane tops or molasses could be used as cattle feed (Dehue et al. 2009).

5.2.2.5 Overview of ILUC-induced GHG emissions

The best estimate considers those input parameters that seem most likely for the case study on Minas Gerais. It also considers the increase in the cattle stocking rate that occurs as a market reaction to the sugarcane area expansion on pasture land. The best estimate without the application of compensation measures amounts to 24 g CO_{2eq} MJ^{-1} of ethanol ($ILUC_{GHG\_net}$) and is more or less in line with the results of other studies: using an allocation approach, Nassar et al. (2010) calculated a value of 7.6 g CO_2 MJ^{-1} of sugarcane ethanol; Fritsche et al. (2010a) calculated 84 g CO_2 MJ^{-1} of ethanol as the maximum ILUC factor for sugarcane ethanol produced in Brazil, but the authors, however, suggest that 50% of this value, i.e. 42 g CO_2 MJ^{-1} of ethanol would be a more realistic value (see Figure 5.9).

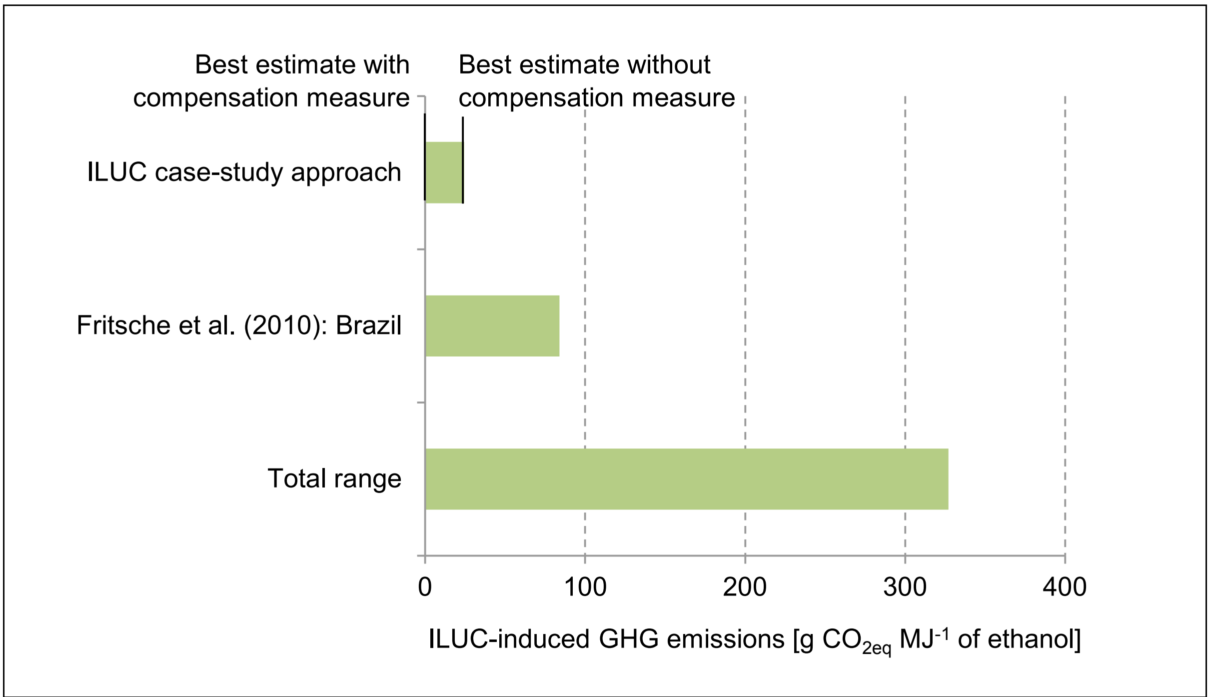

Figure 5.9: Best estimate for ILUC-induced GHG emissions for sugarcane ethanol produced in Minas Gerais, Brazil
Source: Author's case-study approach vs. Fritsche et al. (2010b) and vs. the total range of ILUC factors for ethanol in the secondary research literature (see section 2.2.3) excluding the value for wheat ethanol from Bauen et al.(2010)

The $ILUC_{GHG\_net}$ of 120 g CO_{2eq} MJ^{-1} of ethanol, which reflects the situation without consideration of any efficiency gains, is thus somewhat higher than the 100% ILUC factor calculated according to the model of Fritsche et al. (2010b). Deviations between the emissions presented here and those of Fritsche et al. (2010a) are due to a lower share of tropical rain forest conversion in the study by Fritsche et al. (2010a), as the authors do not link sugarcane expansions to specific LUC in Brazil but rather the global average. CO_2 emissions from LUC, according to Fritsche et al. (2010a), thus account only for 13.5 t CO_2 ha^{-1} yr^{-1} vs. 23 t CO_2 ha^{-1} yr^{-1} in the present work.

Nassar et al. (2010) and De Souza Ferreira Filho and Horridge (2011) also calculated the additionally needed area due to ILUC, using an allocation approach and an economic model. Nassar et al. (2010) claim that only 0.08 ha new land would be necessary for one new hectare of sugarcane. De Souza Ferreira Filho (2011) ascertained a value of 0.14 ha ha^{-1}. Compared with these results, the value of 0.2 ha ha^{-1} of sugarcane calculated by means of the case-study approach is slightly higher.

Compared to the total range of ILUC factors found in the secondary research literature (see section 2.2.3), the values calculated for ethanol produced in Minas Gerais are relatively low. Unlike the situation with sugarcane ethanol production in the Malawi case study, the implementation of compensation measures is not yet planned.

However, adequate compensation measures, such as further increases in the cattle stocking rate, do exist. If the cattle stocking rate were increased as a compensation measure by 0.16% in the overall pasture land in Minas Gerais, a 270,000 ha sugarcane area expansion and thus loss of pasture land could be compensated. GHG emissions from additional fertilizer input on pasture land only amount to 0.4 g CO_{2eq} MJ^{-1} of ethanol. This compensation measure thus has a strongly positive net effect on GHG emissions. As in the case study on Malawi, negative ILUC factors are generally possible, but have not been calculated here, as no compensation measures are currently planned.

5.2.3 GHG emissions due to direct effects

5.2.3.1 System boundary, data sources, and allocation procedure

The CF was calculated for an exemplary site close to Belo Horizonte in the state of Minas Gerais. The mill's output of sugar juice is used for either sugar or ethanol production, depending on the market prices of these products. Thus, ethanol is not produced from a by-product as in Malawi but represents the main agricultural product, given suitable market conditions. The process flow diagram shows the ethanol production directly from sugar juice (see Figure 5.10).

The dataset used for CF calculation is based on practices established in this exemplary mill and the estate's plantation. The company in charge of sugarcane cultivation and ethanol pro-duction completed prepared questionnaires during field research in Brazil (see Table 5.22). It was also possible to use data provided by the doctoral candidate Juan Carlos Claros Garcia, who calculated CFs for the agricultural stage of this specific mill and others in Minas Gerais. The emission factors have been shown in Table 5.11. In those cases where specific data for Brazil were not available, generic values from the IPCC were used. This accounts for emissions from pre-harvest burning, soil N_2O emissions from the use of chemical fertilizer, and CH_4 emissions from vinasse usage. Since specific emission factors for fossil fuels and fertilizers used in Brazil were also not available, default values from the IPCC or else factors recorded for Europe were used as an approximation.

Table 5.22: Basis data: sugarcane cultivation and ethanol production in Minas Gerais

Item	Unit	Quantity	Reference
Sugarcane cultivation			
Cane productivity	t ha^{-1}	75	Questionnaire
Cane trash (dry basis)	t ha^{-1}	14	Own calculation*
Diesel	MJ ha^{-1}	4,332	Claros Garcia**
N fertilizer	kg ha^{-1}	72	Claros Garcia
P fertilizer	kg ha^{-1}	102	Claros Garcia
K fertilizer	kg ha^{-1}	76	Claros Garcia
Lime	kg ha^{-1}	459	Claros Garcia
Pesticides	kg ha^{-1}	3.8	Claros Garcia
Diesel for haulage	MJ t^{-1} of sugarcane	52	Claros Garcia
Ethanol production			
Input sugarcane	t L^{-1} of ethanol	0.016	Questionnaire
Electricity	MJ L^{-1} of ethanol	0.01	Questionnaire
Hydrated lime	kg L^{-1} of ethanol	0.005	Questionnaire
Urea	kg L^{-1} of ethanol	0.0003	Questionnaire
Sulphuric acid	kg L^{-1} of ethanol	0.002	Questionnaire
Caustic soda	kg L^{-1} of ethanol	0.0002	Questionnaire
Output vinasse	L L^{-1} of ethanol	13	Questionnaire
Output sugar	kg L^{-1} of ethanol	0.74	Questionnaire

* Based on a straw/fresh cane ratio of 0.19 (De Figueiredo and La Scala 2011).
** Data provided by the doctoral candidate Juan Carlos Claros Garcia.

Sugarcane is harvested in part manually and in part mechanically. Currently the company applies mechanical harvesting without burning on roughly half of the sugarcane area; the share harvested mechanically is planned to expand within the next few years. As in many regions in Brazil, vinasse is used in *fertigation* – a type of irrigation utilizing a mixture of vinasse and water (Lisboa et al. 2011). Based on a specific set of assumptions, Lisboa et al. (2011) calculated CH_4 emissions of about 720 g ha^{-1} yr^{-1} due to fertigation. This value was carried over in estimating GHG emissions as measured values for the specific site were not available. Pre-harvest burning is conducted on currently 30% of the harvested sugarcane area.

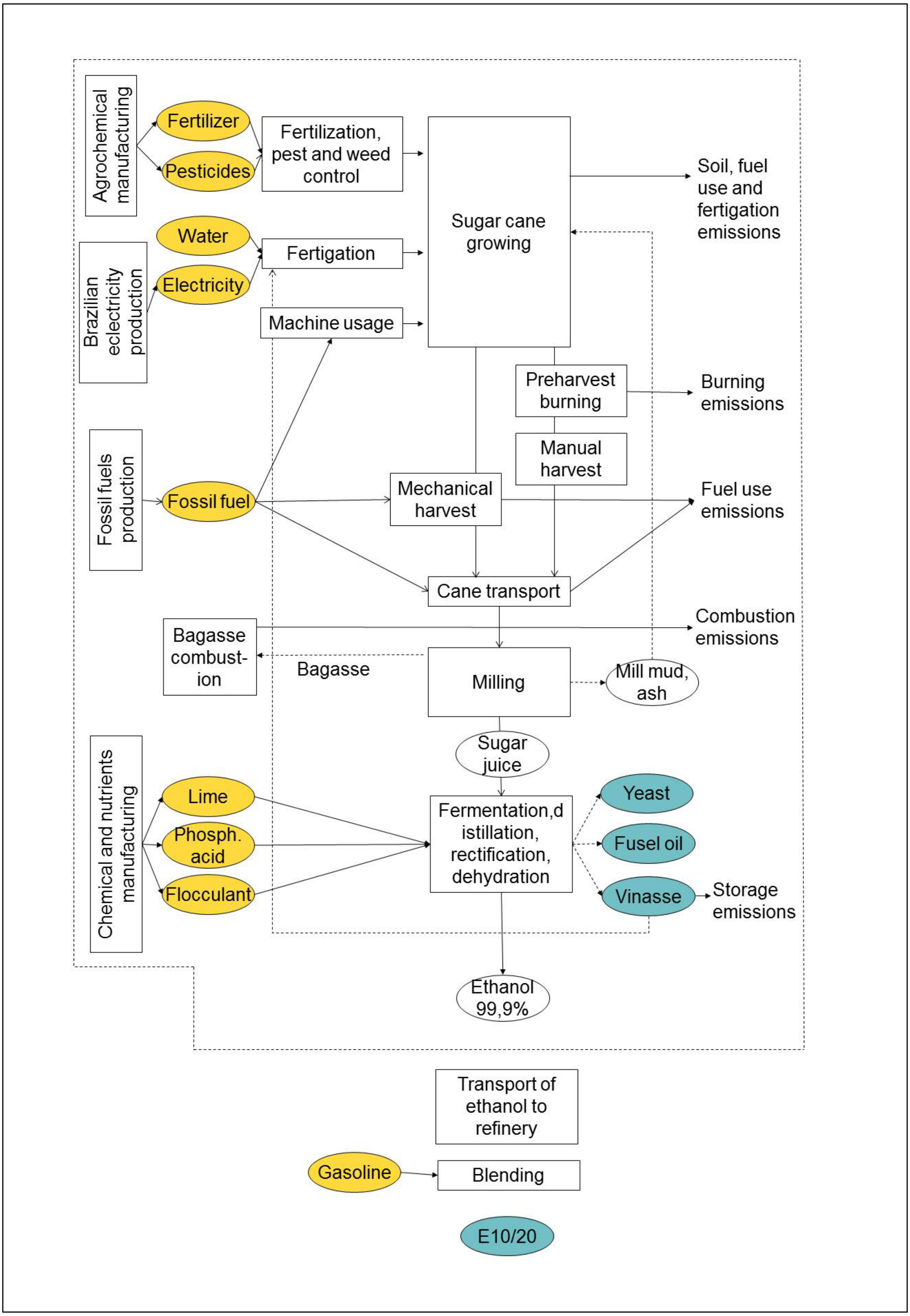

Figure 5.10: Process flow diagram for sugarcane ethanol production in Brazil
The broken line marks the system boundaries; orange ellipses (light grey) are materials and products that enter the production process; blue ellipses (dark grey) mark outputs.

In order to calculate GHG emissions from DLUC (here the conversion of pasture land to a sugarcane plantation), it was possible to utilize data from Macedo et al. (2008). Macedo et al. (2008) provide measured values of soil carbon contents and above-ground carbon contents with regard to various land uses in Brazil. According to this data, the soil carbon content for cultivated pasture land is 52 t C ha^{-1}, and the soil carbon content for unburned sugar cane lies between 44 and 59 t C ha^{-1}. A soil carbon content for unburned sugarcane of 51 t C ha^{-1} was thus used for the calculations. Above-ground carbon content can be ignored, as above-ground biomass is removed from the field in the case of sugarcane cultivation as well as pasture land.

Two scenarios were calculated in order to point out existing optimization potentials concerning the CF. Scenario 1 (SC 2.1) represents the status quo. Scenario 2 (SC 2.2) assumes that cane trash is available to be used as a fuel in electricity generation when switching to green-harvesting. The amount of cane trash was calculated based on a straw/fresh cane ratio of 0.19 (De Figueiredo and La Scala 2011). Only 50% of the overall cane trash is assumed to be removed from field in order to preserve the soil's carbon sink function, as well as for weed and erosion control on the field. Thus, only 95 kg t^{-1} of sugarcane is available as an energy source.

GHG emissions from the cultivation and haulage stage are allocated to sugar and ethanol. Allocation of a share of the environmental burden to bagasse is not necessary, given that bagasse is used in the manufacturing process of sugar and ethanol.

Energy allocation: All inputs and outputs are allocated to the products sugar and ethanol according to LHV, with sugar having an LHV of 16,500 MJ t^{-1} (Rein 2010) and ethanol 21 MJ L^{-1} (ANL 2008). On the basis that 63 L of ethanol and 0.05 t sugar are produced from 1 t of sugarcane at the exemplary site, the relative contribution of sugar vs. ethanol is 0.6:1; emissions are thus allocated as follows: sugar 37% and ethanol 63%. In SC 2.2 all inputs and outputs are allocated to the products sugar, ethanol, and cane trash, with cane trash having an LHV of 16,600 MJ t^{-1} (Fehrenbach et al. 2007). On the basis that 95 kg of cane trash are taken from the field per 1 t of sugarcane, emissions are allocated between sugar, ethanol, and cane trash at 21%, 36%, and 43%, respectively.

Economic allocation: The prices for sugar and ethanol in 2010 were 1,208 R$[13] t^{-1} and 1.05 R$ L^{-1} (652 USD t^{-1} of sugar and 0.57 USD L^{-1} of ethanol[14]) (USDA 2011a), respectively. The relative contribution of sugar and ethanol is thus, 0.9:1 and emissions are allocated between sugar and ethanol at 46% and 54%, respectively. In SC 2.2 all inputs and outputs are allocated to the products sugar, ethanol, and cane trash. The price for cane trash is 17 USD t^{-1} of trash (31 R$ t^{-1} of trash) (Bonomi 2012); emissions are thus allocated between sugar, ethanol, and cane trash at 45%, 53%, and 2%, respectively.

5.2.3.2 Carbon footprint (CF) results

GHG emissions due to sugarcane cultivation and transport to the mill are much lower at the site in Minas Gerais (32 kg CO_{2eq} t^{-1} of sugarcane without DLUC, 35 kg CO_{2eq} t^{-1} of sugarcane with DLUC) than at the sites in Malawi – this even though cane productivity at the Minas Gerais site (75 t ha^{-1}) is significantly lower; yields, however, are slightly higher than the global average sugarcane yield of 71 t C ha^{-1} (Lisboa et al. 2011). The difference in the CF between Minas Gerais and Malawi is mainly due to the lower amounts of N fertilizer, pesticides, and diesel used in Minas Gerais. Sugarcane ethanol produced at this particular site has a CF about 17 g CO_{2eq} MJ^{-1} of ethanol (energy allocation – economic allocation leads to a 15% lower value; see Figure 5.11) and thus easily fulfills the requirements of the RED.

The production and use of fertilizers (46%) are responsible for the largest share of the total CF. Pre-harvest burning, fuel use during the cultivation stage, and sugarcane transport lead to 15, 14 and 13% of the total emissions, respectively, while the other processes contribute very little to total emissions (see Table 5.23).

GHG emissions from DLUC (the conversion of grassland to cropland) account for only 1.2 g CO_2 MJ^{-1} of ethanol when the emissions are distributed over 20 years (7% of the overall CF). This value is in line with the results calculated by Macedo et al. (2008) (29 kg CO_2 m^{-3} of ethanol).

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[13] Real = Brazilian currency

[14] Currency converted to US dollar; 1 USD = 1.84 R$ (http://www.umrechnung24.de/ 2010).

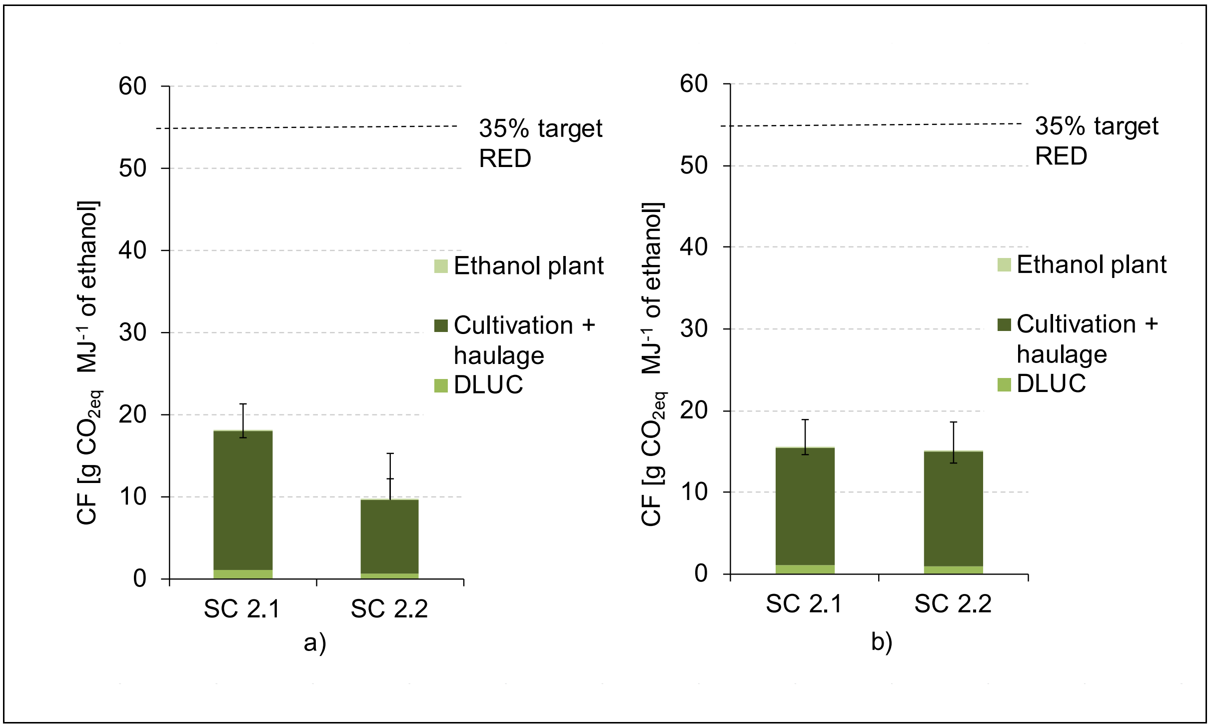

Figure 5.11: CF of sugarcane ethanol produced in Minas Gerais (two scenarios) a) Energy allocation b) Economic allocation.
SC 2.1: Allocation to sugar and ethanol; SC 2.2: Allocation to sugar, ethanol and cane trash. Error bars result from a variation in N_2O emissions of N fertilizer of 0.5–3%.

Table 5.23: CF of sugarcane ethanol production in Brazil (energy allocation)

Items	**CF [kg CO_{2eq} MJ^{-1} of ethanol]**	**Share of total CF [%]**
DLUC	1.2	7
Fertilizer	7.7	46
Fertigation	0.4	3
Pesticides	0.3	2
Fuel	2.4	14
Pre-harvest burning	2.5	15
Haulage	2.2	13
Processes in ethanol plant	0.02	<1
Total	**16.7**	100.0

Fertigation also leads to a relatively low release of GHG emissions and is thus a considerably better way to treat vinasse compared to storage in open ponds and no further use, as is common in Malawi. The process energy demand in the ethanol plant hardly influences the CF of ethanol production, as bagasse is the only feedstock used in the plant for energy production and GHG emissions related to bagasse burning are set to zero.

SC.2.1 and SC 2.2 only differ in the allocation factors applied to ethanol; in particular, when energy allocation is chosen, the additional usage of cane trash disburdens ethanol, as 43% of the GHG emissions that occur in the cultivation stage are allocated to cane trash. In the case of economic allocation, the difference between the two scenarios is negligible, as only 2% of the GHG emissions is allocated to the cane trash due to its low price. The use of cane trash for electricity production thus can improve the CF of ethanol – the extent of the reduction, however, strongly depends on the allocation procedure.

Overall, sugarcane ethanol produced in Minas Gerais has a significantly lower CF than sugarcane ethanol produced in the Southern Region of Malawi. This is mainly due to the use of vinasse in fertigation, which leads to less GHG emissions than the open storage in Malawi, and to the use of bagasse as a fuel in the ethanol plant instead of coal. GHG emissions induced by ILUC without the application of compensation measures are slightly lower than in Malawi. By increasing the cattle stocking rate these emissions could be reduced to zero or even to a negative value. However, in contrast to Malawi, the application of compensation measures is currently not planned.

5.3 Germany – wheat ethanol

Germany represents a very different case compared to the other two case studies: first, the biofuel sector's development is highly driven by EU's biofuel policy, and second, a large share of biofuel consumption is already met by imported biofuels (cf. FNR 2011a; FNR 2011b; BMU 2012).

Public and scientific discussion is dominated by questions about the role biofuels can play in view of the high total fuel consumption and how negative impacts linked to imported biofuels can be avoided. While DLUC in Germany itself is not a very relevant topic, the ILUC effect of the EU's biofuel consumption and production has been heatedly debated in recent years (Al-Riffai et al. 2010; Fritsche et al. 2010a; Laborde 2011; Di Lucia et al. 2012). The case study conducted in the present work provides an overview of wheat ethanol production in Germany and makes suggestions as to how ILUC effects related to biofuel production in Germany could be reduced.

5.3.1 Country characterization

5.3.1.1 Biofuel production

5.3.1.1.1 Policies regarding biofuel production

Biofuel production has been promoted in Germany since the end of the 1990s, when it was exempted from the ecotax introduced by the red-green political coalition. An explicit promotion, however, began only in 2002, with a total tax exemption (tax exemption was replaced by a quota regulation in 2006). Since 2009 – when the RED (2009/28/EC) was launched – biofuel policy and the biofuel sector in Germany have mainly been driven by EU biofuel policy.

The RED (2009/28/EC), for instance, requires EU member states to develop national action plans for renewable energies that include national renewable energy targets for 2020. In August 2010, the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety published its action plan that foresees a 19.6% share of renewable energies in the gross energy consumption by 2020; in the mobility sector, the target for 2020 is 13.2% (BMU 2010).

The biofuels quota act (Biokraftstoffquotengesetz, BioKraftQuG), launched in 2007 and adapted in 2009 (Gesetz zur Änderung der Förderung von Biokraftstoffen, BioKraftFÄndG), establishes the framework for fulfilling the requirements of the RED; it commits the petroleum industry to a specific biofuels quota with respect to total sales volume of fuels. According to the act, 6.25% of total sales of fuels between 2010 and 2014 are to be biofuels; the mandatory sub-quota for biodiesel is 4.4% of total diesel distribution since 2007 (BioKraftQuG) and for ethanol 2.8% between 2009 and 2014 (BioKraftFÄndG).

In 2015 the climate protection quota (Klimaschutzquote) will replace the biofuels quota act. While the biofuels quota refers to energy content of the comparable fossil fuels, the climate protection quota will refer directly to the GHG reduction potential of biofuels (see BioKraftFÄndG). The goal of the new quota is to contribute to a more climate-efficient mobility rather than just increasing the biofuel share. GHG emissions due to the sales of fossil fuels are to be reduced through the use of biofuels by 3%

beginning in 2015, by 4.5% beginning in 2017, and by 7% beginning in 2020 (see BioKraftFÄndG). A reduction of 7% complies with a biofuel share of roughly 10% when a GHG reduction of biofuels vs. fossil fuels of 70% is assumed; in this case the quota would also fulfill the RED requirement of 10% renewable energies in the mobility sector (UFOP 2009). The associated action plan (BMU 2010) calls for meeting the targets established in the biofuel and climate protection quota through additional biofuel and feedstock imports.

In order to avoid a negative impact from the EU's biofuel imports and production within the EU, the RED 2009 established sustainability criteria for biofuel production. In accordance with these criteria, biofuel feedstock is not allowed to be cultivated on land areas with high carbon contents and high biodiversity. Such areas include nature reserves, primary forests, wetlands, and grasslands with a large degree of biodiversity. Germany incorporated these requirements into the act on sustainable production of biofuels (*Verordnung über Anforderungen an eine nachhaltige Herstellung von Biokraftstoffen* – Biokraft-NachV), adopted in September 2009 (Biokraft-NachV).

In order to be counted towards the mandatory national renewable energy targets, biofuels utilized in the EU have to be certified to prove that they comply with the sustainability criteria in the RED. Currently thirteen voluntary certification schemes, such as ISCC or RED CERT, have been approved by the EC (COM 2013b).

As the RED 2009 does not address ILUC in its sustainability criteria, the EC published a proposal in 2012 to amend the original 2009 RED to limit the amount of biofuels produced from oleaginous starch- and sugar-containing plants to 5% of final energy consumption in the mobility sector.

5.3.1.1.2 Data on ethanol production

Unlike in Malawi and Brazil, in Germany less ethanol is produced and marketed than biodiesel. In 2010, sales of ethanol were 1,165 thousand t, biodiesel was 2,529 thousand t, and vegetable oil in the fuel market 61 thousand t (BMU 2012). While the ethanol production of 583 thousand t met only half of domestic consumption, biodiesel production of 2,800 thousand t slightly exceeded biodiesel consumption in 2010 (cf. FNR 2011a; FNR 2011b).

The overall biofuels turnover in 2010, 3,755 thousand t (BMU 2012), was also higher than overall production of 3,383 thousand t (FNR 2011a; FNR 2011b). Germany was thus a net importer of biofuels, as in previous years. As the production capacity for ethanol is roughly 1 million t (FNR 2011b), a greater utilization of available capacity could reduce but would not eliminate imports. In contrast to its steadily increasing consumption, ethanol production levels started to decrease in 2009; consumption and production trends are thus divergent. The main reason for the decrease in production is the competitive advantage of imported, less expensive ethanol (Henniges 2007); imports are thus likely to gain even more relevance in the future.

In order to identify where the imported bioethanol comes from, we must turn our attention to the port of Rotterdam, because all biofuel trade into the EU and among EU states passes through this port. According to the Port of Rotterdam Authorization, the largest share of ethanol imported from overseas into the EU comes from the two largest ethanol producers worldwide, the USA and Brazil (cf. eia 2011); this has certainly been the case in the most recent years (PRA 2012). Although some ethanol has been imported from other European countries, one can assume that all the ethanol that reaches Germany comes from overseas because the EU is likewise a net ethanol importer (cf. eia 2011).

In order to estimate the agricultural area used for ethanol production in Germany, it is necessary to look at domestic production and the types and amounts of feedstock used in biofuel production. Ethanol produced in Germany is based on the feedstocks grain and sugar beet. Grains such as wheat, rye, and corn account for roughly two-thirds of the feedstock used; sugar beet makes up one-third of production. These crops are cultivated mainly domestically, with a negligible amount imported from other European countries (VDB 2011).

Table 5.24 presents the amount of ethanol produced from grain and sugar beet, and the gross and net area needed for feedstock cultivation. In order to calculate the net area, DDGS was taken into account as an important by-product of wheat ethanol production. The overall net area for ethanol production has increased by 83% from 70 thousand ha in 2007 to 128 thousand ha in 2011. Mainly responsible for this expansion is the increase in grain ethanol production.

Table 5.24: Feedstocks and associated cultivation areas for ethanol production in Germany

Source: Data on ethanol production and feedstock share from BDBe (pers. comm., N. Reimers 2011; N. Wendt 2012)

	2007	2008	2009	2010	2011
Ethanol production [1000 t]	315	458	594	604	571
Ethanol from grain [%]	88	61	65	66	71
Ethanol from grain [1000 t]	278	279	384	398	407
Ethanol from sugar beet [%]	8	36	33	33	29
Ethanol from sugar beet [1000 t]	24	164	194	201	164
Area for grain [1000 ha]*	117	117	161	167	171
Area for sugar beet [1000 ha]**	5	32	38	40	32
Total area for ethanol [1000 ha]	121	149	199	206	203
Net area for ethanol [1000 ha]***	70	98	129	133	128

* Calculated with an average wheat yield of 7.5 t ha^{-1} (FAO 2012) and an ethanol yield of 400 L t^{-1} of wheat (IFEU 2008).
** Calculated with an average sugar beet yield of 64 t ha^{-1} (FAO 2012) and an ethanol yield of 100 L t^{-1} of sugar beet (etha+ 2006).
*** Calculated with energy contents of 27 GJ t^{-1} of ethanol and 22 GJ t^{-1} of DDGS (Fehrenbach et al. 2007) and with a DDGS yield of 300 kg t^{-1} of wheat (IFEU 2008).

5.3.1.2 Land-use changes

5.3.1.2.1 Policies regarding land-use changes

Several regulatory instruments in Germany contribute to the protection of the natural ecosystem and limit the conversion of managed forests. The German Federal Forest Act (Bundeswaldgesetz, BWaldG), in existence since 1975, is the primary regulatory means for avoiding deforestation through agricultural expansion.

Property owners are only allowed to clear their forest land and convert it to another land use when given permission by the responsible authorities (§12 BWaldG). In many of the federal states, an environmental impact assessment is first required for areas greater than 10 ha; such restrictions are found, for instance, in the federal states of Baden-Württemberg and Bayern (Art 39A BayWaldG, §9 LWaldG).

In addition to deforestation, the conversion of high-biodiversity grassland to arable land is also to be avoided, according to the RED 2009. Conversion of grassland is addressed through “cross compliance” at the EU level – the EU links its agricultural payments to compliance with various environmental commitments, e.g. a prohibition on the ploughing up of grasslands. There is no restriction, however, as long as less than 5% of the total grassland in a German federal state (reference year 2003) has been affected. Once this threshold is exceeded, the states are obligated to adopt regulations mandating an authorization process for further grassland-to-farmland conversions (BMELV 2006a). In several states, including Schleswig-Holstein, Mecklenburg-Vorpommern and Niedersachsen, the 5% limit has already been exceeded and farmers now have to apply for an authorization before they are allowed to convert grassland to arable land (Nitsch et al. 2010).

The Federal Nature Conservation Act (Bundesnaturschutzgesetz BNatSchG) further prohibits the ploughing of grassland at sites vulnerable to erosion, sites with high ground-water levels, floodplains, and peat lands (BNatSchG).

5.3.1.2.2 Data on land-use changes

Unlike in Malawi and in Brazil, LUC does not play a significant role in Germany. Between 2000 and 2010, the area of forestation in Germany increased slightly, by 235 thousand ha or 2% (see Table 5.25).

Table 5.25: Development of land use between 1996 and 2010 in Germany
Source: BMELV (2012a)

	1996	2000	2004	2008	2009	2010
Agricultural area [1000 ha]	19,314	19,103	18,932	18,765	18,729	18,693
Forest area [1000 ha]	10,491	10,531	10,649	10,735	10,753	10,766
Other [1000 ha]	5,897	6,069	6,125	6,212	6,230	6,254
Total	**35,702**	**35,703**	**35,706**	**35,712**	**35,712**	**35,713**

At the same time, the agricultural area decreased by 410 thousand ha (BMELV 2012a), suggesting that former agricultural areas were afforested within this period. The German forest law thus seems to be fulfilling its goal of protecting existing (largely managed) forest from being converted to other land uses. A more relevant LUC topic than deforestation is the ploughing up of grassland to cultivate more crops. During the period from 2000 to 2010, 393 thousand ha of grassland, i.e. 7.8% of the total former grassland area, were ploughed (see Table A.24 in the appendix).

The crops that have expanded the most during this period and up to 2011 are wheat, silage maize, and rape seed – all three typical bioenergy crops (see Table 5.26). Silage maize is mainly used as a feedstock for biogas production in Germany; wheat is the main feedstock for ethanol production, and rape the main feedstock for biodiesel production. Former set-aside areas that were financially subsidized by the EU until 2007 have obviously since been converted to arable land in order to cultivate such bioenergy crops.

Table 5.26: Expanding crops between 2000 and 2011 in Germany
Source: BMELV (2002, 253; 2004, 989; 2006b, 877; 2008, 942; 2012a)

	2000	2004	2008	2011	Difference 2011 - 2000
Arable land [1000 ha]	11,804	11,899	11,933	11,874	71
Wheat [1000 ha]	2,969	3,112	3,214	3,248	279
Grain maize [1000 ha]	361	462	520	488	127
Rape seed [1000 ha]	1,046	1,267	1,363	1,307	261
Silage maize [1000 ha]	1,155	1,249	1,567	2,029	874
Grass on arable land [1000 ha]	216	209	393	398	181
Leguminous plants [1000 ha]	182	177	244	264	82
Set-aside area [1000 ha]	823	784	310	229	–595

5.3.1.3 Economic data, agricultural production, and trade

In addition to bioenergy production, another potential factor that influences land use in Germany is the increasing global demand for agricultural products. The trade balance for agricultural products (exports minus imports), however, was negative between 2006 and 2010, meaning that a greater quantity of agricultural products was imported than was exported. FAOSTAT data on trade demonstrate that the overall level of imported agricultural products increased in the period from 2000 to 2010 (see Figure 5.12 and Table A.25 in the appendix).

Still, some single crops may be particularly relevant in terms of export quantities. FAOSTAT data show that wheat has been the most relevant crop in this respect in recent years. The trade balance for wheat was always positive between 2000 and 2010, and wheat exports have almost doubled in this period (see Table A.26 in the appendix). The global and domestic demand for wheat, therefore, could represent a driver for the conversion of grassland to arable land in Germany.

Crops with a net import balance in particularly relevant amounts include rapeseed, soybeans, and maize, with all being relevant inputs in the food, livestock, and bioen-

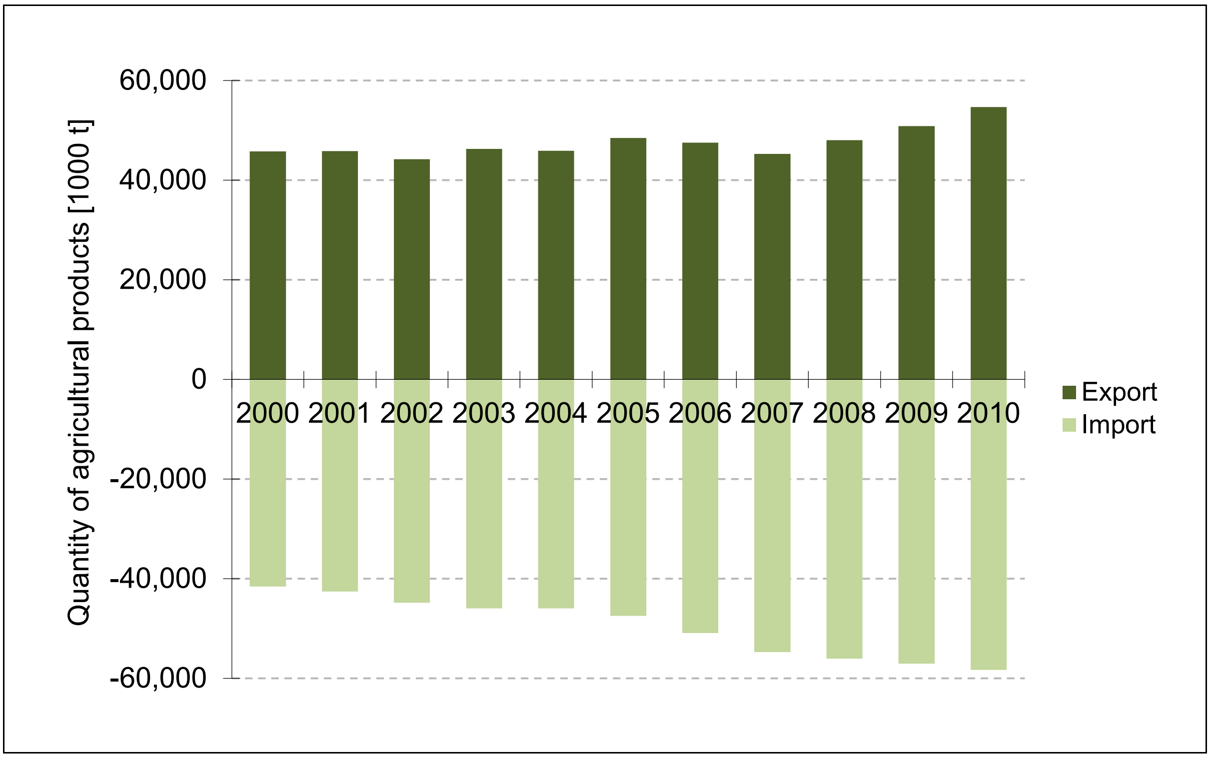

Figure 5.12: Import and export of agricultural products (Germany)
Source: Based on (FAO 2012); data can be found in Table A.25 in the appendix

ergy sectors. Increasing domestic demand within the livestock and bioenergy sectors may thus be an important driver for these imports.

In order to assess the degree to which the domestic market is linked to the global market, the ratios between agricultural product import quantities and food supply and agricultural product export quantities and food supply were calculated. The results show that the ratio between the import of agricultural products and food supply ranged from 43.5 to 58.4% in the period 2000 to 2009; during the same period, the ratio between exports of agricultural products to food supply ranged from 45.2 to 52.0% (see Table A.25 in the appendix). The linkage between domestic and global markets is thus very strong compared to Malawi; in particular, the share of imported quantity of agricultural products in the food supply is quite high for Germany, which can thus be characterized as both an importer and exporter of agricultural products.

The case studies on Malawi and Brazil both mention population growth as a potential factor influencing domestic demand for agricultural products and thus for development of new agricultural areas in the respective countries. In Germany, however, the population declined slightly between 2000 and 2010, reaching a new low of 81.5 million in 2011 (IndexMundi 2011).

In comparison to the global average, meat consumption in Germany is very high, and has increased slightly in recent years, from 84 kg capita^{-1} yr^{-1} in 2000 to 88 kg capita^{-1} yr^{-1} in 2009 (FAO 2012); these numbers correspond to 220 and 210%, respectively, of the global per capita average. Milk consumption during this period increased from 229 to 264 kg capita^{-1} yr^{-1}, corresponding to 292 and 302%, respectively, of the global average for milk consumption (see Table A.27 in the appendix).

Intensity and productivity of agricultural production in Germany are assumed to be significantly higher than in Malawi and Brazil. The average maize yields were used as an approximation for the intensity of agricultural production. Between 2000 and 2010 the average maize yield ranged between 166 and 213% of the global average (see Table A.28 in the appendix). Thus, average crops yields in Germany are already at a high level, and it will probably be difficult to further increase crop yields.

5.3.1.4 Overview of country characterization

Table 5.27 summarizes the information and data given in the previous chapters.

Table 5.27: Key characteristics of Germany

Characteristic	Description
Relevance of biofuel production	Amount of ethanol production is high, ethanol imports are necessary to cover demand
Relevance of LUC	Low, only grassland conversions
Trade dynamic of agricultural products	Global dynamic (export and import)
Intensity of agricultural production	High
Meat and dairy consumption	High

The amount of ethanol produced in Germany is relatively high although not high enough to cover consumption; Germany is thus a net importer of ethanol. LUC is not a relevant topic in Germany; forestation actually increased slightly between 2000 and 2009. The ploughing up of grassland is the only relevant issue with regard to LUC.

Exports and imports of agricultural products are substantial. The trade balance for wheat has been positive in recent years, thus there is a risk that increasing wheat-based ethanol production in Germany will lead to ILUC elsewhere due to reduced wheat exports.

The intensity of agricultural production is assumed to be high as the average maize yields in Germany are significantly higher than the global average maize yields. Measures that increase agricultural yields are thus a less suitable way to reduce ILUC than in Malawi and Brazil. Meat and dairy consumption, in contrast, are very high compared to the global average. Compensation measures that decrease meat or dairy consumption could thus be adequate measures to reduce ILUC.

5.3.2 ILUC due to wheat ethanol production

Ethanol production capacity in Germany is under-utilized; in 2011 seven German ethanol factories, with a combined production capacity of 930 thousand t yr^{-1}, produced roughly 570 thousand t of ethanol (FNR 2011b; BDBe 2012a). Ethanol production furthermore decreased slightly from 2010 to 2011. Given that sugar prices were high at the beginning of 2011, the amount of sugar beet, in particular, used for ethanol production was less in 2011 than in 2010 (BDBe 2012a). Ethanol production from grain more or less remained constant with 2010 levels (see Table 5.24).

As in Brazil, market prices in both the food and biofuel sectors determine the amount of ethanol that is produced from a specific feedstock. Along with ethanol, several by-products of economic relevance occur in the ethanol production process and thus contribute to the profitability of ethanol production. The most relevant by-product is DDGS, which is made from stillage, a thick liquid residue of the distillation process. DDGS is a suitable feedstock in the livestock sector due to its high protein content. Wheat brans from grinding wheat and yeast cells from ethanol production can also be used as additional feed in livestock production (BDBe 2012b).

In this section the ILUC effect for wheat ethanol produced in Germany will be estimated. In contrast to the case studies on Malawi and Brazil, there was no cooperation with a biofuel feedstock or ethanol producer and no actual or planned wheat expansion for the purpose of ethanol production was known. The German Bioethanol Industry Association (BDBe), in 2011 when the case study was conducted, anticipated that ethanol production would increase in 2012. ILUC, therefore, was estimated for a theoretical case of wheat ethanol expansion.

As actual data from the BDBe later showed, ethanol production did increase in 2012; however, more ethanol was produced from sugar beets than from wheat, and the amount of wheat used for ethanol production actually decreased from 2011 to 2012 (BDBe 2013). This makes clear that applicability of the case study approach to annual crops is rather limited, as it is difficult to foresee market developments and actual feedstock expansions. Thus, the following calculation represents a theoretical case of increasing wheat cultivation for ethanol production in Germany.

Most of the ethanol manufacturers in Germany are located in the federal state of Saxony-Anhalt (IWR 2010). In this region the area used for wheat cultivation expanded from 316 thousand ha in 2007 to 342 thousand ha in 2011 (see Table 5.28).

Table 5.28: Expanding crops between 2007 and 2011 in Saxony-Anhalt
Source: StaLa (2013)

	2007	2008	2009	2010	2011	Difference 2011 - 2007
			[1000 ha]			
Wheat	316	333	340	346	342	27
Other grains	242	266	260	233	226	-16
Sugar beet	48	46	46	45	49	1
Potatoes	13	13	13	13	14	1
Rape seed	181	161	169	171	159	-22
Others	115	122	128	143	160	45

At the same time, the area used for rapeseed production decreased significantly. Section 5.3.1.1 also demonstrated that existing ethanol production capacity is not yet being fully utilized. Based on this information, it was assumed that an additional 20 thousand ha of wheat is going to be cultivated in Saxony-Anhalt and used for ethanol production in this federal state. This was the basis for the ILUC estimation.

One has to notice, however, that when annual crops such as wheat are used as feedstocks in ethanol production, it may be difficult to trace the origin of the feedstock. Farmers often do not sell wheat directly to the ethanol producer (which is assumed here), but rather to traders or via a grain exchange. This is in contrast to perennial crops such as sugarcane, where the specific plantations that provide the feedstock can easily be traced.

5.3.2.1 ILUC without implementation of compensation measures

This section provides an analysis of the anticipated ILUC effect due to the wheat area expansion scenario assumed for the federal state of Saxony-Anhalt. The gross expansion area (GEA) is assumed to be 20,000 ha. According to Lywood et al. (2009b), 78% of additional output of EU cereals could be achieved through yield increases and only 22% would result from area expansion. In Germany, however, the yield increase is expected to be lower than the average of the EU member states, as large yield increases have already been realized. Therefore, a 75% share of area expansion in the total incremental output growth of wheat was assumed. The current ethanol yield is 62 GJ ha^{-1} of wheat[15]; given the assumptions mentioned, the yield would increase to 82 GJ ha^{-1} of wheat.

The expansion is assumed to occur on arable land. It is rather difficult to estimate which crops are going to be replaced. Within recent years, the area used for other grains as well as for rapeseed has particularly decreased; therefore it was assumed that the area used for these crops will further shrink.

In step 2, the net expansion area (NEA) was calculated, with only a share of the expansion being attributed to ethanol and another share allocated to the by-product DDGS. Energy allocation results in a distribution of roughly 44% of the expansion to DDGS and 56% to ethanol (F_{all} = 0.56), so that 11 thousand ha are allocated to ethanol. As described in section 4.1, ILUC could theoretically occur in the country itself or elsewhere; this is estimated in step 3. Using the data and information provided in section 5.3.1, it is possible to broadly estimate where ILUC induced by wheat area expansion in Germany is likely to occur. Overall, one could observe in Germany:

- a slight increase in forest area in recent years (I_{luc} is low)
- a constant decrease in agricultural area in recent years (I_{luc} is low)
- a slight loss of grassland in recent years (I_{luc} is high)
- a high ratio of import quantities to supply of agricultural products (I_{market} is low)
- a high ratio of export quantities to supply of agricultural products (I_{market} is low)

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[15] Based on a wheat yield of 7.3 t ha^{-1}, a LHV of 26.7 MJ kg^{-1} of ethanol (Fehrenbach et al. 2007) and an ethanol yield of 400 L t^{-1} of wheat (IFEU 2008).

Based on these observations, it is likely that ILUC will mainly occur outside the country. In the following analysis it is assumed that ILUC spillover is 100%. The main reason is that conversion of natural ecosystems to managed grassland or cropland has not happened in the past despite a substantial increase in biofuel production.

In step 4, efficiency gains are considered. First a scenario without implementation of any particular compensation measures will be demonstrated. The data on Saxony-Anhalt shows that mainly rapeseed and grains other than wheat have been displaced by wheat; however, wheat is an annual crop, and is thus a component in various crop-rotation systems, which makes observations about future crop displacements more difficult. Thus, as ILUC spillover is assumed to be 100% the overall worldwide area used as arable land is regarded as the reference area. This is contrary to the case study on Malawi and Brazil, where specific displacements, for maize and cattle farming, respectively, are considered. In Germany as well as worldwide, we can expect further yield increases in the future, so some compensation will take place. As a simplification it was assumed that the average crop yield would increase by 50% if the relation between NEA and the reference area is one. This assumption was made for Germany as well as for the case that the displacement occurs elsewhere. Thus, overall 5.6 thousand ha ($ILUC_{glob\_net}$) will additionally be needed in order to maintain the same agricultural product output.

In step, 5 ILUC-induced CO_2 emissions are estimated based on information about global average CO_2 emissions due to LUC (ΔCO_{2glob}). ΔCO_{2glob} is assumed to be 13.5 t CO_2 ha^{-1}, in accordance with Fritsche et al. (2010a). GHG emissions due to $ILUC_{glob\_net}$ are thus 46 g CO_2 MJ^{-1} of ethanol in total ($ILUC_{GHG}$). Without any consideration of efficiency gains, the emission factor would be 123 g CO_2 MJ^{-1} of ethanol. Overall, half of the displacement is thus compensated by the expected yield increase.

5.3.2.2 ILUC with implementation of compensation measures

Specific compensation measures can further contribute to reducing ILUC-induced GHG emissions. As in the case study on Brazil, the analysis of compensation measures was conducted based on the point of view of the feedstock producer and that of the administrative unit.

Company point of view

Starting with a planned expansion of 20,000 ha in Saxony-Anhalt, it is necessary to determine the size of the arable land for which we are accounting for additional intensification, i.e. beyond that which will anyway occur. As in the other case studies, the reference area used for the implementation of compensation measures is assumed to be equal to the NEA, i.e. 11,200 ha. A single (but lasting) 100% increase in average yield would be enough to completely compensate ILUC induced by the wheat area expansion. Such large increases, however, are difficult to realize in Germany as crop yields and fertilizer inputs are already high (see section 5.3.1.3).

One possibility would be to invest in the breeding of higher-yielding varieties in order to greater crop yields in future; however, the compensation area will have to be larger as yields will nevertheless not double. Another possibility is to finance a project to increase crop yields in other countries; however, implementation of such a measure would be more appropriate for the federal government in Germany. Most potential measures to increase yields in Germany or elsewhere, therefore, could only be implemented at the national level.

Country-level (administrative) point of view

As mentioned above, one possibility is to invest in the development of greater-yielding varieties in order to achieve higher future crop yields. However, such a measure will probably only be successful in the long term. The cultivation of genetically modified plants is also an option; however, one that is politically undesirable due to potential environmental and health risks.

The investment in one or more projects to increase yields at specific sites elsewhere is a promising option for reducing ILUC from wheat ethanol expansion. The case study on Malawi illustrates how such an investment could be designed. If Germany assumed a part of the financial investment – in addition to the usual funding of projects intended to promote economic cooperation and development – this could be credited as a compensation measure for ILUC. A concrete option would be to finance a part of the SVIP – the irrigation project planned for implementation in Malawi as a public-private partnership. Assuming a financial share of 15% of the overall budget required for the food crops area of 13,421 ha in the SVIP would be enough to completely compensate ILUC due to wheat area expansion for ethanol production; this calculation is based on the LY scenario (see section 5.1.2.2).

Another measure that could be implemented at the national level is a reduction in the consumption of land-intensive agricultural products. These are mainly meat and dairy products. As Germany has a very high level of meat and dairy consumption (see section 5.3.1.3), reducing per capita consumption would seem to be a suitable option. Von Witzke et al. (2011) calculated the size of the area needed for the production of 1 kg bovine meat to amount to 35 m² kg^{-1}. Besides the area required for grazing, the authors considered the agricultural area required for the provision of concentrated feeds such as soy meal. Given that the NEA is 11,200 ha, bovine meat consumption in Germany would have to decrease by 3,200 t in order to completely compensate $ILUC_{glob\_net}$. This represents 0.3% of bovine meat consumption in 2009 (one million t (FAO 2012)).

5.3.2.3 GHG emissions from efficiency gains

Measures that enable efficiency gains in agricultural production mostly lead to the release of additional GHG emissions. These emissions have to be taken into account in order to determine overall net ILUC emissions ($ILUC_{GHG\_net}$). Analog to the other case studies, it is assumed that 50 kg N ha^{-1} are additionally applied when the relation between NEA and the agricultural reference area is 1. When taking into account an emission factor for N fertilizer production of 7.5 kg CO_{2eq} kg^{-1} of N fertilizer and N_2O emissions of 1% of the total amount of applied N, the additional GHG emissions (EFF_{GHG}) amount to 4.3 g CO_{2eq} MJ^{-1} of ethanol if no specific compensation measures are being implemented (see Table 5.29).

Table 5.29: ILUC factors for additional wheat ethanol produced in Saxony-Anhalt with and without consideration of GHG emissions from efficiency gains

Best estimates	**$ILUC_{GHG}$**	**EFF_{GHG}**	**$ILUC_{GHG\_net}$**
	[g CO_{2eq} MJ^{-1} of ethanol]	**[g CO_{2eq} MJ^{-1} of ethanol]**	**[g CO_{2eq} MJ^{-1} of ethanol]**
Without compensation measure	46.0	4.3	50.3
With compensation measure			
Investment in SVIP (LY)	0.0	0.8	0.8
Reduced meat consumption	0.0	-23.4	-23.4

Compensation measures such as a financial participation in the SVIP can lead to additional GHG emissions given that additional fertilizer application is necessary in order to achieve the efficiency gains described in the project plan.But if Germany takes over a financial share of 15% in the overall budget required for the food crops area of 13,421 ha in the SVIP, GHG emissions from additional fertilizer application (60 kg ha^{-1}) will only amount to 0.8 g CO_{2eq} MJ^{-1} of ethanol. The benefit from avoided land use thus clearly outweighs the additional GHG emissions caused by implementation of this compensation measure.

The reduction in meat consumption leads, in contrast to the compensation measures discussed so far, to an additional saving in GHG emissions beyond the positive impact on the overall agricultural land demand. This is due to the fact that cattle farming leads to high GHG emissions, in particular to high CH_4 emissions due to enteric fermentation. According to Hirschfeld et al. (2008), GHG emissions from beef production range between 8 and 17 kg CO_{2eq} kg^{-1} of beef. Taking a middle value of 12 kg CO_{2eq} kg^{-1} of beef, a reduction in beef consumption by 3,200 t would save 38,400 t CO_{2eq}; this translates to −23 g CO_{2eq} MJ^{-1} of ethanol.

To reduce meat consumption thus is a particularly promising measure for freeing up agricultural area and additionally reducing GHG emissions related to cattle farming; the same holds true for the consumption of dairy products. One political option to decrease meat consumption would be higher (and more realistic) meat prices; as soon as we internalize the external costs of meat production, e.g. by means of a tax, meat prices would increase and consumption likely decrease.

5.3.2.4 Overview of ILUC-induced GHG emissions

The best estimate considers those input parameters that seem most likely for the German case study. It also considers those yield increases that occur as a market reaction to wheat area expansion on arable land in Germany. The best estimate without application of compensation measures amounts to 50 g CO_{2eq} MJ^{-1} of ethanol ($ILUC_{GHG\_net}$).

This value is substantially lower than the maximum ILUC factor of 136 g CO_2 MJ^{-1} of wheat ethanol produced in the EU, calculated by Fritsche et al. (2010a); see Figure 5.13). This is due to the facts that the efficiency gains considered in the case-study approach half the ILUC factor and that the share of area expansion in the total incremental output growth of wheat was only assumed to account for 75%. As soon as we set this to its maximum level of 100% and do not consider efficiency gains, $ILUC_{GHG}$ would increase to 123 g CO_2 MJ^{-1} of wheat ethanol and thus be in line with

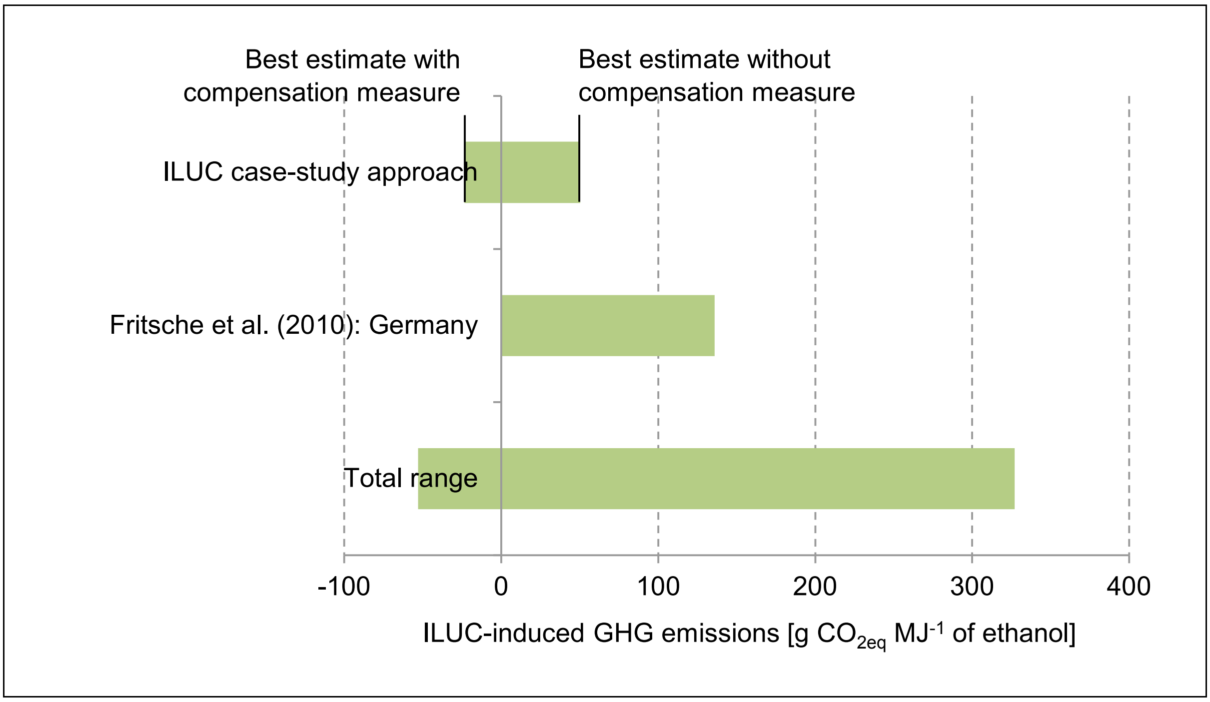

Figure 5.13: Best estimates for ILUC-induced GHG emissions for wheat ethanol produced in Saxony-Anhalt, Germany
Source: Author's case-study approach vs. Fritsche et al. (2010b) and vs. the total range of ILUC factors for ethanol in the secondary research literature (see section 2.2.3)

the maximum ILUC factor calculated by Fritsche et al. (2010a). Bauen et al. (2010) found negative ILUC factors for wheat ethanol in several exemplary scenarios. The authors explain their findings by way of the provision of DDGS, which leads to less soy bean cultivation elsewhere, so that in sum land is freed up. Energy allocation in this case study thus leads to higher ILUC factors when compared to system expansion, the approach chosen by Bauen et al. (2010). In comparison to the total range of ILUC factors found in secondary research literature (see section 2.2.3) the best estimate calculated for wheat ethanol produced in Saxony-Anhalt are rather low. In contrast to the case study on sugarcane ethanol production in Malawi, the implementation of compensation measures is not yet planned.

Compensation measures, however, could significantly reduce ILUC-induced GHG emissions. As crop yields in Germany are already very high, we need to find other measures than those in the case studies on Malawi and Brazil. The possibilities include investing in measures that increase yields elsewhere (outside the country) or to reduce meat and/or dairy consumption in Germany. Both options lead to significant net GHG savings. If Germany takes over a financial share of 15% in the overall budget for the food crops area of 13,421 ha in the SVIP in Malawi, $ILUC_{GHG}$ amounts to zero and $ILUC_{GHG\_net}$ amounts to 0.8 g CO_{2eq} MJ^{-1} of wheat ethanol. If meat consumption in Germany is reduced by 3,200 t yr^{-1} on a one-time, permanent basis, $ILUC_{GHG}$ will be zero. A negative value for $ILUC_{GHG\_net}$ is even possible: −23 g CO_{2eq} MJ^{-1} of ethanol, because of reductions in GHG emissions associated with beef production, particularly those due to enteric fermentation.

5.3.3 GHG emissions due to direct effects

5.3.3.1 System boundary, data sources, and allocation procedure

For the purposes of this dissertation, the CF of wheat ethanol was calculated using secondary data. This deviation as compared to the case studies on Malawi and Brazil is due to a lack of availability of primary data in Germany. German companies, when asked for cooperation and the provision of data, pointed to the sensitivity of such data and respectfully declined their cooperation. Although it would obviously have been better to use more similar data sources for all three case studies, the consequences are not considered to be particularly serious for the following reasons:

- Agricultural practices as they are established in Germany are well described by the Association for Technology and Structures in Agriculture (KTBL); the association regularly publishes a comprehensive database on fuel consumption, agrochemical inputs, and yields for several crops. Data on wheat cultivation is included in this database, so that secondary data of good quality is readily available.
- German and European research institutes have in recent years built up a broad database on inputs and outputs of wheat ethanol production in Central Europe (Kaltschmitt and Reinhardt 1997; Fritsche et al. 2004; Mortimer et al. 2004; Schmitz 2005; Zah et al. 2007; Rettenmaier et al. 2008). The database is available in part and can be used for CF calculations. An updated database was generated as a part of the project “BioEnergieDat” (Poganietz and Schebek 2011), but final data was not yet available when the case study was conducted.

Figure 5.14 shows the process flow diagram for ethanol production from wheat. The dataset used for characterizing the wheat cultivation is based on established practices in Germany. Data were drawn from KTBL (2006), a recognized source for data on agricultural practices, and from Schmitz (2005) (see Table 5.30).

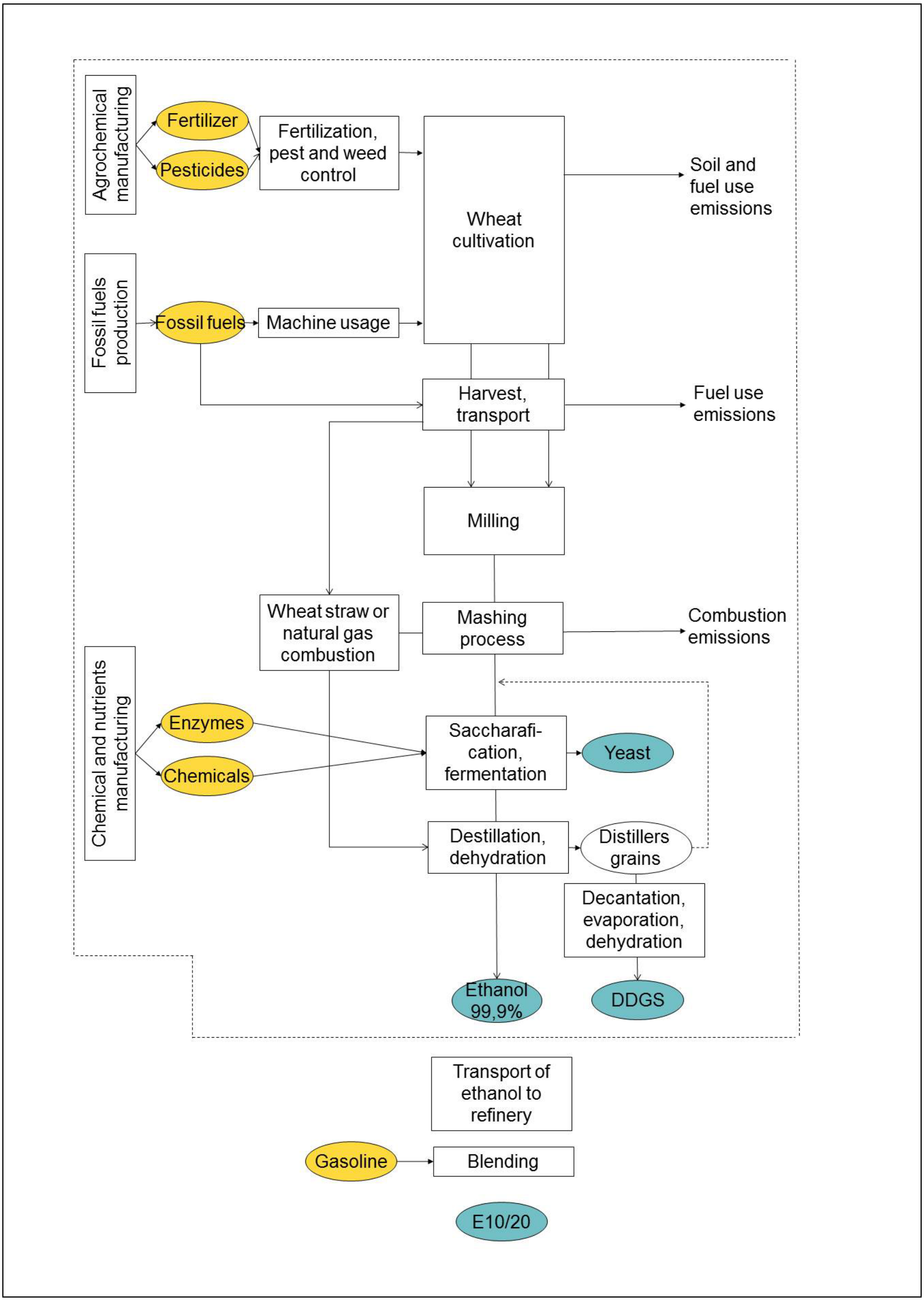

Figure 5.14: Process flow diagram for wheat ethanol production in Germany
The broken line marks the system boundaries; orange ellipses (light grey) are materials and products that enter the production process; blue ellipses (dark grey) mark outputs.

Table 5.30: Basis data: wheat cultivation in Germany

Item	Unit	Quantity	Reference
Wheat productivity (grains)	t ha^{-1}	7.9	KTBL (2006)
Diesel (incl. haulage)	MJ ha^{-1}	3,500	KTBL (2006)
N fertilizer	kg ha^{-1}	95	KTBL (2006)
P fertilizer (as P_2O_5)	kg ha^{-1}	65	KTBL (2006)
K fertilizer (as K_2O)	kg ha^{-1}	120	KTBL (2006)
Pesticides	kg ha^{-1}	3.5	Schmitz (2005)

The emission factors used for the impact assessment can be found in Table 5.11. Data for the ethanol and DDGS manufacturing stages were mainly drawn from Schmitz (2005), who presents data for an ethanol production plant with a capacity of 150,000 thousand L of ethanol; this was complemented by data from Mortimer et al. (2004) (Table 5.31).

Table 5.31: Basis data: wheat ethanol production in Germany

Item	Unit	Quantity	Reference
Input wheat	t L^{-1} of ethanol	0.0025	Schmitz (2005)
Enzymes	L L^{-1} of ethanol	0.00125	Schmitz (2005)
Sulphuric acid	kg L^{-1} of ethanol	0.023	Mortimer et al. (2004)
Caustic soda	kg L^{-1} of ethanol	0.035	Mortimer et al. (2004)
Diammonium phosphate	kg L^{-1} of ethanol	0.023	Mortimer et al. (2004)
Calcium chloride	kg L^{-1} of ethanol	0.0007	Mortimer et al. (2004)
Natural gas / wheat straw	MJ L^{-1} of ethanol	7.0	Derived from Schmitz (2005)
Electricity	MJ L^{-1} of ethanol	1.6	
Output DDGS	kg L^{-1} of ethanol	0.8	Schmitz (2005)

Enzymes are needed in the fermentation process in order to convert glucose to ethanol; according to Schmitz (2005), the production of enzymes requires 100 MJ L^{-1} of enzymes. Ethanol and DDGS manufacturing also require a considerable amount of energy, approx. 8.6 MJ L^{-1} of ethanol[16] in all. In order to consider various options as

[16] This value was calculated based on figures in Schmitz (2005); it is in line with an exemplary study for a plant in Schwedt, where wheat ethanol and DDGS are produced, and the overall energy consumption within the ethanol production plant is 9.4 MJ L^{-1} of ethanol (see IFEU 2008).

to how to provide this energy, two scenarios were calculated: one (SC 3.1) with natural gas as the fuel source used in ethanol manufacturing and another (SC 3.2) with wheat straw as the fuel source.

According to KTBL (2006), the grain-straw ratio is between 1:0.8 and 1:1.3. The wheat grains productivity is 7.9 t ha^{-1} (KTBL 2006); the amount of straw is thus assumed to be 7 t ha^{-1} based on a wheat grains-to-straw ratio of 1:1.1. Since straw is an important source of humus, a portion of the straw should remain on field in order to retain the carbon stock in soil. According to Kehres (2010), the wheat cultivation and harvest removes roughly 340 kg of humus ha^{-1}, whereas 580 kg of humus are added to the soil when 7 t of straw ha^{-1} remain on field. Thus, in order to reach an offset of the humus loss, only 2 t of straw should be removed from the field. Wheat straw has a LHV of about 17.2 MJ kg^{-1}, so 2 t of straw ha^{-1} would result in 11 MJ L^{-1} of ethanol; when we consider an overall efficiency of cogeneration of 88% (electrical efficiency: 38%; thermal efficiency: 48%) the output energy amounts to 9.3 MJ L^{-1} of ethanol – an amount of energy sufficient for the ethanol and DDGS manufacturing process. Straw is treated as a by-product that is directly used in the ethanol production process, so that an allocation of GHG emissions to straw can be avoided. As described in section 4.2, both energy and economic allocation were used to allocate the GHG emissions to the products ethanol and DDGS.

Energy allocation: All inputs and outputs are allocated to the by-products based on the LHV. DDGS has a LHV of 21,800 MJ t^{-1} (Fehrenbach et al. 2007) and ethanol a LHV of 21 MJ L^{-1} (Fehrenbach et al. 2007; ANL 2008). On the basis of 400 L of ethanol and 0.3 t of DDGS being produced from 1 t of wheat grains in Germany (Schmitz 2005), this implies a relative contribution of DDGS vs. ethanol of 0.8:1; emissions are allocated between DDGS and ethanol at 44% and 56%, respectively.

Economic allocation: The prices for DDGS and ethanol are around 0.165 EUR kg^{-1} (Heißenhuber 2011) and 0.58 EUR L^{-1} (ICIS 2012) (0.2 USD kg t^{-1} DDGS and 0.7 USD L^{-1} of ethanol). The relative contribution of DDGS vs. ethanol thus is 0.22:1; emissions are allocated between DDGS and ethanol at 18% and 82%, respectively.

The RED 2009 requires CO_2 emissions related to DLUC to be included in the CF. Where expansions take place on arable land, GHG emissions are set to zero in accordance with the RED (2009/28/EC). Ploughing up grassland in order to provide additional wheat grain, however, may occur in Germany. GHG emissions resulting from conversion of grassland account for roughly 7.3 t CO_2 ha^{-1} yr^{-1} (see Table 5.32).

In those cases where wheat grain for ethanol production is provided by former grassland, CO_2 emissions from DLUC would thus amount to 31 g CO_2 MJ^{-1} of ethanol[17]. From a climate perspective, grassland conversions should therefore be strictly prohibited; ILUC is also a possible consequence, as most grasslands are already being used, e.g. grassland production for dairy farms or biogas production.

Table 5.32: CO_2 emissions from LUC in Germany (allocated over 20 years)
Source: Data on land conversion based on (BMELV 2012b), data for the calculation of emission factors based on IPCC (2006b)

Land use	Converted area between 2000 and 2009	CO_2	CO_2
	[1000 ha]	[1000 t yr^{-1}]	[t ha^{-1} yr^{-1}]
Grassland to arable land conversion	329	2,400	7.3

* The calculation is based on IPCC (2006b); above-ground biomass = 13.6 t dm ha^{-1}, carbon fraction of dry matter = 0.5, $SOC_{Ref\ (Grassland)}$ = 85 t C ha^{-1}; all final stock change factors = 1 (IPCC 2006b)

5.3.3.2 Carbon footprint (CF) results

The most recent global wheat yield is 3 t ha^{-1} (FAO 2012); thus, the average wheat yield in Germany of almost 8 t ha^{-1} is more than double the global average. Suitable climate conditions as well as optimal fertilizing strategies adapted to local conditions are responsible for these comparatively high yields. GHG emissions due to wheat cultivation and transport to the ethanol plant account for 190 kg CO_{2eq} t^{-1} of wheat or 1.5 t CO_{2eq} ha^{-1}. Emissions per hectare are thus much higher compared to sugarcane cultivation. The largest share, about 66%, comes from N fertilization; a further 21% results from fossil fuel consumption.

The overall CF of wheat ethanol produced in Germany with natural gas as the fuel source in ethanol manufacturing (SC 3.1) is 26 g CO_{2eq} MJ^{-1} of ethanol using an energy allocation (see Table 5.33). Wheat ethanol thus fulfills the 35% GHG emissions savings vs. fossil fuels mandated by the RED 2009. Economic allocation leads

[17] The calculation is based on the following assumptions: ploughing up 1 ha of grassland leads to 7.3 t CO_2 ha^{-1} yr^{-1} (see Table 5.32); ethanol yield = 3160 L ha^{-1}; allocation to ethanol: 56%; density of ethanol = 0.79 kg L^{-1}; LHV of ethanol: 26.7 MJ kg^{-1}.

to a CF of about 39 g CO_{2eq} MJ^{-1} of ethanol – a value 46% higher compared to energy allocation (see Figure 5.15).

Table 5.33: CF due to wheat ethanol production in Germany (energy allocation, SC 3.1)

Items	CF [g CO_{2eq} MJ^{-1} of ethanol]	Share in total CF [%]
Fertilizer	9.6	37
Pesticides	0.4	1
Fuel	2.6	10
Subtotal cultivation	12.6	*48*
Ethanol manufacturing	13.8	52
Total	**26.4**	**100**

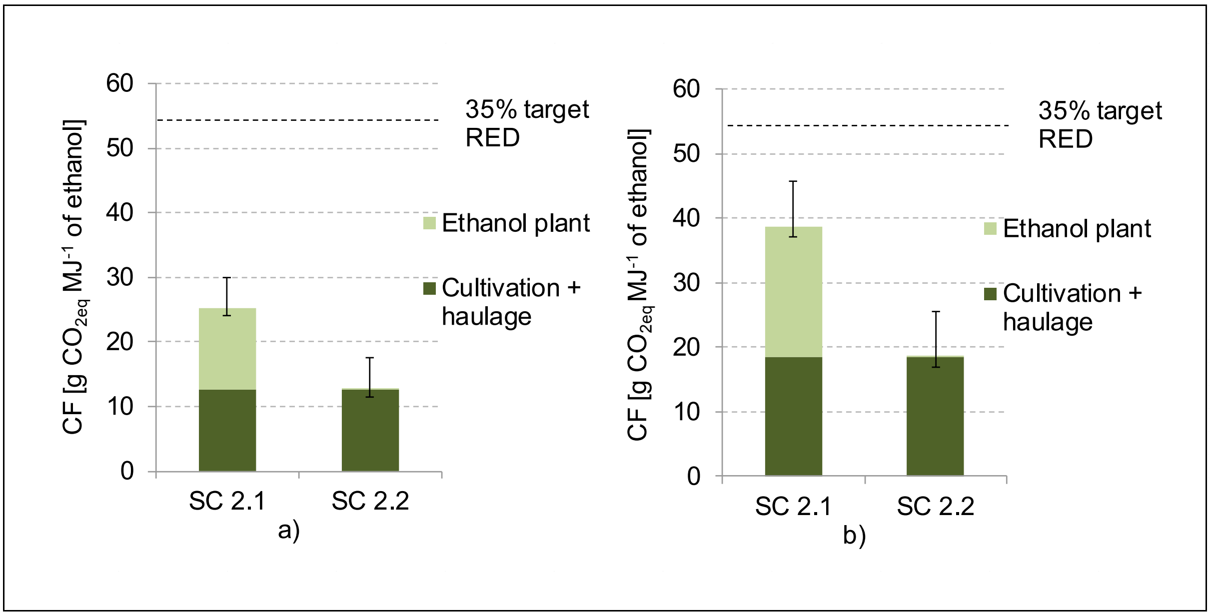

Figure 5.15: CF of wheat ethanol produced in Germany (two scenarios)
a) Energy allocation, b) Economic allocation
SC 3.1: Heat production utilizing natural gas as a fuel; SC 3.2: heat production utilizing wheat straw as a fuel. Error bars result from a variation in N_2O emissions from N fertilizer of 0.5–3%.

The processes in the ethanol plant contribute to 52% to the overall CF in SC 3.1. This considerably large share of the total emissions is due to a high energy demand in ethanol and DDGS manufacturing. In SC 3.2, in which wheat straw is used as a fuel, the overall CF is significantly lower: 13 g CO_{2eq} MJ^{-1} of ethanol when using energy allocation, and 19 g CO_{2eq} MJ^{-1} of ethanol for economic allocation. On the other hand, the CF will increase to 58 g CO_{2eq} MJ^{-1} of ethanol if wheat is cultivated on former grassland given that the CO_2 emissions from DLUC have to be considered. Ploughing up grassland should thus be avoided more stringently.

Overall, wheat ethanol produced in Germany has a significantly lower CF than sugarcane ethanol produced in Malawi and a slightly higher CF than sugarcane ethanol produced in Minas Gerais, Brazil. GHG emissions induced by ILUC without application of compensation measures are somewhat higher than in Malawi and in Brazil; however, these emissions can be avoided by implementing adequate compensation measures, such as financial investments in irrigation systems elsewhere or a reduction in meat consumption in Germany.

6 Analysis of the case-study approach

Following application of the case-study approach in the three case studies detailed in the previous chapter, this chapter deals with methodological issues and in particular with an assessment of the robustness of the results. The methodological analysis of the case-study approach includes the following steps:

1. With the help of a sensitivity analysis, those input parameters will be identified that significantly influence the results (section 6.1.1).

2. A parameter variation as determined by considering parameter uncertainty will indicate the potential range of results for $ILUC_{GHG\_net}$ (section 6.1.2).

3. It will be shown how the range of results for $ILUC_{GHG\_net}$ changes when compensation measures are being considered (section 6.1.3).

4. An approach will be introduced that allows for allocation of the final LUC CO_2 emissions between expanding agricultural activity and agricultural activity directly displacing natural ecosystems (section 6.1.4).

5. The ILUC case-study approach will be evaluated against the background of the quality criteria introduced in chapter 3 (section 6.2).

6. Finally, consideration is given to possibly combining the ILUC case-study approach with economic models in order to benefit from the advantages of both types of models (section 6.3).

6.1 Sensitivity analysis

Several parameters are involved in the ILUC case-study approach and most of them are characterized by a more or less high degree of uncertainty. Uncertainty means that a specific input parameter can fall within a potential range of values; often, the distribution of parameter values can be described by a specific distribution probability, a well-known example being the Gaussian or normal distribution. In many cases, however, the distribution of parameter values is just as likely to be uncertain.

All input parameters influence the final value of $ILUC_{GHG\_net}$. The extent of the influence, however, depends on the potential range of values and on the degree to which a slight change in a specific parameter changes $ILUC_{GHG\_net}$. The percentage deviation of $ILUC_{GHG\_net}$ for a defined variation of an input parameter is called parameter sensitivity. The greatest uncertainty in the case-study approach is assumed to be found in steps 3 and 4: As explained in the description of the methodology in section 4.1, the value chosen for F_{spill} is only an estimate; similarly, the degree to which the biofuel feedstock expansion leads to a yield increase on the reference area can only be estimated (step 4). Thus, one objective of the sensitivity analysis was to assess the consequences of these specific uncertainties.

First, the sensitivity analysis was conducted for a situation in which no compensation measures are being implemented (exemplary for the case study on additional wheat ethanol production in Germany). In this case, input parameters that enter into the case-study approach and thus influence $ILUC_{GHG\_net}$ include the following:

- share of area expansion in the total incremental output growth of biofuel feedstock (Area% (feedstock); see Lywood et al. (2009b))
- allocation factor in order to consider by-products (F_{all})
- location of ILUC: within the country or elsewhere (F_{spill})
- type of final LUC and related CO_2-emissions (average LUC CO_2 emission factor)
- share of yield increase in the total incremental output growth of crops (Yield%)
- additionally applied amount of fertilizer in order to achieve the yield increase
- biofuel yield (MJ ha^{-1}) (including uncertainty on biofuel feedstock yields (kg ha^{-1}) and biofuel yields (MJ kg^{-1}))

In the following, the influence of each of these parameters on $ILUC_{GHG\_net}$, as well as the potential range of $ILUC_{GHG\_net}$, will be demonstrated.

6.1.1 Influence of input parameters on $ILUC_{GHG\_net}$

The influence of the above-mentioned input parameters on $ILUC_{GHG\_net}$ was determined by modifying the value of each single parameter, one at a time. Varying each of the input parameters allows for the identification of those with the greatest influence on $ILUC_{GHG\_net}$; the results of varying the base values by plus and minus 100% are illustrated in Figure 6.1. The horizontal axis visualizes the percent variation of the input parameters; the vertical axis shows the results of the $ILUC_{GHG\_net}$ calculation.

Figure 6.1 reveals linear relations between most of the input parameters and $ILUC_{GHG\_net}$; the biofuel yield is the only input parameter with a non-linear relation; this parameter strongly influences $ILUC_{GHG\_net}$ as soon as the biofuel yield decreases by more than a few percentage points.

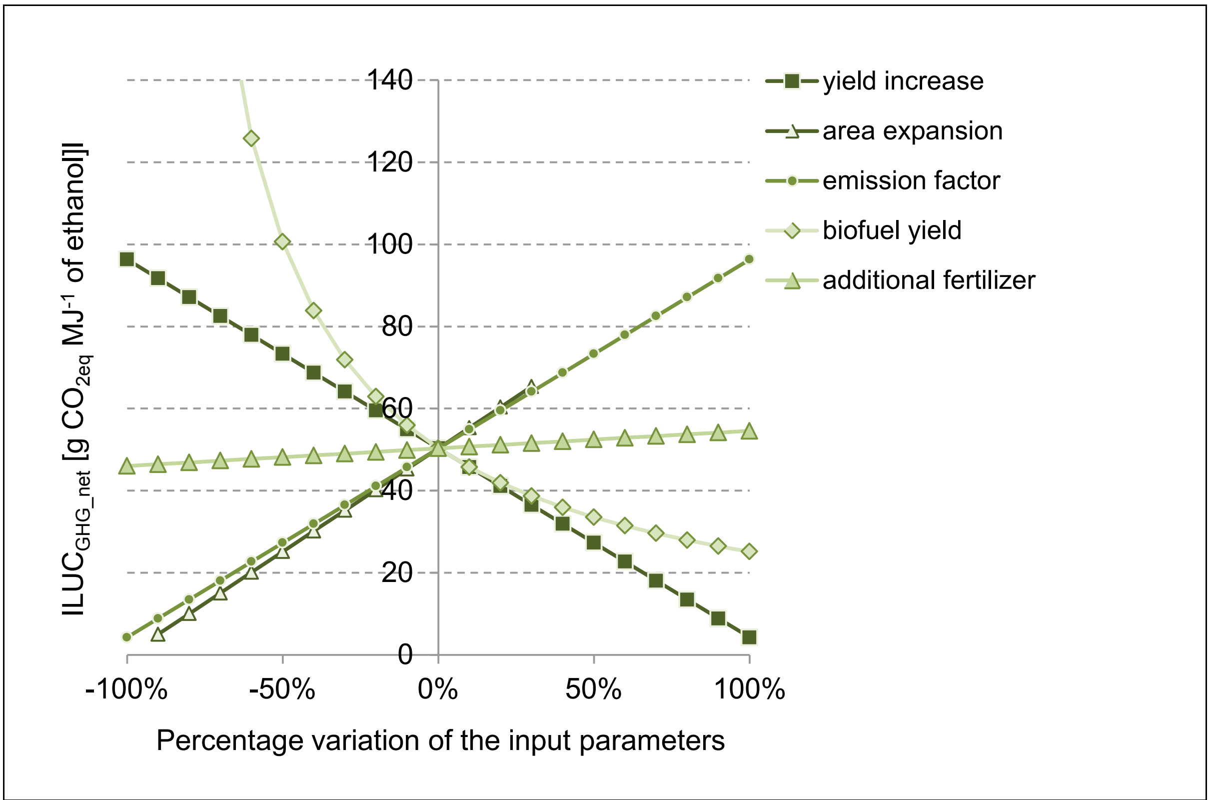

Figure 6.1: Influence of various input parameters on $ILUC_{GHG\_net}$
(Exemplary for wheat ethanol produced in Germany)

To determine the sensitivity, which is characterized as the absolute value of the percentage deviation of $ILUC_{GHG\_net}$ relative to the best estimate, incremental changes of 10% of the base value are input into the model. Within the range of plus or minus 10%, the share of area expansion in the total incremental output growth of biofuel feedstock, the average LUC CO_2 emission factor, the share of yield increase in the total incremental output growth of crops in general, as well as the biofuel yield, show a significant and similarly large influence on $ILUC_{GHG\_net}$ (see Table 6.1); the sensitivity to these input parameters, calculated for the case study on Germany, is 9 to 11%. Only the amount of additional fertilizer application has a relatively small influence on $ILUC_{GHG\_net}$, with a sensitivity of only 1%.

Table 6.1: Parameter sensitivity of $ILUC_{GHG\_net}$ (best estimate for wheat ethanol: energy allocation; sensitivity analysis: parameter variation of minus 10%)

	$ILUC_{GHG\_net}$	Deviation compared to best estimate	Sensitivity
	[g CO_{2eq} MJ^{-1} of ethanol]	[%]	[%]
Best estimate	50.3		
Sensitivity analysis			
Area% (feedstock) = 67.5%	45.3	10	10
Yield% (all crops) = 45%	54.9	–9	9
LUC CO_2 emission factor = 12 t CO_2 ha^{-1}	45.7	9	9
Biofuel yield = 55 GJ ha^{-1}	55.9	–11	11
Amount of additional fertilizer = 54 kg N ha^{-1}	49.9	1	1

Figure 6.1 and Table 6.1 do not include a variation of F_{all} and F_{spill}. With respect to allocation procedure, a variation of plus-minus 10% does not make sense, given that F_{all} takes either the one value or the other, depending on the choice of allocation procedure. F_{spill} is also not included in the analysis, the reason being that F_{spill} mainly affects the average LUC CO_2 emission factor, so that the latter parameter is dependent on the former; the average LUC CO_2 emission factor has therefore been included separately in the analysis. However, as sensitivity to the LUC CO_2 emission factor is high, we can conclude that sensitivity to F_{spill} is also high.

The sensitivity analysis so far allows us to identify those parameters that largely influence $ILUC_{GHG\_net}$ when the input values change by a fixed percentage of 10%. However, it is not only the sensitivity as so determined that affects the relevance of a parameter's uncertainty; there is also the range of possible values for each parameter; these can vary from one case study to another. Thus, in the following the potential range of values for all input parameters and for the case studies is described.

Share of area expansion in the total incremental output growth of biofuel feedstock: The relative percentage of area expansion in the total incremental output growth of biofuel feedstock can theoretically be between zero and 100%. When it is zero all output growth is provided by yield increases; when it amounts to 100%, all output growth is due to area expansion. Lywood et al. (2009b) modeled contributions of between 22 and 90% for various biofuel feedstocks. Given that in Malawi sugarcane yields, at 111 t ha^{-1}, are already very large compared to other regions of the world, a

70% share of area expansion in the total incremental output growth was assumed to be the minimum, with 100% as the maximum value. In the other two case studies, 10 and 100% were chosen as minimum and maximum values.

Allocation factor: The value of F_{all} largely depends on the methodology chosen for allocation. In chapter 5 energy allocation based on product LHV was used to calculate $ILUC_{GHG\_net}$. Economic allocation, however, was shown to be another feasible allocation procedure. In the case study on sugarcane ethanol production in Malawi, F_{all} is 0.071 when using energy allocation and 0.011 using an economic allocation. In the case study on sugarcane ethanol production in Brazil, F_{all} is 0.5 (energy allocation) or 0.41 (economic allocation). In the case study on wheat ethanol produced in Germany, F_{all} is 0.56 (energy allocation) or 0.82 (economic allocation). These values were chosen as minimum and maximum values, respectively.

Location of final LUC: Whether ILUC is likely to occur within the biofuel-producing country itself or to spill over the border depends on several parameters that can also change over time (see section 4.1). F_{spill} can, in principle, take values between zero and one; however, the analyses in the case studies showed that F_{spill} is very likely to be low in the cases of Malawi and Brazil and high in the case of Germany. Therefore, 0.5 was chosen as a maximum value for Malawi and Brazil and as a minimum value for Germany. The minimum value for Malawi and Brazil was assumed to be zero and the maximum value for Germany was assumed to be 1. The value of F_{spill} determines which of the two – the average LUC CO_2 emission factor within the country or the average global LUC CO_2 emission factor – is weighted more heavily and thus more strongly influences $ILUC_{GHG\_net}$.

Average LUC CO_2 emission factor in the biofuel-producing country: CO_2 emissions associated with an ecosystem-to-cropland conversion are characterized by a high degree of uncertainty for several reasons. First, carbon stocks have not been analyzed systematically for all relevant ecosystems and regions (Plevin et al. 2010). The IPCC (2006b) therefore provides a wide range of carbon stock values for a number of ecosystems and regions. The prediction of the share of forest, grassland, and wetland conversion in the overall LUC in a specific country as well as in the global average is also characterized by uncertainty. While the observation of land-cover changes based on remote sensing has improved steadily in recent decades, the prediction of prospective land-cover changes is still based largely on assumptions. Thus, a rather wide range of forest and grassland conversion contributions in the overall ecosystem conversion were utilized within the sensitivity analysis (see Table 6.2). Minimum and maximum CO_2 emissions attributed to LUC were calculated based on the IPCC methodology (2006b), with the exception of emissions from wetland conversion, which were taken from Plevin et al. (2010).

Table 6.2: Minimum and maximum average LUC CO_2 emission factors (Malawi, Brazil, Germany)
Source: Emission factors for forest and grassland conversion based on IPCC (2006b); emission factors for wetland conversion based on Plevin et al. (2010)

Parameter	Malawi	Brazil	Germany
Share forest [%]	20–85	20–85	0–10
Share grassland [%]	13–80	13–80	88–100
Share wetland [%]	0–2	0–2	0–2
Emission factor forest [t CO_2 ha^{-1} yr^{-1}]	13–22.5	11.5–38.0	2.0–30.3
Emission factor grassland [t CO_2 ha^{-1} yr^{-1}]	0.5–2.8	0.8–4.3	0.3–2.6
Emission factor wetland [t CO_2 ha^{-1} yr^{-1}]	50–150	50–150	50–150
Min. average emission factor [t CO_2 ha^{-1} yr^{-1}]	3.0	2.9	0.3
Max. average emission factor [t CO_2 ha^{-1} yr^{-1}]	22.5	35.9	8.3

Average LUC CO_2 emission factor elsewhere: According to Fritsche et al. (2010a), 270 t CO_2 ha^{-1} were assumed as a global average CO_2 emission factor for LUC as a consequence of biofuel feedstock expansion. The exact value depends on the specific proportions of the ecosystem conversion (e.g. forest-to-cropland conversion) and on the land conversion CO_2 emission factors. After a review of the literature, Plevin et al. (2010) chose the following ecosystem conversion fractions and LUC emission CO_2 factors in order to determine the potential range of CO_2 emission factors:

- forest to cropland: 15–50%, 350–650 t CO_2 ha^{-1}
- wetland to cropland: 0–2%, 1000–3000 t CO_2 ha^{-1}
- grassland to cropland: 48–85%, 75–200 t CO_2 ha^{-1}

These ranges result in minimum and maximum average CO_2 emission factors of 116 t CO_2 ha^{-1} and 481 t CO_2 ha^{-1}, which were carried over as minimum and maximum values and, in accordance with the RED 2009, allocated over 20 years, so that the final average emission factors used here are 13.5 t CO_2 ha^{-1} yr^{-1} (basis value), 5.8 t CO_2 ha^{-1} yr^{-1} (minimum), and 24.1 t CO_2 ha^{-1} yr^{-1} (maximum).

Share of yield increase in the total incremental output growth of crops (Yield%): As already indicated, setting the expected yield increase for the agricultural area in the baseline and in the biofuel expansion scenario is a challenging task. To simplify matters, in Malawi and Germany it was assumed that 50% of the displaced crops will be provided by agricultural area expansion, and the other half through yield increases. For cattle farming in Brazil, a greater share of yield increase in the total output growth (80%) was assumed, as the productivity of cattle farming in Brazil is relatively low and can be increased by raising the stocking rate and slaughter weight. Lywood et al. (2009b) found values for Yield% of between 10 and 78% for selected crops. As a simplification, these values were used as the minimum and maximum values for agricultural production in general, but a limitation of this assumption is that Lywood et al. (2009b) only investigated biofuel feedstock crops – the values may not be transferable to other crops. For cattle farming in Brazil, 50% and 90% were used as the minimum and maximum values, for reasons already given.

Additional amount of fertilizer: The amount of additional fertilizer applied in order to reach the forecasted yield growth rate depends, among other things, on location and type of crop. In the Malawian and German case studies it was assumed that 60 kg N ha^{-1} are additionally applied when the relation between NEA and the agricultural reference area equals one. In the Brazilian case study, it was assumed that 50 kg P_2O_5 ha^{-1} were additionally applied in order to realize the increase in the cattle stocking rate; minimum and maximum values were assumed to be ± 50%.

Biofuel yield: The biofuel yield might also vary depending on the specific site and the specific time of harvest. Uncertainty about the specific biofuel yield per hectare, however, is relatively low. The values used in the case studies are in line with biofuel yield ranges provided by FNR (2009): sugarcane ethanol 135–166 GJ ha^{-1}, wheat ethanol: 55–70 GJ ha^{-1}. Because of these rather small ranges, the input parameter was only varied ± 15% in order to determine minimum and maximum values:

- sugarcane ethanol produced in Malawi: 16 GJ ha^{-1} ± 2
- sugarcane ethanol produced in Brazil: 147 GJ ha^{-1} ± 22
- wheat ethanol produced in Germany: 62 GJ ha^{-1} ± 9

Table 6.3 shows the minimum and maximum values finally used to determine the potential range of results and Table 6.4 lists the results of the sensitivity analysis using the minimum and maximum values in the $ILUC_{GHG\_net}$ calculation.

Table 6.3: Basis value, minimum and maximum values of various input parameters for calculation of minimum and maximum $ILUC_{GHG\_net}$
Source: Shares of area expansion and yield increase taken from Lywood et al. (2009b); minimum and maximum biofuel yields from FNR (2009)

Parameter	Sugarcane ethanol Malawi	Sugarcane ethanol Brazil	Wheat ethanol Germany
Area% (feedstock) [%]	100 (70;100)	77 (10;100)	75 (10;100)
F_{all}	0.071 (0.011)	0.50 (0.41)	0.56 (0.82)
F_{spill}	0 (0.5)	0 (0.5)	0.5 (1)
Yield% (all crops) [%]	50 (10; 78)	80 (50; 90)	50 (10; 78)
Additionally applied fertilizer [kg ha^{-1}]	60 ± 30	50 ± 25	60 ± 30
Biofuel yield [GJ ha^{-1}]	16 ± 2	147 ± 22	62 ± 9
Average LUC CO_2 emission factor within country [t CO_2 ha^{-1} a^{-1}]	16.3 (3.0; 22.5)	23.0 (2.9; 35.9)	7.3 (0.3; 8.3)
Average LUC CO_2 emission factor elsewhere [t CO_2 ha^{-1} a^{-1}]	13.5 (5.8; 24.1)	13.5 (5.8; 24.1)	13.5 (5.8; 24.1)

Table 6.4: Percentage deviations of $ILUC_{GHG\_net}$ compared to the best estimate when applying the minimum and maximum values for each input parameter as documented in Table 6.3

	Malawi		Brazil		Germany	
Parameter	**Min.**	**Max.**	**Min.**	**Max.**	**Min.**	**Max.**
Area% (feedstock)	–28	–	–86	29	–87	33
F_{all}	–85	–	–18	–	–	46
F_{spill}	–16	–	–	–42	–21	–
Yield% (all crops)	74	–52	147	–49	73	–51
Additionally applied fertilizer	–4	4	–1	1	–4	5
Biofuel yield	16	–12	18	–13	18	–13
Average LUC CO_2 emission factor within country	–76	35	–86	55	–30	4
Average LUC CO_2 emission factor elsewhere	–52	72	–57	79	–52	72

In contrast to the percentage variation within the first stage of the sensitivity analysis, the biofuel yield turns out to have a minor influence on $ILUC_{GHG\_net}$, as the range of possible biofuel yields is rather narrow compared to those of other input parameters. The influence of the additional amount of fertilizer still is very small. All other parameters have a comparably similar and strong influence on $ILUC_{GHG\_net}$. In particular, the allocation factor, the average LUC CO_2 emission factors, the share of area expansion in the total incremental output growth of biofuel feedstock, and the share of yield increase in the total incremental output growth of crops strongly influence the result.

Thus, uncertainty and its influence on $ILUC_{GHG\_net}$ is particularly high in step 1 of the ILUC quantification, in which the share of area expansion in the overall feedstock output is considered; in step 4, in which the yield increase that is caused by biofuel feedstock expansion is considered; in step 3, in which the location of the final LUC is estimated; and in step 5, in which LUC CO_2 emissions factors enter the model.

6.1.2 Potential range of $ILUC_{GHG\_net}$

In addition to the sensitivity of $ILUC_{GHG\_net}$ to variations of a single input parameter, another indicator of robustness is the potential range of results. A range of results arises when entering minimum and maximum values for all relevant input parameters at once. One question with regard to the results' robustness, and especially with regard to the discussion of integrating regionally specific ILUC factors into political regulation, is the question of whether $ILUC_{GHG\_net}$ differs significantly between the various case studies when considering the potential range of results.

First, the range of results was calculated without consideration of compensation measures as this is how most of the existing approaches work. Figure 6.2 visualizes the potential ranges of $ILUC_{GHG\_net}$ for all three case studies when entering the minimum and maximum values listed in Table 6.3. The average emission factor for LUC elsewhere enters the model equally in all three case studies; therefore this parameter was excluded from the analysis.

$ILUC_{GHG\_net}$ ranges from 1 to 112 g CO_{2eq} MJ^{-1} of ethanol for sugarcane ethanol produced in Malawi, from 1 to 144 g CO_{2eq} MJ^{-1} for sugarcane ethanol produced in Brazil, and from 1 to 200 g CO_{2eq} MJ^{-1} for wheat ethanol produced in Germany. Thus, the range of results is very similar in the case studies on Brazil and Malawi, but

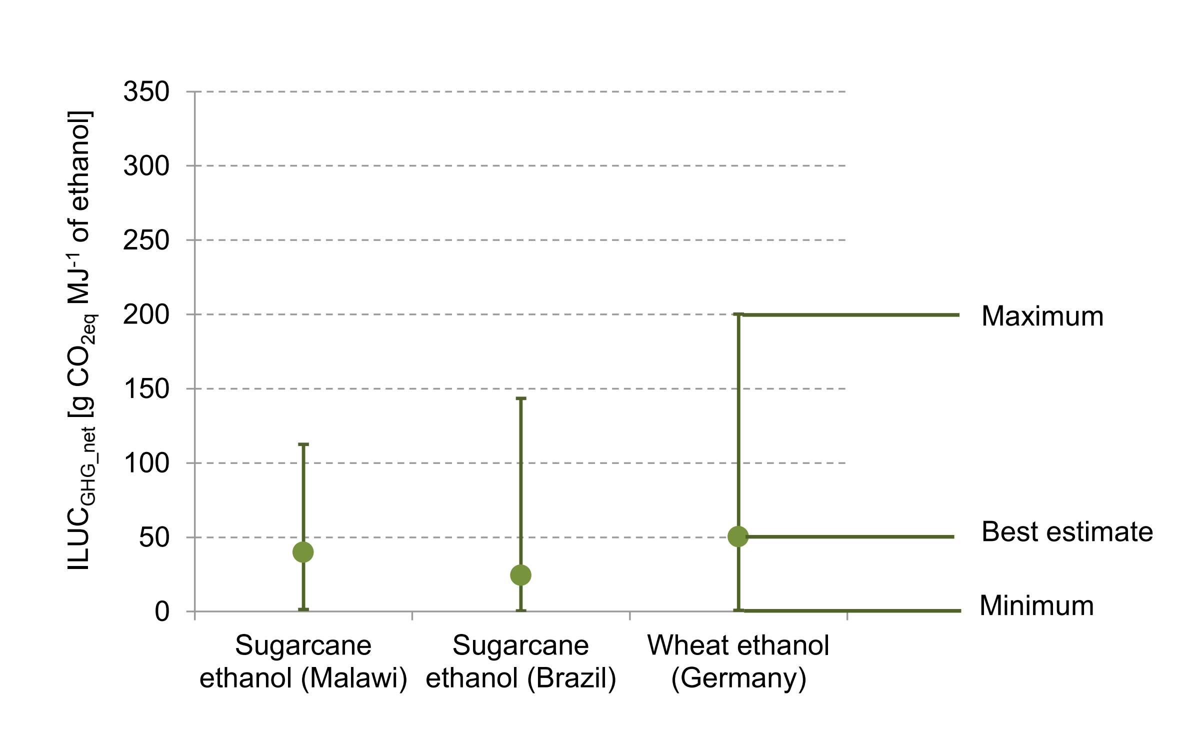

Figure 6.2: Ranges of and best estimates for ILUC$_{GHG_net}$ in the case studies
The ranges result from a calculation with minimum and maximum values estimated for the input parameters for the case studies on sugarcane ethanol produced in Malawi and Brazil and on wheat ethanol produced in Germany.

broader in the case of wheat ethanol produced in Germany. This is mainly due to a greater difference in the allocation factors than in the other case studies.

In all three cases the range of potential ILUC$_{GHG_net}$ values is rather large, a point worth noting, given that ILUC factors are being discussed for inclusion in policy regulations for the biofuel market. As the ranges for ILUC$_{GHG_net}$ strongly overlap, this also suggests that the variability of ILUC$_{GHG_net}$ is too high to actually allow an assessment of which of types of ethanol should be preferred with regard to a low ILUC$_{GHG_net}$.

Although the ranges of results may be too broad – it is possible that in some cases the minimum and maximum values assumed are too high or too low – this only partially explains why Laborde (2011) – using a Monte Carlo simulation – found much lower ranges for ethanol produced from different feedstock. The 95th percentile for sugarcane ethanol is 26.5 g CO_2 MJ^{-1} of ethanol and for wheat ethanol 18.4 g CO_2 MJ^{-1} of ethanol (Laborde 2011); however, the author focused on the variation of parameters that affect the economic behavior within the economic model. Laborde (2011) thus neither considered the uncertainty in carbon stocks of the different land cover types nor the uncertainty of the proportion of different land types converted to cropland. The results of Plevin et al. (2010), as well as those presented here, however, demonstrate that the average LUC CO_2 emission factor, in particular, does affect final CO_{2eq} emissions per Megajoule of ethanol.

As discussed earlier, it may be possible to narrow the range of results when choosing “more likely” input parameter ranges. To do so, however, we must learn more about the specific distribution of probability of the various input parameters. Given that the share of area expansion and yield increase in the total incremental output growth of feedstock and the average LUC CO_2 emission factors are responsible for the wide range of results, and that the uncertainty about these factors is not likely to soon be reduced (Plevin et al. 2010), the range will most likely remain rather broad.

The next section highlights the methodology for considering compensation measures and investigates how the ranges may change when compensation measures are included in the ILUC quantification.

6.1.3 Methodology for considering compensation measures

All parameters that influence $ILUC_{GHG\_net}$ also influence the amount by which the productivity of a specific area has to increase in order to compensate $ILUC_{GHG\_net}$. Furthermore, the methodology for considering compensation measures includes its own challenges, which will be discussed in this section.

The case-study approach takes an expanding biofuel production situation with implementation of a compensation measure and compares it to a baseline situation (no expansion, no compensatory measures). In most cases, characterization of the compensation scenario is highly challenging as will be shown in the following.

The case study on Malawi is the only example in which a compensation measure is actually planned. This section therefore focuses on this specific case study, which clearly illustrates the challenge of characterizing the compensation scenario: The results presented in section 5.1.2 rely on the assumption that 1% of the investment required to finance the implementation of the irrigation system on the 13,421 ha that are planned to be used for food crop cultivation can be fully credited to the additional biofuel production; however, even if the sugar company’s participation in the overall financing were clearly known, the percentage that could be credited to sugarcane ethanol would be difficult to estimate given that the main driver for the investment is sugar production. In order to analyze the sensitivity of $ILUC_{GHG\_net}$ to this input parameter, the share allocated to ethanol in the SVIP budget was varied from 0.5 to 1.5%. This relatively slight change alone would change the result significantly; in the LY scenario $ILUC_{GHG\_net}$ becomes:

- 31 g CO_{2eq} MJ^{-1} of ethanol when allocating 0.5% to sugarcane ethanol
- –11 g CO_{2eq} MJ^{-1} of ethanol when 1% is allocated to sugarcane ethanol
- –55 g CO_{2eq} MJ^{-1} of ethanol for a 1.5% allocation

The extent to which the measures can be credited to biofuel expansion thus has a vital influence on the effect of the compensation measure on $ILUC_{GHG\_net}$, and thus must be carefully considered.

A key decision relates to the methodology of how the increase of productivity is considered. In the basic approach, the increase in the physical yield, i.e. annual growth rate of yield or stocking rate, was applied in order to consider the effect of the compensation measures. The comparison of the HY and LY scenarios in section 5.1.2 already demonstrated the huge influence of the amount of physical yield increase. Sensitivity analyses with respect to the physical yield increase resulting from specific compensation measures are thus recommended.

There are also other possibilities for addressing the increase in productivity besides physical yield increase; these include, for instance, consideration of the increase of CU, energy yield, and monetary value. In each case, an additional factor must be multiplied with the physical yield: CU t^{-1} of agricultural product when considering net energy content of agricultural products, LHV t^{-1} of agricultural product for heating value, and USD t^{-1} of agricultural product in order to consider monetary value.

An analysis was conducted on the effect of choice of approach, again using the example of the SVIP in Malawi. As explained in section 5.1.2, the affected food crop area, consisting of maize, sorghum, and rice, is 13,421 ha. If 1% of the compensation effect is allocated to sugarcane ethanol, the compensation area is 134 ha. The same proportional usage (share of crops) was assumed for before and after implementation of the SVIP in order to avoid distortions in the results due to variability in crop-specific yields. The expected increase in physical yield on the compensation area due to implementation of the SVIP is 553% in the LY scenario.

Application of the other methodological approaches produces divergent results: While the overall increase of CU and LHV for the entire area – 581% and 600%, respectively (see Table 6.5 and in the appendix) – are higher than the overall physical yield increase (553%), the overall increase in monetary value of 371% is significantly lower (see Table A.10 in the appendix). This is due to the fact that rice simultaneously has the highest producer price and lowest physical yield.

Table 6.5: Current and planned land uses in the SVIP, physical yields, and cereal units before and after implementation of the SVIP (LY scenario)
Source: Project description; expected yields from Fandika et al. (2008); CU from TLL (2006)

	Assumed utilization [ha]	Current yield [t ha^{-1}]	Current yield [t CU*]	Planned utilization [ha]	Expected yield [t ha^{-1}]	Expected yield [t CU*]
Maize	91	0.53	53	91	5.0	501
Sorghum	7	0.59	3	7	5.0	29
Rice	36	1.1	36	36	3.0	99
Total	134		92	134		629

* Maize: 1.1 CU; sorghum: 0.84 CU; rice: 0.92 CU; pulses, 1.36 CU

These differing percentage increases in productivity will affect the final values. $ILUC_{GHG\_net}$ becomes:

- –11 g CO_{2eq} MJ^{-1} of ethanol when considering physical yield increase
- –16 g CO_{2eq} MJ^{-1} of ethanol when considering the increase in CU
- –19 g CO_{2eq} MJ^{-1} of ethanol when considering the increase in heating value
- 17 g CO_{2eq} MJ^{-1} of ethanol when considering the increase in monetary value

Accounting for the effect of compensation measures thus significantly influences the final $ILUC_{GHG\_net.}$ By choosing a specific approach, it is possible to specifically consider those agricultural product characteristics deemed to be relevant for the displacement effect. Depending on the specific circumstances, the parameter that drives ILUC might not necessarily be the physical loss of agricultural products. The choice of a specific approach thus must be based on considerations similar to those arising in the choice of a specific allocation measure, where the goal is likewise to choose characteristics of particular relevance for a specific group of products.

Finally, there is an interest in determining the range of results for $ILUC_{GHG\_net}$ when the implementation of compensation measures is being considered in the ILUC calculation. The values presented in Table 6.3 were input as minimum and maximum values. Additional minimum and maximum values on the expected yield increase and the share of investment allocated to ethanol were used for the case study on Malawi in order to consider the specific compensation measure (see Table 6.6). In the other case studies the implementation of compensation measures is not yet planned, so no additional values are entered.

Table 6.6: Basis value, minimum and maximum values of various input parameters when considering compensation measures
Yield increase includes assumptions on physical yield increase (LY and HY) and on the methodological approach to how the yield increase is being considered; monetary value and LHV provide the minimum and maximum values

Parameter	Sugarcane ethanol Malawi
Yield increase [%]	553 (371;1076)
Share of investment allocated to ethanol [%]	1 (0.5;1.5)

$ILUC_{GHG\_net}$ now ranges from –200 to 74 g CO_{2eq} MJ^{-1} of additional sugarcane ethanol produced in Malawi. The ranges for $ILUC_{GHG\_net}$ for the case studies in Brazil and Germany do not change as the implementation of compensation measures is currently not planned there. The results illustrated in Figure 6.3 prove that the error bars still overlap. As the shape of the distribution of the input parameter values is not known, there is no reason to conduct a variance analysis. In comparison to the results without consideration of compensation measures, however, the following becomes clear: $ILUC_{GHG\_net}$ is likely to be significantly lower in cases where compensation measures are being implemented than in cases without compensation measures. There is furthermore a good chance that $ILUC_{GHG\_net}$ will take on a negative value if ambitious compensation measures are being implemented.

To really make sure that ILUC and related GHG emissions are avoided, the share in the investment required to finance the implementation of the irrigation system on the 13,421 ha that are planned to be used for food crop cultivation must be at least 1.3%. In that case all values in the range of $ILUC_{GHG\_net}$ would be negative.

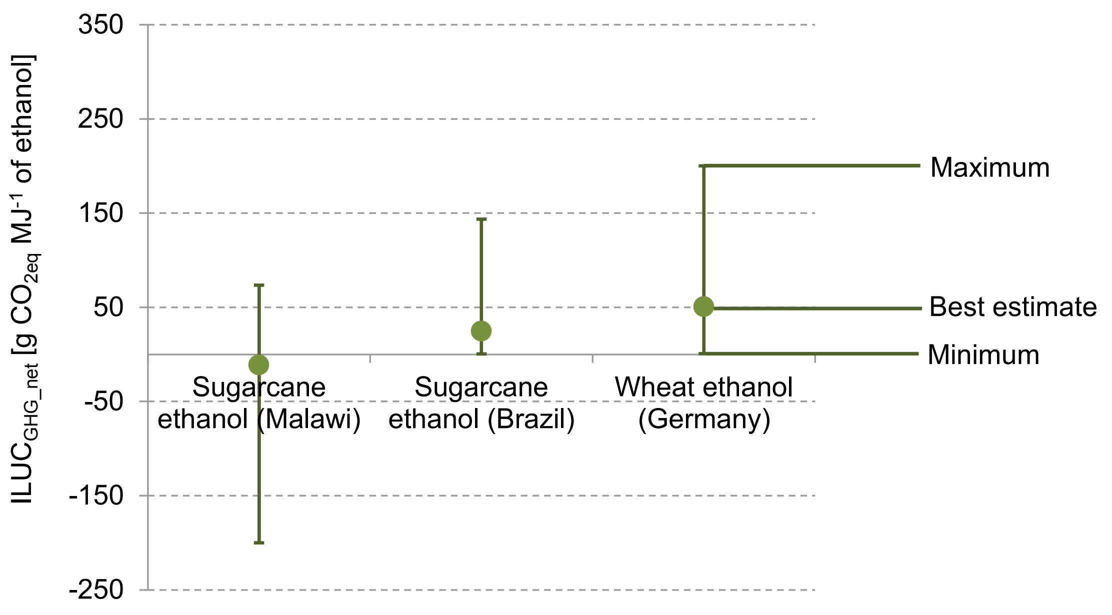

Figure 6.3: Ranges of and best estimates for $ILUC_{GHG\_net}$ in the case studies including compensation measures
The ranges result from calculations using the minimum and maximum values estimated for all input parameters of the case studies on sugarcane ethanol produced in Malawi and Brazil and on wheat ethanol produced in Germany.

6.1.4 Allocation: agricultural expansion vs. direct displacement

Allocation is known to have a strong influence on LCA and CF results in almost all cases where a process outputs more than one product. The results presented in section 6.1.1 demonstrated that switching from an energy-based to an economic allocation can change $ILUC_{GHG\_net}$ by more than 80%. With regard to allocation, another topic that has not been discussed in the scientific literature on ILUC so far but may be of relevance is the question of whether and how the final CO_2 emissions from LUC should be allocated between expanding agricultural activity – here, biofuel feedstock – and agricultural activities that directly displace a natural ecosystem.

ILUC due to biofuel feedstock expansion is always DLUC in another area of agricultural production (Delzeit et al. 2011, 2). The same LUC thus can be defined as the DLUC of a specific agricultural activity that displaces a natural ecosystem as well as the ILUC resulting from expanded agricultural activity elsewhere. With regard to the quantification of ILUC factors, the current common practice is to debit all CO_2 emissions from the final LUC to the expanding biofuel feedstock thus disburdening any agricultural activities that directly displace natural ecosystems.

GHG emissions arising from DLUC, however, are to be included in CF calculations according to the PAS 2050 (BSI 2011) and may be included according to the GHG Protocol (WRI and WBCSD 2011). As emissions from DLUC must be included in the CF of biofuels, according to the RED 2009, it is a logical consequence to do the same with all other agricultural products. However, as soon as we broaden the scope of the CF for all agricultural products, the question arises as to how to proportionately debit CO_2 emissions resulting from the final LUC between biofuel feedstock expansion and agricultural activity that directly displaces the natural ecosystem. Given that both forms of agricultural activity bear a part of the responsibility either by indirectly or by directly pushing natural ecosystems conversion, it seems reasonable that all products resulting from those agricultural activities should share the burden of CO_2 emissions (Finkbeiner 2013). Thus, there is a need for a methodology that allows for consideration of the impact of both types of agricultural activity – expanding agricultural production as well as production that directly displaces a natural ecosystem; this is a typical situation for allocation.

As the following example will show, consideration of ILUC leads to either a free-rider effect or double counting when no distinction in allocation is made between expanding and directly displacing agricultural activities. As an example, the case of Brazil is taken, where sugarcane displaces pasture land in the Amazon Legal, which is followed by further deforestation in order to generate new pasture land.

In section 5.2 it was shown that 0.2 ha of new pasture land will result from forest conversion when the sugarcane area expands by one hectare. The CO_2 emissions released by the final LUC thus have to be allocated to the products gained on 0.2 ha of pasture land and on one hectare of sugarcane.

CO_2 emissions resulting from the conversion of Amazonian rain forest to pasture land are calculated to be 30.5 t CO_2 ha^{-1} yr^{-1} for a period of 20 yr based on IPCC (2006b). Overall 6.7 t CO_2 yr^{-1} will be released, as only 0.2 ha of new pasture land are necessary in order to compensate the loss of one hectare of pasture land in the South-Central Region. The main products gained are sugarcane ethanol (147 GJ) and beef (45 kg); other products, such as fibers, have not been considered. Figure 6.4 visualizes the displacement effect caused by sugarcane area expansion and demonstrates the results of ILUC and DLUC quantification when ILUC quantification is carried out as is currently done (A), when applying the concept of carbon footprinting with ethanol and beef (B, C), and when applying various allocation procedures (D–F).

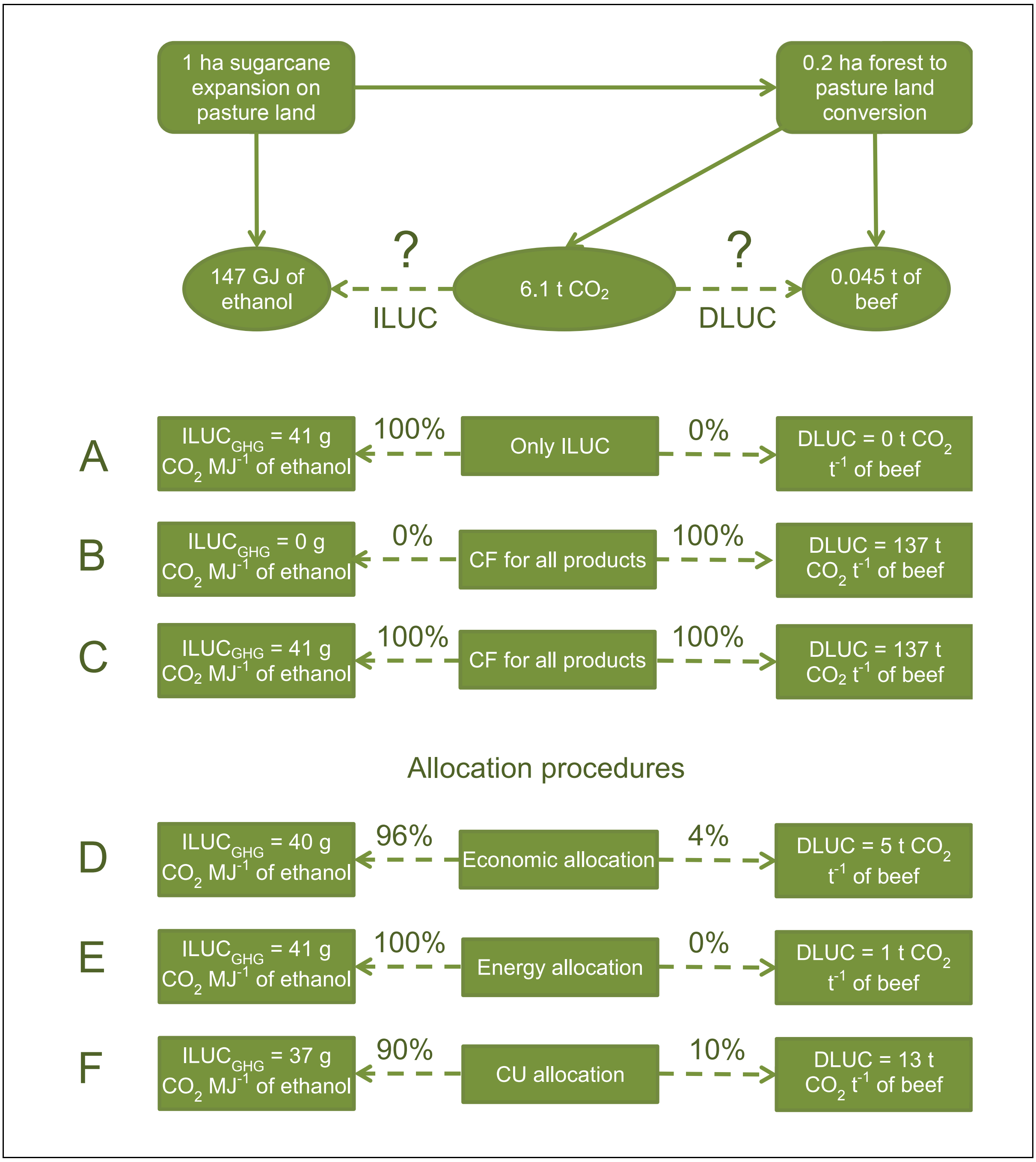

Figure 6.4: Options for allocating LUC CO_2 emissions
Allocation is shown for the case of additional sugarcane ethanol and displaced beef production. Calculated using an ethanol yield of 147 GJ ha^{-1} and a beef yield of 0.22 t ha^{-1}.

According to the ILUC quantification approach addressed within the scope of the EU's biofuel policy, all CO_2 emissions from the final LUC are debited to the expanding sugarcane ethanol production (see case A). Based on an average ethanol yield of 147 GJ ha^{-1}, CO_2 emissions from ILUC amount to 41 g CO_2 MJ^{-1} of ethanol. This approach, however, has the effect of disburdening cattle farming that directly displaces forested land from responsibility for any LUC-induced CO_2 emissions; although DLUC due to the generation of new pasture land would occur, in the CF calculation for beef the emissions from DLUC would be set to zero. This, however, can lead to a *free-rider effect*, as the party directly profiting from the final LUC is not held accountable for any of these LUC-induced CO_2 emissions – not even in a scenario in which the product CF is used as a market incentive to reduce carbon emissions in the economy. Thus, such an approach, in which all LUC CO_2 emissions are allocated to the expanding biofuel feedstock, fails to provide a market incentive for LUC reduction that specifically addresses those directly benefitting from deforestation.

If the scope of the CF were broadened and applied to all agricultural products as it is now applied to biofuels, ILUC would no longer exist, as DLUC would be completely charged to the respective agricultural activity directly displacing the natural ecosystem (case B). Thus, in the chosen example all CO_2 emissions from LUC are debited to beef thus at the same time disburdening sugarcane ethanol. This option would, however, not consider the potential indirect effect of expanding crops, which has been identified as a relevant concern in the case of biofuel production (Fritsche et al. 2010a; Lapola et al. 2010; Laborde 2011).

Case C addresses ILUC as it is currently done while at the same time allowing the inclusion of CO_2 emissions from DLUC into the CF of beef. This would cause *double counting* of the LUC-induced CO_2 emissions. According to the ISO standard on LCA, double counting should be avoided (ISO 14044 2006), and thus this does not represent an appropriate approach for handling LUC-induced CO_2 emissions.

Allocation of LUC-induced CO_2 emissions was therefore tested in order to avoid both double counting and free-rider incentives. Several methods are available, including energy, economic, and CU allocation methods, each with its own respective allocation factor (see Table 6.7).

Table 6.7: Data used to derive allocation factors for the Brazilian case study: physical yields, cereal units, monetary value, and lower heating values for sugarcane ethanol and beef produced in Brazil

Source: Based on Fehrenbach et al. (2007), Gopal (2009), Lisboa et al. (2011), Beilicke (2010), IBGE (2010), Nassar et al. (2010), BMELV (2011), CEPEA (2012), TU Dresden (2012)

	Yield* [kg ha^{-1}]	CU** [kg ha^{-1}]	CU [kg ha^{-1} LUC]	Allocation factor [%]
CU allocation				
Ethanol	5,510	2,672	2,672	90.5
Beef	223	1,395	279	9.5
Economic allocation		**Monetary Value*** [R$ ha^{-1}]**	**Monetary Value [R$ ha^{-1} LUC]**	
Ethanol	5,510	7,324	7,324	96.5
Beef	223	1,312	262	3.5
Energy allocation		**LHV**** [MJ ha^{-1}]**	**LHV [MJ ha^{-1} LUC]**	
Ethanol	5,510	147,124	147,124	99.6
Beef	223	2,752	550	0.4

* Calculated using an average sugarcane yield of 75 t ha^{-1}; average ethanol yield 93 L t^{-1} of sugarcane; stocking rate 1.027; average slaughter weight of bovine animals 217 kg
** Calculated using 47.5 kg molasses t^{-1} of sugarcane, 0.75 dt CU dt^{-1} of sugarcane, average ethanol yield 93 L t^{-1} of sugarcane (0.48 dt CU dt^{-1} for ethanol); 6.26 dt CU dt^{-1} of beef
*** Calculated using the average producer prices of 5.89 R$ L^{-1} for beef and 1.05 R$ L^{-1} of ethanol
**** Calculated with a LHV of 26.7 MJ kg^{-1} of ethanol and a LHV of 25.2 MJ kg^{-1} of dry beef (water content: 51%)

Depending on the allocation procedure, the percentage of the overall LUC CO_2 emissions allocated to ethanol varies between 90 and 100%. The resulting ILUC CO_2 emissions were in the range between 37 and 41 g CO MJ^{-1} of ethanol, and DLUC CO_2 emissions were between 1 and 13 g CO_2 t^{-1} of beef. The results prove that the choice of allocation procedure influences the ILUC factor of ethanol and the CF of beef. The values, however, are in a similar range compared to the situation without allocation in which the allocation factor is either zero or 100% (100% ILUC: 41 g CO_2 MJ^{-1} of ethanol; 100% DLUC: 137 g CO_2 t^{-1} of beef).

The choice of allocation procedure thus influences the assessment of both beef and ethanol, albeit not to the same degree as the general decision on how to consider DLUC and ILUC. The difference between allocation and “normal” ILUC quantification without allocation is the greatest in the case of CU allocation when ILUC emissions debited to ethanol are 10% lower than without allocation.

As already indicated, the advantage of allocating LUC CO_2 emissions to all directly and indirectly expanding agricultural activities and end products is that both free-rider effects and double counting can be avoided. In the scope of this dissertation the allocation approach has only been applied to one simplified case study; thus, more research and case studies are needed before results can be generalized.

Allocation also poses methodological problems. In many cases it may be difficult or even impossible to link a biofuel feedstock expansion to a specific LUC. As the example of the German case study has shown, the specific location of the final LUC remains in many cases unforeseeable, especially when ILUC is likely to spill over the border. Thus, for ILUC induced by wheat expansion for ethanol production in Germany, it is scarcely possible to say where and which sort of LUC will take place and which agricultural activity will follow the natural ecosystem conversion.

Finally, a model that covers the entire agricultural sector will be necessary to properly allocate LUC CO_2 emissions between all direct and indirect drivers for natural ecosystem conversion. Thus, the allocation approach presented here may have to serve as a first approximation that highlights the relevance of this topic; further research is needed on the problem of double counting when allocating ILUC-induced emissions entirely to the expanding feedstock and including DLUC-induced emissions in the CF of all agricultural products.

6.2 Evaluation against quality criteria

The ability of a model to allow for sensitivity analysis with regard to methodological decisions as well input parameter variation is one of the most important criteria for ascertaining the suitability and quality of an ILUC quantification approach. However, as introduced in chapter 3, several other criteria that an ILUC quantification model should fulfill were also identified. In the following a systematic look is taken at the extent to which the ILUC case-study approach fulfills these criteria.

General requirements

Level of detail: The case-study approach uses the most detailed statistical data available on the cultivation of specific crops, yields, and typical displacement effects in specific regions. Thus, the level of detail in the characterization of the agricultural sector and the expected LUC in specific regions is rather high.

Sensitivity analysis: As demonstrated, all input parameters were varied in order to analyze the input parameter and methodology sensitivities of the results. In all three of the case studies reviewed here, the potential range of results was ascertained.

Timeliness of data: The timeliness of data used in the case-study approach depends on the specific data available in each situation. In general, desk and field research yields more up-to-date data than does the use of harmonized data, such as in CGE modeling. Data from the official database FAOSTAT, however, which was used for instance to derive economic indicators, is usually two years behind, and thus does not necessarily reflect the present situation. The agricultural trade data, especially, is crucial for estimating where ILUC takes place. Thus, more recent data would be preferable in order to improve the reliability of the results. The same goes for LUC – with regard to LUC in the three studies presented here, data availability showed a strong variation among the case-study countries.

Applicability with regard to data availability: The quality and extent of available data in the three case studies presented here differed. FAOSTAT data was used to derive economic indicators, so that generally data for all countries was available, but of differing quality. FAOSTAT provides in part roughly estimated data; the data it derives from public authorities, however, is of rather high quality. The availability of data on LUC also varies greatly between countries; various sources are possible, such as the GGIs, land-cover monitoring and/or statistical data provided by local authorities.

Applicability with regard to time required for data collection: In the studies presented here, roughly three months per case study were necessary for data collection, one month of which was spent on desktop research, one month preparing for, and one month doing field research in order to fill data gaps and check specific assumptions with the help of expert interviews. Field research is particularly necessary in order to identify whether ILUC compensation measures are taking place or being planned. A fourth and fifth months were finally required to consolidate and evaluate the data.

Transparency and traceability: The case-study approach is designed such that other researchers can recalculate the results, if desired, and conduct their own sensitivity analyses or make ILUC calculations for other case studies.

Avoiding double counting (separation of DLUC and ILUC): The possibility of avoiding double counting represents an advantage of the methodology presented here, especially in comparison to economic modeling, which does not distinguish between DLUC and ILUC. In the case of economic modeling, the separation of DLUC and ILUC requires a qualitative interpretation by the researcher, so there is always a risk of double counting when an ILUC factor is added to the CF. In the case-study approach, DLUC and ILUC can clearly be separated; furthermore, it is possible to allocate the final LUC between the expanding biofuel feedstock and the agricultural activity actually displacing the natural ecosystem.

Ability to consider various indirect effects

Supply of by-products: By-products are considered by allocating land demand for feedstock cultivation to all accruing products. In order to test robustness, energy and economic allocations are applied; other allocation approaches such as CU allocation can also be considered.

Efficiency gains: The ILUC-reducing effect of efficiency gains in biofuel feedstock cultivation as well as in agricultural activities in general are considered in the ILUC case-study approach; the approach also takes into account GHG emissions that accrue as a consequence of the additional fertilizer application (EFF_{GHG}) needed to achieve the efficiency gains. Economic models normally do not take into account such emissions, nor do they consider specific mitigation or compensation measures. This possibility, of considering additional compensation measures, is another advantage of the case-study approach. With the help of scenario calculations, the mitigation effect of several options can be calculated, allowing for a comparison of the effect of implementing various measures to reduce ILUC.

Changing diets: The overall demand for agricultural products, which can change as a market reaction to biofuel feedstock expansion, is not considered in the ILUC case-study approach. However, a reduction in demand is considered as an ILUC compensation measure in the case study on Germany. As the calculation in the German case study proves it is generally possible to allow for certain premises on changing diets in the ILUC case study approach; however, if unintended changes in diet are to be integrated, such premises would have to be based on rough assumptions or developed with the help of economic modeling.

Changing total fuel and energy demand: The overall fuel and energy demand remains constant in the current application of the case-study approach. Once data on changes in overall fuel demand as a consequence of biofuel production become available, these numbers could be integrated into the case-study approach.

Changing consumption and investment patterns: Changes in household income are a potential consequence of participation in biofuel feedstock cultivation. Such effects were not considered in the case-study approach. Rebound effects, however, probably occur when those who benefit from participation in biofuel production alter their consumption patterns. These changes can increase or decrease the overall GHG emissions, depending on the products being consumed; these effects have not been analyzed and would require other methodologies. Whether such emissions should be considered in the calculations is a sensitive matter, as their inclusion could be perceived as "punishing" the economic development of a developing country. Another example, of a less ethical nature, is a company that generates a profit from biofuel production, which it can then choose to invest in various activities; the effect of this investment on the overall GHG emissions depends on the specific activity chosen. The general principle is that if one indirect effect is to be included in the CF, then all indirect effects should be included.

One limitation of the case-study approach thus is that it only takes into account selected indirect effects. While the methodology considers ILUC, efficiency gains, and the supply of by-products, it only partially considers changes in diet, and does not consider changing fuel demand or changing consumption patterns as a consequence of an increasing income or profit. More research is required on the question how far the quantification of indirect effects should go and in cases where specific indirect effects are being selected, the criteria for their selection.

Ability to consider regional heterogeneity (regionalization)

The ability to consider regional heterogeneity with regard to biophysical aspects, aspects of land use, and political and economic aspects is a specific strength of the

ILUC case-study approach. However, in the three case studies presented here, several limitations were also faced concerning the availability of regional data.

Biophysical aspects: Data on carbon fluxes in the above- and below-ground soil carbon contents was in part difficult to come by. While data availability was rather good for the Brazilian case study, regionally specific data for the case study on Malawi was not available; in the latter case default values provided by the IPCC (2006b) were therefore used. Data on current and expected productivity of various agricultural activities as well as on the expected productivity due to the implementation of compensation measures was more easily found. In general, more regional studies on carbon fluxes and the effect of measures to intensify agricultural activities are required in order to provide a robust data set for such analyses.

Aspects of land use: One step in the case-study approach is to estimate where ILUC will occur – within the biofuel producing country itself or elsewhere (cross-border). In those instances where it is expected to occur within the country itself, data on LUC is gathered at the regional level in order to predict the carbon fluxes. Data from land-cover monitoring and statistical data on historic and current land-use change can be (and were both) used in order to describe regional LUC; however, data availability and timeliness of data showed a strong variation among the case-study countries.

Political, economic, and cultural aspects: Legislation with regard to land use, such as national ecosystem protection and land-use policy and enforcement, were included in the case-study approach as they help to estimate where ILUC will take place. Economic indicators with regard to the production, import, and export of agricultural products were also calculated in order to assess the location of ILUC. Societal preferences, as well as land tenure and ownership, have not been studied systematically; however, they were kept in mind while conducting interviews and cross-checking the assumptions made for the input parameters that enter the case-study approach.

Along with these criteria, a model should generally allow for assessment of *various impact categories*. Indeed, one limitation of the case-study approach is that it is currently limited to a single impact category, the CF; this, however, is true for all ILUC quantification models that currently exist. ILUC obviously can also have positive or negative effects on biodiversity (Van Oorschot et al. 2010) and local water quality and availability; therefore, further research on the impact of ILUC on these environmental effects is required. The case-study approach, however, does output the ILUC in ha MJ^{-1} of ethanol, so that further analysis and assessment are possible.

A limitation of the *application* of the model is that it has so far only been applied in ethanol case studies. Substitution, however, is primarily known to occur in the case of biodiesel production; vegetable oils used in biodiesel production will presumably always be replaced by palm oil produced in Indonesia or Malaysia, given that palm oil currently represents the cheapest vegetable oil available (Bauen et al. 2010). In step 3, in which the location of ILUC is estimated, such relations have to be considered; ILUC caused by an increase of rapeseed biodiesel production in Germany is not only likely to spill across the border but also to occur in Indonesia or Malaysia, so that a relatively precise forecast of the location of the final LUC would be possible.

The case studies furthermore allow assessment of the *applicability* of the ILUC case-study approach *to specific types of feedstock*. While the approach can be used quite effectively with perennial crops – cases in which a biofuel feedstock expansion can actually be observed (case studies on Malawi and Brazil) – the applicability to annual crops is rather limited as it is only possible to estimate whether an overall expansion of a specific crop area will occur or not. The case study on Germany shows this limitation; here, the identification and design of compensation measures could rely on expansion scenarios of several biofuels in order to cover a potential range of events and results. Furthermore, if it is known that a new biofuel plant will be put into operation, a combination of economic models might help to establish adequate assumptions in order to run the ILUC case-study approach and estimate ILUC.

6.3 Potential combinations with economic models

As shown in the previous section, the ILUC case-study approach offers several advantages in comparison to economic models. While most of the existing models are top-down approaches that take as their starting point the EU-mandated increases in biofuel demand, the case-study approach works as a bottom-up approach, starting with the biofuel feedstock expansion itself. Advantages of this approach are in particular the possibility of including regional conditions regarding feedstock cultivation and LUC and the consideration of compensation measures in the ILUC quantification. By doing so, it is possible to determine more realistic ILUC factors for specific biofuel feedstock expansions than can be achieved by means of a top-down approach, for instance CGE models. Economic models, however, also offer advantages that are not possible solely by means of the ILUC case-study approach. A discussion of how the case-study approach could be combined with economic models follows below.

Feedstock trade: Biofuel feedstock production is the starting point with the ILUC case-study approach. In the case studies presented here biofuel production takes place in the same country as the biofuel feedstock cultivation. Generally, it is even the same actor cultivating the feedstock and producing the biofuel; however, this must not necessarily be the case. With annual crops it is much more difficult to observe feedstock expansion and link it with biofuel production. Furthermore, the feedstock expansion and biofuel production need not take place in the same country; thus it will be necessary to link a specific feedstock expansion with specific biofuel production located elsewhere. Such relationships can be worked out based on a market analysis and expert interviews as described in Bauen et al. (2010), or they can be determined based on economic modeling. After such linkages have been ascertained, the ILUC case-study approach could then be applied as described here.

Location of LUC: As already mentioned in section 6.1.1, determination of the location of LUC is characterized by a high degree of uncertainty. Economic modeling might help to verify or adjust the assumptions made in the case studies presented here.

Changing diets: The overall demand for agricultural products could change as a market reaction to biofuel feedstock expansion. Such effects are not considered in the ILUC case-study approach. Economic models that cover linkages between several sectors can help to provide information on how food consumption may change as a consequence of increasing biofuel production.

Changing total fuel and energy demand: Overall fuel and energy demand remains constant in the current application of the case-study approach. Economic modeling can provide data on changes in overall fuel demand as a consequence of biofuel production; these numbers could be integrated into the case-study approach.

Changing consumption and investment patterns: Changes in household income and companies' profits are potential consequences of biofuel feedstock cultivation and biofuel production. Such effects were not considered in the ILUC case-study approach. Collaboration in a multidisciplinary team, e.g. in the “Fair Fuels?” project, generally allows for integration of micro-economic aspects in ILUC quantification. In the Malawian case study, a household survey was carried out by Raoul Herrmann, an agrarian economist; the goal of the survey was to analyze the extent to which the household income and food security of smallholder farmers participating in sugarcane cultivation differs from those not participating. The results of the survey demonstrate that outgrower farmers at Dwangwa Sugar enjoy substantial benefits in terms of household income, but impacts on food and nutritional security also depend on intra-household processes, health, and educational factors (Herrmann 2012). If such impacts are to be included in the calculation of GHG emissions from indirect effects, a next step would be to analyze the extent to which those who benefit from participation in biofuel feedstock and biofuel production alter their consumption patterns; microeconomic models are required in order to conduct such an analysis.

7 Comparison of the case-study results

This chapter brings together the results of the application of the ILUC case-study approach (chapter 5) and the results of the sensitivity analysis (chapter 6). It begins with an overview of the case-study characterizations in order to highlight differences and similarities between the countries (section 7.1). Then, the results for $ILUC_{GHG\_net}$, the net GHG emissions due to feedstock expansions in the case-study countries, will be compared and the chapter 1 hypotheses tested (section 7.2). Finally, the CF results will be compared, optimization potentials demonstrated, and the relevance of $ILUC_{GHG\_net}$ when considering the CFs discussed (section 7.3)

7.1 Case-study characterizations

The three countries chosen as case-study countries – Malawi, Brazil and Germany – not only represent different development stages, they also represent differing characteristics, for instance with regard to the trade dynamic of agricultural products and the relevance of LUC and biofuel production. Inasmuch as these characteristics influence the location and extent of ILUC, a comparison of the results is particularly interesting. Table 7.1 summarizes the information and data about the case-study countries as reported in the sections 5.1.1, 5.2.1 and 5.3.1.

Table 7.1: Key characteristics of the case-study countries

Characteristic	Malawi	Brazil	Germany
Relevance of biofuel production	Low amount of ethanol production, expansion expected	High amount of ethanol production, expansion expected	High amount of ethanol production, ethanol imports
Relevance of LUC	High	High	Low
Trade dynamic of agricultural products	Regional dynamic	Global dynamic, export-oriented	Global dynamic, export and import
Intensity of agricultural production	Low	Medium	High
Meat and dairy consumption	Very low	High	High

While the amount of ethanol produced in Malawi is still very low, *ethanol production* in Brazil and Germany is already substantial. Sugarcane is the most important feedstock for ethanol in Malawi and Brazil, whereas in Germany ethanol is mainly produced from wheat and sugar beets. In Malawi sugarcane ethanol production is expected to increase in the future, largely due to the high import costs for fossil fuels and the national objective of establishing a secure energy supply. In Brazil, sugarcane ethanol is already the most important biofuel with regard to domestic production, consumption, and exports. Although an ethanol crisis of sorts took place between 2008 and 2012 due to decreasing sugarcane yields and decreasing ethanol production, Brazilian sugarcane ethanol will presumably recover or even expand its relevance in the Brazilian and global fuel market. Sugarcane area expansion is thus highly likely. In Germany, the amount of ethanol produced is relatively high, although not high enough to fully meet domestic demand. Germany is and will in the future likely remain a net ethanol importer.

The *relevance of LUC* varies greatly in the case-study countries. LUC is a relevant topic in Malawi, which has a huge rural population and where a high share of the country's area is already used for agriculture. Deforestation is mainly due to wood fuel collection as solid biomass is the most important fuel; however, agricultural area expansion is another relevant driver for LUC. Therefore, there is a risk of ILUC occurring as a consequence of biofuel feedstock expansion. LUC, and in particular deforestation, are also relevant topics in Brazil; although sugarcane area expansion mainly takes place in the South-Central Region, and thus far away from the Amazon rainforest, it presumably contributs indirectly to deforestation. In Germany LUC is a not a relevant topic, and forestation actually increased slightly between 2000 and 2009. The only current issue with regard to LUC is the loss of grassland due to conversion.

The *trade dynamic of agricultural products* is a relevant issue with regard to the question of where ILUC is likely to occur – within the case-study country itself or elsewhere (over the border). A rather regional trade dynamic, together with a high relevance of LUC in the country of interest, indicates that ILUC is more likely to occur in the country itself. This is the case in Malawi, where the ratio (by quantity) of agricultural imports to domestic food supplies, as well as the ratio of agricultural exports to food supplies, is low. The trade in agricultural products is thus assumed to mainly take place at the regional level. In contrast, the trade dynamic of agricultural products in Brazil is export-oriented; the ratio of agricultural imports to food supplies is low, while the ratio of agricultural exports to food supplies is high. The high ratio between export quantities and food supply indicates that Brazil could export less in order to compensate increasing biofuel feedstock cultivation. However, this is apparently not occurring, since overall exports of agricultural products steadily increased from 2000 to 2010. ILUC is therefore also likely to occur within Brazil. In Germany, the export and import levels of agricultural products are substantial and roughly equal. This rather global dynamic, together with the low relevance of LUC in Germany, indicates that ILUC will likely spill over the border.

The *intensity of agricultural production* is relevant with regard to the question of whether agricultural yields can be increased in order to reduce ILUC. The intensity of agricultural production in Malawi is assumed to be low, as the average maize yield in Malawi is significantly lower than the global average. The intensity of agricultural production in Brazil is assumed to be moderate as the maize yield in Brazil is slightly lower than the global average. Measures that increase agricultural yields are thus promising ILUC compensation measures in both Malawi and in Brazil. In contrast, the intensity of agricultural production in Germany is high, as the average maize yield in Germany is significantly higher than the global average. Measures that increase agricultural yields are thus less suitable for the reduction of ILUC.

Meat and dairy consumption data for the case-study countries are a relevant factor. Meat and dairy are both land-intensive, and thus intentional modifications to the consumption pattern of either could function as an ILUC compensation measure. In Malawi, meat and dairy consumption are very low compared to the global average; because of this, compensation measures that decrease meat or dairy consumption are inadequate in Malawi. In contrast, meat and dairy consumption in Brazil and Germany are relatively high (roughly four times the global average in Germany). Compensation measures that decrease meat or dairy consumption are thus suitable measures for reducing ILUC in Brazil and in Germany in particular.

7.2 Comparison of ILUC-induced GHG emissions

This section provides a comparison of best estimates for $ILUC_{GHG\_net}$ – net GHG emissions due to ILUC per MJ of biofuel – that occur as a consequence of ethanol feedstock expansion in the case studies, with and without implementation of compensation measures. It includes a test of the hypotheses presented in chapter 1.

The best estimates with regard to $ILUC_{GHG\_net}$ indicate that increased sugarcane ethanol production in Malawi and Brazil, like increased wheat ethanol production in

Germany, leads to high levels of GHG emissions due to ILUC if no compensation measures are being implemented or if such measures are not considered in the ILUC quantification. In this case $ILUC_{GHG\_net}$ amounts to 40 g CO_{2eq} MJ^{-1} of sugarcane ethanol produced in Malawi, 24 g CO_{2eq} MJ^{-1} of sugarcane ethanol produced in Minas Gerais in Brazil, and 50 g CO_{2eq} MJ^{-1} of wheat ethanol produced in Germany.

$ILUC_{GHG\_net}$ ranges between 1 and 112 g CO_{2eq} MJ^{-1} of sugarcane ethanol produced in Malawi, 1 and 144 g CO_{2eq} MJ^{-1} of sugarcane ethanol produced in Brazil, and 1 and 200 g CO_{2eq} MJ^{-1} of wheat ethanol produced in Germany. As the distribution of the input parameters is unknown, it is not possible to further limit the range of results, which is noticeably higher in the case of wheat ethanol produced in Germany; this is mainly due to the fact that the allocation factors in this case study differ more greatly than in the others (see section 6.1).

If compensation measures are being implemented and are accounted for in the ILUC quantification, the best estimates for $ILUC_{GHG\_net}$, as well as the associated ranges will significantly differ from the scenario without consideration of compensation measures as the following paragraphs will show.

Malawi is the only case study where the implementation of a compensation measure, an investment in a large-scale irrigation system, is planned to take place. Dehue et al. (2009) likewise identified the implementation of an irrigation system as a potential measure for reducing the ILUC risk of biofuels. The authors conducted a case study on sugarcane ethanol production in the Philippines; irrigation was assumed to be implemented in the sugarcane area itself, such that less additional land was required than would have been necessary without this measure.

In the Southern Region in Malawi, the new irrigation region will include not only the sugarcane area but also fields of staple crops cultivated by smallholder farmers. Sugarcane area expansion will mainly occur on land used for maize cultivation, the most important staple crop in the region. By increasing the maize yield on the newly irrigated area and by making sure that smallholder farmers benefit from the irrigation system, this measure can help to reduce or even overcompensate ILUC. A precondition for this measure to function as a compensation measure is that the sugar and/or ethanol company participate in the planned public-private partnership and assume a greater share of the financing than is required for the sugarcane area only.

The best estimate for $ILUC_{GHG\_net}$ is –11 g CO_{2eq} MJ^{-1} of ethanol if the compensation measure is included. The actual value of $ILUC_{GHG\_net}$, however, strongly depends on the extent of the yield increase that irrigation brings and the share of investment that can be attributed to sugarcane ethanol as a compensation measure. $ILUC_{GHG\_net}$ ranges from –200 to 74 g CO_{2eq} MJ^{-1} of sugarcane ethanol additionally produced in Malawi if input parameter uncertainty is considered (see section 6.1.3 and Figure 7.1). In order to make sure that ILUC does not occur, the share in the overall investment assumed by the sugar or ethanol companies as a compensation measure would have to be at least 1.3%, thus making the entire range of results for $ILUC_{GHG\_net}$ negative. The best estimates and ranges for $ILUC_{GHG\_net}$ for the case studies in Brazil and Germany remain unchanged as no compensation measures are currently planned. Given the information on ILUC, related GHG emissions, and the ranges of results from the case studies, it is possible to test the first hypothesis.

Hypothesis 1: Sugarcane area expansion in the case-study regions in Malawi and Brazil and wheat area expansion in the case-study region in Germany, for the purpose of additional ethanol production, lead to ILUC and thus to additional GHG emissions that can be detected by means of the ILUC case-study approach.

Application of the ILUC case-study approach indicates that ILUC, and thus additional GHG emissions, will occur in all three case studies if no compensation measures are implemented. Using the ILUC case-study approach, however, it is possible to consider the impact of compensation measures when they occur. The case study on Malawi demonstrates that ILUC will not occur if sufficient investments in measures to increase agricultural yields and decrease the overall demand for agricultural land are undertaken; $ILUC_{GHG\_net}$ can even turn negative, indicating the occurrence of overcompensation. As implementation of the compensation measure in Malawi is very likely to take place, ILUC will not necessarily occur in this specific case. Hypothesis 1 thus is verified for the case studies on Brazil and Germany, in which no compensation takes place, but is falsified for the case study on Malawi.

Knowledge about the impact of compensation measures also helps in testing the second hypothesis.

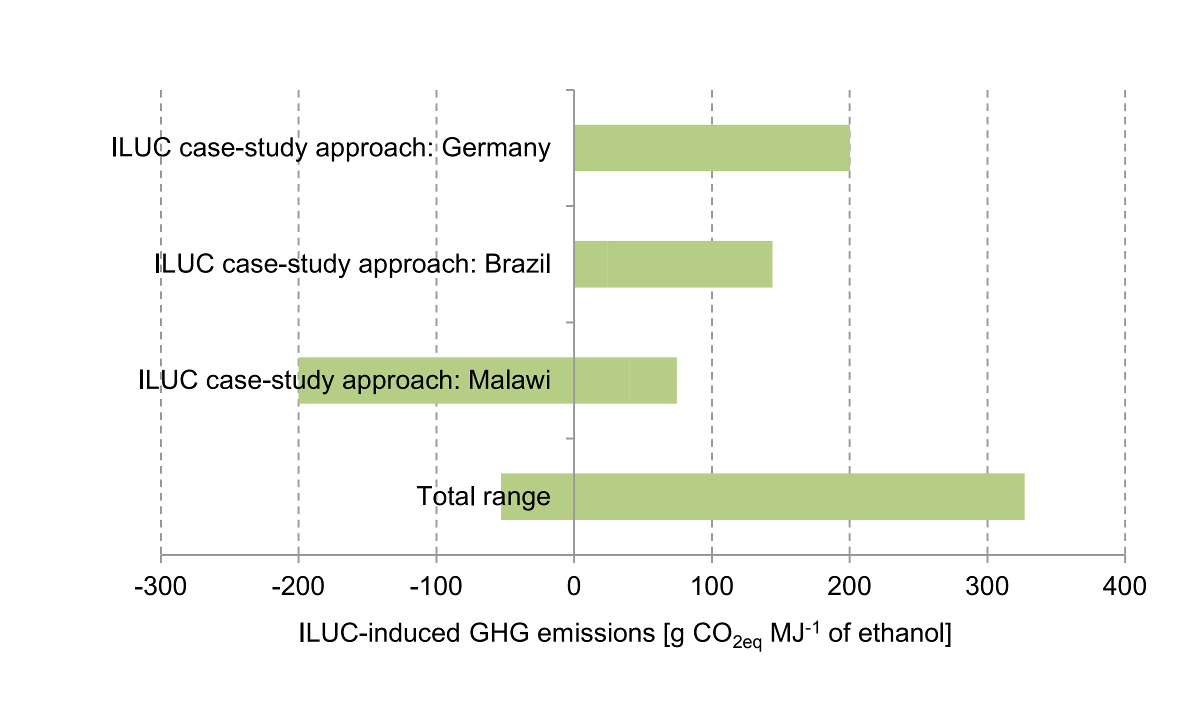

Figure 7.1: Ranges of $ILUC_{GHG\_net}$ in the case studies compared to secondary research literature
Source: Author's case-study approach vs. the total range of ILUC factors for ethanol in the secondary research literature (see section 2.2.3).
Compensation measures are only considered in the case study on Malawi, where implementation is planned to occur.

Hypothesis 2: If regionally specific factors are considered in the quantification of ILUC and the related GHG emissions, as in the ILUC case-study approach, these regional factors will significantly influence biofuel-specific ILUC factors.

The results presented already demonstrate that the extent of ILUC and the related GHG emissions obviously strongly depend on whether compensation measures linked to a specific biofuel feedstock expansion are being implemented.

Furthermore, the best estimates for $ILUC_{GHG\_net}$ with no consideration of compensation measures and the sensitivity analyses, presented in section 6.1, both prove that there are other regional factors besides the implementation of compensation measures that influence the extent of ILUC and related GHG emissions.

If compensation measures are not considered, the best estimate for $ILUC_{GHG\_net}$ resulting from additional sugarcane ethanol production in Minas Gerais, Brazil, is slightly lower than the best estimates for sugarcane ethanol additionally produced in the Southern Region of Malawi and wheat ethanol additionally produced in Saxony-Anhalt in Germany. This is due to the respective regional conditions of ethanol production, the relevance and type of LUC, and the respective agricultural practices.

Although ILUC is more likely to occur within Brazil itself, where the LUC CO_2 emission factor is noticeably higher than the global LUC CO_2 emission factor, $ILUC_{GHG\_net}$ for sugarcane ethanol produced in Brazil (24 g CO_{2eq} MJ^{-1} of ethanol) is rather low. This is due to the fact that the cattle stocking rate in Brazil is expected to increase as a consequence of sugarcane area expansion on pasture land, an increase in productivity that significantly reduces the expected ILUC and the related CO_2 emissions.

In the case study on Malawi, ILUC is also assumed to occur in the country itself, where the LUC CO_2 emission factor is lower than in Brazil but is still higher than the global average emission factor. However, the effect of the expected yield increase on the agricultural area that will occur as a market effect of biofuel feedstock expansion is expected to be lower in Malawi than in Brazil given that substantial financial investments, for instance in irrigation systems, are necessary in order to significantly increase the agricultural yields. Such large investments are usually not possible for smallholder farmers, who cultivate the major part of agricultural land in Malawi. Other actors, such as the sugar or ethanol company or an international donor, need to take over such investments – as described for the SVIP in Malawi.

The best estimate for $ILUC_{GHG\_net}$ related to wheat ethanol produced in Germany is higher than that of sugarcane ethanol produced in Brazil or in Malawi. Since ILUC is likely to spill over the border, the comparatively low average LUC CO_2 emission factor of 13.5 g CO_2 ha^{-1} is used in the calculation. The overall $ILUC_{GHG\_net}$ is still relatively high, mainly because the ethanol yield per hectare is much lower as compared to sugarcane ethanol.

Fritsche et al. (2010a) also found slightly higher ILUC factors for wheat ethanol produced in the EU than for sugarcane ethanol produced in Brazil, due to a lower ethanol yield in the case of wheat ethanol. Dehue et al. (2009), on the other hand, argued that wheat ethanol has a low ILUC risk as long as the wheat is cultivated within the EU and is cultivated such that exports do not decline. The authors thereby considered a high share of yield increase in the total incremental output growth of wheat. In the ILUC case-study approach a lower value was chosen, as the wheat area expansion occurs in Germany itself where the wheat yields are already high so that the potential yield increase is lower than in other EU countries.

Bauen et al. (2010) even found negative ILUC factors for wheat ethanol in several model scenarios because they incorporated a reduced land use for soy bean cultivation due to the provision of DDGS. The ILUC case-study approach, in contrast, works with allocation of the land demand on all accruing products, here ethanol and DDGS. The methodology of how by-products are considered thus crucially influences the ILUC factor; allocation does not result in negative ILUC factors.

The results of the ILUC case-study approach, as well as the results of the sensitivity analyses, demonstrate the extent to which regionally specific parameters influence $ILUC_{GHG\_net}$. Particularly relevant parameters include the average LUC CO_2 emission factors, both in the country itself and elsewhere (sensitivity: 9%, if the parameter changes by plus or minus 10%); this value was exemplarily calculated for the case study on Germany. Thus, F_{spill} is particularly relevant, as this parameter decides how the LUC CO_2 emission factors are weighted in the calculation; similarly relevant are the parameters' share of area expansion in the total incremental output growth of biofuel feedstock (Area%; sensitivity: 10%), and the share of yield increase in the total incremental output growth of crops (Yield%; sensitivity: 9%).

Hypothesis 2 thus can be verified, as regionally specific conditions definitely influence the amount of ILUC and the related GHG emissions detected with the case-study approach. However, although the case studies and the sensitivity analysis demonstrate how much the occurrence of ILUC depends on specific local conditions, the ranges of $ILUC_{GHG\_net}$ and thus the uncertainty about several input parameters is too high to conclude which location of ethanol feedstock expansion and ethanol production should be preferred with regard to a low $ILUC_{GHG\_net}$. Thus, although hypothesis 2 can be verified, this does not mean that significant variation between the regional ILUC factors can be found when uncertainty is considered. Only if compensation measures are being implemented and are considered in the ILUC calculation is it possible – depending on type and extent of the compensation measures – to conclude that ethanol production in a specific case should be preferred.

With the present information it is then possible to test hypothesis 3.

Hypothesis 3: GHG emissions due to ILUC occurring as a consequence of sugarcane expansion in Malawi and Brazil and wheat expansion in Germany, for the purpose of additional ethanol production, are lower than the default value for the CF of fossil fuels (83.8 g CO_{2eq} MJ^{-1} of fuel); biofuels thus potentially can still yield lower GHG emissions as compared to fossil fuels.

By only looking at the best estimates, it is possible to conclude that in all case studies $ILUC_{GHG\_net}$ is lower than the default value for the CF of fossil fuels; biofuels thus potentially still yield lower total GHG emissions as compared to fossil fuels. However, the best estimates are higher than 21 g CO_{2eq} MJ^{-1} of biofuel, meaning that the biofuels would presumably no longer save 60% of GHG emissions compared to fossil fuels as will be required in the future by the RED. If the ranges of results for $ILUC_{GHG\_net}$ are considered, these statements can no longer be made – the maximum values in all three cases for $ILUC_{GHG\_net}$ are then higher than the default value for the CF of fossil fuels and the minimum values are lower than 21 g CO_{2eq} MJ^{-1} of biofuel.

What can be concluded is that a clear statement about whether ILUC leads to CO_{2eq} emissions lower than the CF of fossil fuels cannot be made, as the required knowledge on input parameter distribution is not available. Therefore, it is also not possible to determine whether biofuels still save GHG emissions compared to fossil fuels. Hypothesis 3, thus, can neither be verified nor falsified. This uncertainty should be taken into account when designing the regulatory framework at the EU level.

The relevance of compensation measures with regard to reducing the overall demand for agricultural land has already been discussed. Hypothesis 4 additionally addresses the question of whether additional GHG emissions due to the implementation of compensation measures are released in any significant amount.

Hypothesis 4: Regionally specific ILUC compensation measures reduce the overall demand for agricultural land; however, they produce additional GHG emissions at the same time. If both effects are considered, the specific compensation measures identified in the case studies will still lead to a net GHG reduction.

In order to test this hypothesis it is necessary to further look at the compensation measures that have been identified as appropriate for the three case studies.

As already described, in Malawi implementation of a large irrigation system is planned; this measure functions as a compensation measure because the sugar company will assume a share of the investment. Additional fertilizer application is likely to occur on the newly irrigated area in order to reach the predicted yield increase. Production and application of chemical fertilizers lead to additional GHG emissions; these, however, only amount to a few grams of CO_{2eq} per MJ of biofuel, and are thus much lower than the reduction in CO_{2eq} emissions resulting from a reduced demand for agricultural land; they are already accounted for in the above value of –11 g CO_{2eq} MJ^{-1} of sugarcane ethanol produced in the Southern Region.

Suitable measures for compensating ILUC also exist in Brazil. In this country it is mainly cattle farming that is being displaced by sugarcane. The stocking rate could be increased through the promotional efforts of the government or local authorities or by companies that operate a sugar and ethanol mill in parallel with cattle farming such that they could guarantee a significantly higher stocking rate than the state averages (cf. Dehue et al. 2009). The bigger the reference area, the less of an increase in the stocking rate is necessary in order to compensate a specific expansion of the sugarcane area. In order to assure that stocking rates remain at a higher level and do not drop back down too soon, additional P fertilizer will probably be necessary in order to maintain or increase pasture land productivity (Fearnside 1980). Thus, additional GHG emissions will occur as a consequence of the compensation measures. Such fertilizer-induced emissions, however, are much lower than the overall GHG savings, due to the reduced ILUC effect.

The compensation measures identified as being suitable for Malawi and Brazil confirm hypothesis 4. Both measures decrease the overall demand for agricultural land, even while leading to additional GHG emissions. The net effect, however, is clearly a saving of GHG emissions.

In the case of wheat ethanol produced in Germany, a reduction in ILUC is more complicated than in Brazil and Malawi. Yields in Germany are already at a very high level; any further increases would be difficult to realize. Investments in irrigation systems elsewhere could be a suitable option for reducing ILUC due to biofuel production in Germany. Such an arrangement may lead to additional GHG emissions, depending on the source of energy used for operating the irrigation system, but the example of the system described in the Malawian case study proves that net GHG savings are possible and even likely in the case of such investments.

Another possible compensation measure would be an incentivized reduction of the consumption of land-intensive agricultural products such as meat and dairy products. Wirsenius et al. (2011), for instance, showed that agricultural emissions in the EU27 can be reduced by roughly 32 million tons of CO_{2eq} by means of a GHG-weighted tax on animal food products corresponding to €60 per ton CO_{2eq}. As Germany has very high levels of meat and dairy consumption, reducing per capita consumption would seem to be a suitable option. If meat consumption in Germany were to be reduced on a one-time, permanent basis by 3,200 t yr^{-1} $ILUC_{GHG}$ linked to the 20,000 ha wheat expansion under consideration would be zero, and $ILUC_{GHG\_net}$ negative (−23 g CO_{2eq} MJ^{-1} of ethanol), because of reductions in GHG emissions associated with beef production, particularly those due to enteric fermentation.

The case study on Germany thus makes clear that there are compensation measures that would not only decrease the demand for agricultural land but lead to additional GHG savings, for instance, by reducing the demand for specific products and thus additionally saving the GHG emissions linked to the production of these products. The net GHG effect is thus clearly a GHG emissions saving.

Hypothesis 4 thus can be confirmed as net GHG savings would occur in the three case studies if the identified compensation measures were implemented. Since several other compensation measures exist, additional analyses are needed in order to determine whether all measures achieve a net GHG saving.

The strong influence of compensation measures on $ILUC_{GHG\_net}$, however, already indicates that the possibility of including the effect of compensation measures is precisely the advantage offered by the regionalized ILUC case-study approach.

The fifth hypothesis deals with the effect of allocating LUC-induced CO_2 emissions between the expanding biofuel feedstock and the agricultural activity that directly displaces the natural ecosystem.

Hypothesis 5: If CO_2 emissions from the final natural ecosystem conversion are allocated between indirect and direct drivers of the final LUC, ILUC-induced CO_2

emissions will be significantly lower than if CO_2 emissions are, as is commonly done, entirely debited to the indirect driver biofuel feedstock expansion.

Finkbeiner (2012) already noted the need for an approach that considers the direct as well as the indirect impact of the various drivers of natural ecosystem conversion. The idea behind the allocation is that every ILUC is the DLUC of another agricultural activity. Thus, debiting all CO_2 emissions to the indirect driver would incur either double counting or a free-rider effect. The effect of an approach that appropriately allocates the induced CO_2 emissions between both forms of agricultural activity – expansion of biofuel feedstock as well as agricultural activities displacing a natural ecosystem directly – was tested for the case study on Brazil.

Sugarcane expansion in Brazil mainly displaces pasture land, leading to deforestation in the Amazon region in order to produce new pasture land. Due to efficiency gains, one hectare of sugarcane expansion leads to the generation of only 0.2 ha of new pasture land (according to best estimates). Charging all CO_2 emissions from the final LUC to the expanding ethanol production has the disadvantage that it disburdens any cattle farming that directly displaces forest of responsibility for LUC-induced CO_2 emissions, posing the risk of a free-rider effect; as soon as the scope of the CF is conscientiously applied to all agricultural products in the same manner that it is now applied to biofuels, ILUC disappears, as DLUC is entirely charged to agricultural activities displacing the natural ecosystem directly. Accounting for ILUC as it is currently done, however, would lead to double counting of the LUC-induced CO_2 emissions by burdening ethanol as well as meat. In order to avoid triggering a free-rider effect as well as double counting, different approaches for allocating LUC-induced CO_2 emissions between ethanol and beef have been tested.

The difference between an allocation approach and “normal” ILUC quantification, which charges all CO_2 emissions from LUC to the expanding biofuel, is greatest in the case of cereal unit (CU) allocation, when ILUC emissions debited to ethanol are 10% lower than without allocation. Hypothesis 5 thus can be confirmed for the case study on Brazil.

Further application and enhancements of the allocation model approach are needed in order to further address the problems of avoiding double counting and the consideration of the various drivers when relating LUC-induced GHG emissions to products.

7.3 CFs of ethanol produced in the case studies

The question of whether biofuels reduce GHG emissions vs. fossil fuels when ILUC-induced GHG emissions are considered not only depends on the level of $ILUC_{GHG\_net}$. It also depends on the extent to which GHG emissions are due to indirect effects linked to the production and substitution of fossil fuels, as well as on the respective CF of biofuels. The former aspect is currently under investigation in various research activities (cf. Pieprzyk and Kortlüke 2010; Grafton et al. 2012), but has so far not been analyzed in detail; $ILUC_{GHG\_net}$ is thus only compared to the default value for the CF of fossil fuels in this work. The latter aspect, the level of the respective CF of biofuels, will be addressed in this section by comparing the CFs of the ethanol products produced at the specific sites in Malawi, Brazil and Germany.

As Figure 7.2 shows, sugarcane ethanol produced in the Southern Region of Malawi has a significantly higher CF than ethanol produced in Minas Gerais, Brazil, and in Germany (115 g CO_{2eq} MJ^{-1}, 17 g CO_{2eq} MJ^{-1}, and 26 g CO_{2eq} MJ^{-1} of ethanol); the product thus does not fulfill the requirements of the RED 2009. Although only a small portion of the emissions occurring in the cultivation stage in Malawi is allocated to ethanol (the major share is attributed to sugar), cultivation-related emissions are higher in Malawi than in Brazil. This is due to high levels of N fertilizer and diesel consumption in Malawi and to GHG emissions from pre-harvest burning, an activity more common in Malawi than in Brazil. GHG emissions from N fertilizer applications, mainly in the form of N_2O emissions, contribute to the greatest share of the overall GHG emissions in the cultivation stage in all three case studies (33% for Malawi, 50% in Brazil, and 66% in Germany). In the case of sugarcane, another relevant share, 31% in the Malawi case study and 16% in Brazil, results from pre-harvest burning. These results are in line with findings from Lisboa et al. (2011), who identified precisely these two sources, along with fuel use in the cultivation stage, as being of the greatest relevance for the overall CF of ethanol from sugarcane.

Sugarcane yields in the Southern Region of Malawi (111 t ha^{-1}) are considerable higher than in Minas Gerais, Brazil, (75 t ha^{-1}) or the global average of 71 t ha^{-1} (cf. Lisboa et al. 2011). Given this situation, it is reasonable to assume that sugarcane ethanol production in Malawi could achieve a significantly lower CF than at present. Measures to improve the CF of ethanol include field analyses to optimize fertilization.

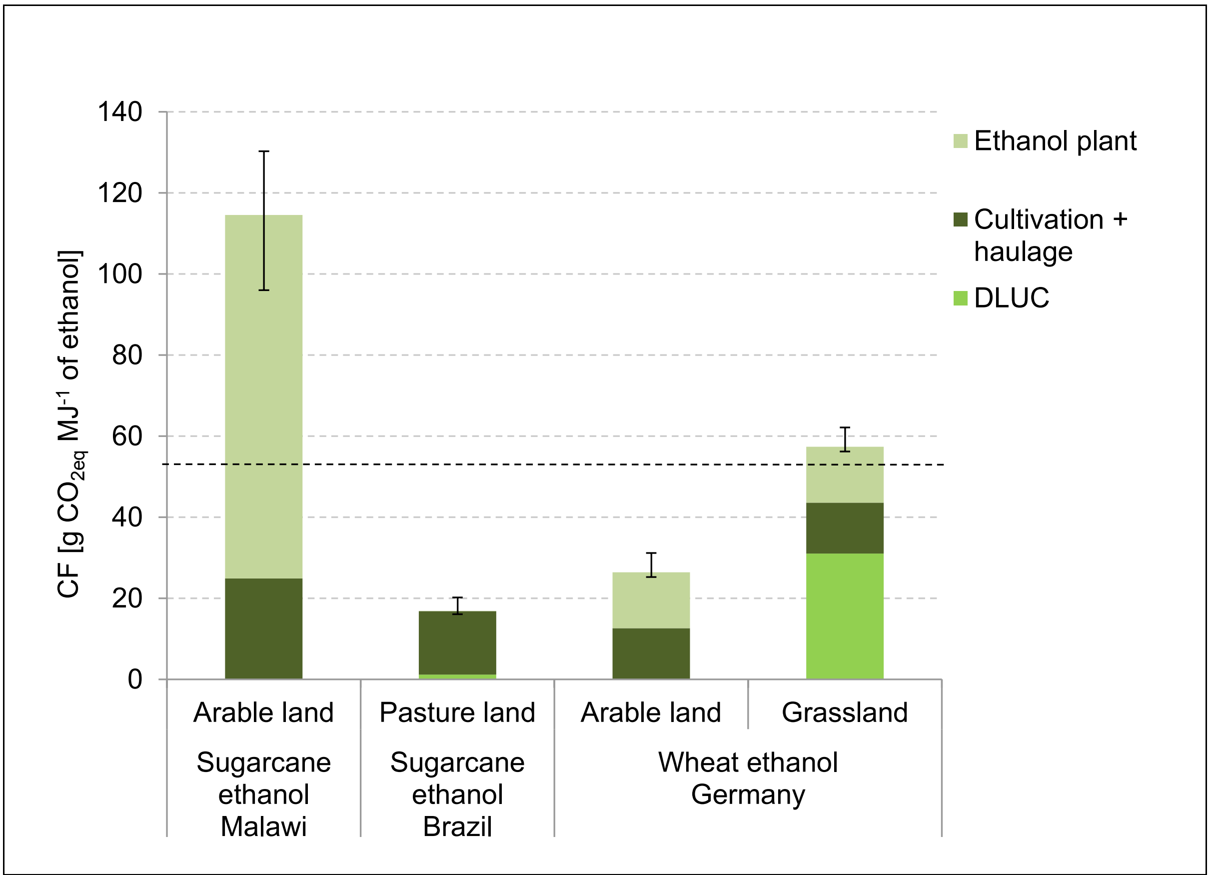

Figure 7.2: CF of ethanol produced in the case study regions in Malawi, Brazil and Germany

Based on the status quo at the sites in the case studies, respectively; thus, the values refer to scenario SC 1.1, SC 2.1, and SC 3.1. Error bars result from a variation of N_2O emissions from N fertilizer of between 0.5–3% and in the Malawian case study, of a variation in the MCF (methane correction factor) of between 0.1–0.3.

The main reasons for the high CF of sugarcane ethanol produced in Malawi, however, are to be found in the ethanol manufacturing. First, coal is used to provide the process energy needed in the ethanol plant; second, the liquid residue vinasse is stored in open ponds. Both processes lead to remarkably high GHG emissions. Vinasse storage in open ponds leads to particularly high CH_4 emissions and is thus an inacceptable practice with regard to its climate impact. In order to improve the CF of ethanol vinasse could be used for biogas production due to its high organic carbon content; second, switching to green harvesting would provide amounts of cane trash that could be used as a fuel in the ethanol plant. The results from the Brazilian case study furthermore prove that fertigation is a much better option for treating vinasse. Lisboa et al (2011) commented that fertigation is the most common way to use vinasse. As the Malawian case study shows, this is not true for all countries.

The results from the site in Minas Gerais also demonstrate just how low the CF of sugarcane ethanol production can be when sugar and ethanol production are combined in one mill and when bagasse is used to produce all process energy needed for manufacturing. Sugarcane ethanol produced in such a way easily fulfills the requirements of the RED 2009. Switching to green harvesting can reduce the overall CF even more, given that the additional biomass can partly be used for energy production. Another option is to use the additional biomass for carbon sequestration in soil, as De Figueiredo and La Scala (2011) suggest.

Wheat ethanol production in Germany also fulfills the requirements of the RED 2009; however, it has a slightly larger CF than sugarcane ethanol produced in Brazil – one reason being the lower ethanol yield per hectare. Furthermore, natural gas is used to provide process energy in the exemplary plant in Germany. GHG emissions from the usage of natural gas could be avoided by using wheat straw as a fuel. Punter et al. (2004) have already identified using a straw-fired combined heat and power plant feeding surplus electricity to the grid as being the best option to reduce GHG emissions of wheat ethanol production; however, to utilize wheat straw as a fuel in the ethanol plant one carefully has to calculate the carbon balance in soil in order to conserve the soil functions. In the case study on wheat ethanol, it was calculated that 2 t of wheat straw would be enough to provide the energy required in ethanol manufacturing, leaving 5 t of wheat straw on field – enough to conserve the soil functions. The CF of wheat ethanol increases significantly when grassland is being converted to wheat cultivation area; ploughing up grassland thus should be avoided in order to protect its function as a carbon sink.

What do these findings on the CFs mean with regard to the ILUC-induced GHG emissions? While the CF of sugarcane ethanol produced in Malawi does not fulfill the requirements of the RED 2009 – with or without taking into account the best estimates for $ILUC_{GHG\_net}$ – sugarcane ethanol produced in Brazil would fulfill the requirements, even if the best estimate for $ILUC_{GHG\_net}$ was considered. Wheat ethanol produced in Germany only fulfills the RED requirements if $ILUC_{GHG\_net}$ is overlooked. Thus, the overall effect of $ILUC_{GHG\_net}$ strongly depends on the specific biofuel CF and on the best estimate of $ILUC_{GHG\_net}$.

8 Conclusion

For the past five years, ILUC due to biofuel feedstock expansion and the associated GHG emissions have been controversial topics of discussion within the context of the EU's biofuel policy. Given that biofuels were once promoted because they promised to reduce GHG emissions in the mobility sector, studies on CO_{2eq} emissions from ILUC have meanwhile repeatedly raised the question as to whether biofuels actually do reduce GHG emissions compared to fossil fuels.

Several studies have dealt with methodological questions on how to quantify ILUC, and many studies have provided figures for ILUC-induced CO_{2eq} emissions resulting from the expanding EU's biofuel demand. However, various scientific questions still remained unanswered, not the least of which are questions regarding the need for and feasibility of regionalization of ILUC quantification, the relevance of compensation measures for ILUC, and their net effect on GHG emissions.

CGE, the type of model most frequently used for ILUC quantification, only allows consideration of regionally specific conditions to a very limited degree. PE models are more often used to characterize a country's agricultural sector in greater detail, including country-specific data and information, but do not address linkages to other sectors. Lahl (2010) initially developed a simplified deterministic approach that considered regionally specific factors that might influence the final ILUC CO_{2eq} emission factor of a specific type of biofuel; however this approach offers a rather imprecise proposition as to how the location of the final LUC is to be determined and which average LUC CO_2 emission factor should be used.

Furthermore, existing quantification models are not intended to consider the effect of measures that could help to avoid ILUC. Potential compensation measures, such as investments in an increase of agricultural productivity, however, are expected to be regionally specific as well, so that linking ILUC quantification and the consideration of regionally specific compensation measures is a promising approach.

Thus the main *research questions* addressed here were first, whether regional factors significantly influence ILUC such that regional and biofuel-specific ILUC factors can be derived, and second, which measures might exist at the regional level that could help to avoid ILUC. With regard to compensation measures, there is also the question of the net GHG effect, given that many potential compensation measures, such as increased fertilizer application, reduce overall land demand but at the same time lead to additional GHG emissions due to fertilizer application. Finally another research question addressed was how CO_2 emissions from the final LUC could be allocated between the expanding biofuel feedstock and the agricultural activities that displace the natural ecosystem directly. The idea behind this question is that if we intend to broaden the scope of product carbon footprinting to all agricultural products, accounting for ILUC and DLUC will lead to double counting. This could be avoided by allocation of the LUC CO_2 emissions to both agricultural activities.

The *objectives* of the dissertation were thus to develop a case-study approach to quantifying regional and biofuels-specific ILUC factors; to calculate ILUC-induced GHG emissions from feedstock expansion for ethanol production at specific sites in Malawi, Brazil, and Germany; to identify regionally specific ILUC mitigation measures and to quantify their net effect on GHG emissions. Given that input parameter uncertainty is known from existing studies to be quite high, further objectives were to analyze the sensitivity of the results with respect to the variability of specific input parameters and to determine the potential range of results. With the help of this analysis, it was possible to assess whether significant variation in regional ILUC factors can be found. Another objective was to test an allocation approach that allows for the allocation of LUC-induced CO_2 emissions according to the type of conversion – biofuel feedstock expansion and agricultural expansion that directly displaces the natural ecosystem. Finally, to establish whether the specific biofuels fulfill the requirements of the RED 2009, an analysis of the CF was carried out for the current situation as well as after implementation of measures to improve the CF.

8.1 The ILUC-quantification case-study approach

The deterministic ILUC-quantification case-study approach developed here as a part of this dissertation includes five main steps. In contrast to most of the existing approaches that model ILUC from the top down, starting with EU-mandated increasing biofuels demand, the case-study method is designed as a bottom-up approach that starts with the additional feedstock cultivation for production of a specific biofuel.

After quantifying the gross expansion area of a specific biofuel feedstock at a specific site, in step 1, the net expansion area is calculated by allocating the additional land demand between all accruing products with the help of energy allocation, in step 2.

In step 3, the location where ILUC is expected to take place is estimated by means of information and data on: economic indicators (e.g. production and trade of agricultural products), natural ecosystem conversions, and the respective land-use and ecosystem protection policies in the country of interest.

Step 4 provides for consideration of expected efficiency gains due to the expansion of biofuel feedstock and the effect of specific compensation measures on the overall demand for agricultural land. The first requires estimation of how much the yield of the agricultural activity on the reference area is expected to increase due to the biofuel feedstock expansion. Values calculated by Lywood et al. (2009b) could be partially utilized in order to set the share of yield increase in the overall incremental output growth of agricultural production (Yield%). In addition, time series on the development of yields in specific regions, as well as statistical analyses, are used to estimate Yield%. The second aspect, the consideration of compensation measures implemented or financed by companies or administrative entities, requires information on the specific compensation measure and its effect on land demand. Step 4 then finally gives us the net ILUC effect in terms of area additionally needed due to biofuel feedstock expansion despite expected yield increases and despite the implementation of specific compensation measures. If the compensation measure reduces the overall land demand to a degree that the area released is bigger than the biofuel feedstock expansion area, the final result of step 4 will be negative.

In step 5, the final LUC is converted to CO_2 emissions per MJ of biofuel with the help of data on LUC and the IPCC (2006b) methodology. In addition, the GHG emissions that are expected to arise as a consequence of efficiency gains and as a consequence of implementing specific compensation measures are calculated in order to ascertain the net GHG effect. This is relevant because yield increases may not only lead to area savings but also to additional GHG emissions, e.g. as a result of additional fertilizer applications. Finally, the overall GHG emissions are related to the additional amount of biofuels produced as a consequence of feedstock expansion.

The ILUC case-study approach was applied to additional sugarcane ethanol production in the Southern Region of Malawi and in the state of Minas Gerais, in Brazil, and to additional wheat ethanol production in the state of Saxony-Anhalt in Germany.

8.2 Net ILUC-induced GHG emissions

The net ILUC-induced GHG emissions ($ILUC_{GHG\_net}$) were calculated using the new case-study approach. $ILUC_{GHG\_net}$ considers CO_{2eq} emissions from the final LUC, the positive effect of efficiency gains with regard to reducing the land demand, as well as its negative effect, e.g. GHG emissions resulting from additional fertilizer application. In the first step, a so-called best estimate for $ILUC_{GHG\_net}$ without the implementation of compensation measures was calculated; best estimate here means the most likely values for all input parameters were input in the model. Afterwards, the effects of specific compensation measures carried out by companies or administrative entities were analyzed. Uncertainty and sensitivity analyses were subsequently conducted, and the potential range of results for $ILUC_{GHG\_net}$ was calculated.

The best-estimate values for $ILUC_{GHG\_net}$ related to ethanol production in the case studies without consideration of compensation measures indicate that sugarcane area expansion in the Southern Region of Malawi and in Minas Gerais, Brazil, and wheat area expansion in Saxony-Anhalt, Germany, lead to similarly high levels of ILUC-induced GHG emissions (24 g CO_{2eq} MJ^{-1} of sugarcane ethanol produced in Minas Gerais, 40 g CO_{2eq} MJ^{-1} of sugarcane ethanol produced in the Southern Region in Malawi, and 50 g CO_{2eq} MJ^{-1} of wheat ethanol produced in Saxony-Anhalt). However, if implementation of compensation measures is considered, the best estimate for $ILUC_{GHG\_net}$ becomes –11 g CO_{2eq} MJ^{-1} of ethanol produced in Malawi, as the planned implementation of an irrigation system is linked to the sugarcane area expansion. The values for the other case studies do not change, as no compensation measures are currently planned in Brazil or Germany.

Hypothesis 1 says that sugarcane area expansion in the case-study regions in Malawi and Brazil and wheat area expansion in the case-study region in Germany, for the purpose of additional ethanol production, lead to ILUC and thus to additional GHG emissions that can be detected with the ILUC case-study approach.

According to the ILUC case-study approach, ILUC and related GHG emissions will occur in all three case studies if no compensation measures are being implemented. However, the ILUC case-study approach just aims to considering the impact of compensation measures. The case study on Malawi shows that ILUC does not occur if sufficient investments in measures that increase agricultural yields and decrease the overall demand for agricultural land are undertaken. The case study furthermore demonstrates that $ILUC_{GHG\_net}$ can turn negative, meaning that overcompensation is occurring. The implementation of the compensation measure in Malawi will most likely take place, thus ILUC will not necessarily occur in this specific case. Hypothesis 1 thus can be verified for the case studies on Brazil and Germany, in which no compensation takes place, but falsified for the case study on Malawi.

Several regional factors, as well as methodological decisions, were furthermore found to have a significant impact on $ILUC_{GHG\_net}$. In particular, the choice of allocation procedure proved to significantly influence the final results. With regard to input parameter sensitivity, $ILUC_{GHG\_net}$ is particularly affected by the location where ILUC takes place, the average LUC CO_2 emission factor, the share of area expansion in the total incremental output growth of biofuel feedstock, the share of yield increase in the total incremental output growth of other agricultural production, and the biofuel yield. The amount of additional fertilizer applied to reach the expected increase in productivity has a comparatively small influence on $ILUC_{GHG\_net}$, so that the positive effect of an increase in productivity achieved by higher amounts of fertilizer application on land demand mostly overcomes its negative impact on direct GHG emissions.

Hypothesis 2 says that if regionally specific factors are considered in the quantification of ILUC and the related GHG emissions, as is the case in the ILUC case-study approach, these regional factors will significantly influence the biofuel-specific ILUC factors. Hypothesis 2 can be verified, as regionally specific conditions do definitely influence the extent of $ILUC_{GHG\_net}$; however, the ranges for $ILUC_{GHG\_net}$ are broad and strongly overlap when considering input parameter uncertainty (1–112 g CO_{2eq} MJ^{-1} of additional sugarcane ethanol produced in Malawi, 1–144 g CO_{2eq} MJ^{-1} in Brazil, and 1–200 g CO_{2eq} MJ^{-1} in Germany). If compensation measures are considered, the range for $ILUC_{GHG\_net}$ is between –200 and 74 g CO_{2eq} MJ^{-1} of additional sugarcane ethanol produced in Malawi. The ranges for the other case studies do not change as no compensation measures are planned.

In general, input parameter uncertainty thus would appear to be too high to make a proper assessment of which type of ethanol should be preferred with regard to a low $ILUC_{GHG\_net}$. Thus, although the case studies do show that regionally specific conditions influence net ILUC GHG emissions, this does not necessarily mean that a significant variation between the regional ILUC factors can be found when uncertainty is considered. Only when the implementation of compensation measures linked to specific biofuel feedstock expansions is considered, the ILUC case-study approach may detect significant differences between regional specific values for $ILUC_{GHG\_net}$.

Hypothesis 3 says that GHG emissions due to the occurrence of ILUC as a consequence of sugarcane expansion in Malawi and Brazil and wheat expansion in Germany, for the purpose of additional ethanol production, are lower than the default value for the CF of fossil fuels (83.8 g CO_{2eq} MJ^{-1} of fuel) and that biofuels thus potentially still can save GHG emissions as compared to fossil fuels. By looking at the best estimates, one can conclude that in all case studies $ILUC_{GHG\_net}$ is lower than the default value for fossil fuels but higher than 21 g CO_{2eq} MJ^{-1} of biofuel, meaning that the biofuels would no longer save 60% of GHG emissions compared to fossil fuels, as will be required in the future. If the ranges of results for $ILUC_{GHG\_net}$ are considered, these statements can no longer be made – in all case studies the maximum values for $ILUC_{GHG\_net}$ are higher than the default value for the CF of fossil fuels, and the minimum values are lower than 21 g CO_{2eq} MJ^{-1} of biofuel. What can be concluded, is that a clear statement about whether ILUC leads to GHG emissions higher than the CF of fossil fuels cannot be made, as the required knowledge about input parameter distribution is lacking. Hypothesis 3 can thus neither be verified nor falsified; this uncertainty should be taken into account when designing the regulation framework at the EU level.

8.3 Compensation measures to reduce ILUC

A specific feature of the ILUC case-study approach is the possibility to consider the effect of ILUC compensation measures. Various measures are suitable for compensating ILUC. In this dissertation increases in agricultural productivity and the reduction in consumption of land-intensive products were identified and analyzed as applicable compensation measures. Whether these are suitable measures in a specific country depends on several regionally specific factors. These include existing intensity of agriculture in the case-study country, which determines the extent to which crop yields can be further increased (if at all), and consumption patterns, as current per capita meat and dairy consumption determine whether an incentivized reduction of such products represents a suitable compensation measure.

In the *Southern Region of Malawi*, prospective sugarcane expansions will occur on land currently used for maize cultivation, thus incurring the risk of ILUC. The expansion, however, is linked to the implementation of a large-scale irrigation system. This investment offers a possibility for avoiding ILUC, as the intensity of agriculture is low in Malawi and the irrigation system is also intended to serve the agricultural needs of the smallholder farmers living in the immediately surrounding region, leading to substantial increases in staple crop yields. The best estimate for $ILUC_{GHG\_net}$ with the implementation of the irrigation system is –11 g CO_{2eq} MJ^{-1} of ethanol, the negative value indicating overcompensation. Additional N fertilizer is probably necessary in order to reach the prospected yield increase, but the subsequent GHG emissions – already included in the –11 g CO_{2eq} MJ^{-1} of ethanol – are much lower than the GHG emissions savings due to the reduced ILUC effect.

In *Minas Gerais, Brazil*, cattle farming is being displaced by sugarcane area expansion. Presently no compensation is planned. One possible measure, though, would be to increase the cattle stocking rate, either through the efforts of the government or local authorities, or by companies that operate sugar/ethanol mills in parallel with cattle farming, which would allow them to guarantee a significantly higher stocking rate than the state average. If we assume that the sugarcane area will expand by 270,000 ha in the South-Central Region, an increase of 0.16% of the stocking rate on the overall pasture land in this region will be necessary in order to compensate ILUC. Additional P fertilizer will probably also be necessary in order to increase the long-term pasture land productivity, but the GHG emissions resulting from such applications will be much lower than the GHG savings due to the reduced ILUC effect.

As crop yields in *Germany* are already at a high level, additional increases are difficult to realize. Investments in irrigation systems elsewhere could be a suitable option for reducing ILUC due to biofuel feedstock expansion in Germany. Additional GHG emissions might occur, depending on the source of energy used for operating the irrigation system; however, the case study on Malawi proves that such investments can be realized in a way that net GHG savings will occur. Another option would be an incentivized reduction of the consumption of land-intensive agricultural products such as meat and dairy. Per capita meat and dairy consumption in Germany is much higher than the global average; such reductions therefore would appear to be a suitable option for Germany. A reduction in meat consumption will not only lead to savings in CO_2 emissions through avoidance of LUC, but also reductions in the GHG emissions associated with beef production, especially from enteric fermentation. The case study shows that $ILUC_{GHG}$ will be zero if meat consumption in Germany is reduced by 3,200 t yr^{-1}, and $ILUC_{GHG\_net}$ is even negative (–23 g CO_{2eq} MJ^{-1} of ethanol).

Hypothesis 4 says that regionally specific ILUC compensation measures reduce the overall demand for agricultural land, but at the same time produce additional GHG emissions. If both effects are considered, it is hypothesized that the specific compensation measures identified in the case studies will still lead to a net GHG reduction, and this can be confirmed. The compensation measures identified as being suitable for Malawi and Brazil demonstrate a decrease in both the overall demand for agricultural land and additional GHG emissions from supplementary fertilizer application; the net effect is clearly a reduction in GHG emissions. The case study on Germany demonstrates that there are compensation measures that would not only decrease the demand for agricultural land but also lead to additional GHG savings.

These results can be transferred in part to other countries with characteristics similar to those of the case-study countries. Measures that increase agricultural yields will very likely lead to net GHG savings in countries where the current intensity of agricultural production is low. If a sufficient water source is available, implementation of an irrigation system may be a suitable compensation measure. Measures that decrease meat or dairy consumption will only be appropriate measures in countries with high levels of meat and dairy consumption.

The methodology, by which the effect of compensation measures is considered, however, is very sensitive to input parameter uncertainty and methodological decisions. It can be challenging, for instance, to determine what share of a measure should be considered as compensation for biofuel feedstock expansion; the Malawian case study illustrates this challenge. The irrigation system will be financed as a public-private partnership, presumably with the involvement of the Malawian government, an international donor, and the sugar company. The share of the resulting yield increase to be considered as a compensation measure for ethanol production can be derived on the basis of the sugar company's financial contribution relative to the overall budget. Given that the main driver for this investment is sugar production, only a small portion of the amount contributed should be credited to ethanol. Input parameter variation leads to values for $ILUC_{GHG\_net}$ that range from 31 g CO_{2eq} MJ^{-1} of ethanol when allocating 0.5% to –55 g CO_{2eq} MJ^{-1} when allocating 1.5% to ethanol. Thus, the share of the overall impact of the compensation measure that can be attributed to the biofuel decisively influences $ILUC_{GHG\_net}$ and should be set with care.

Moreover, the method by which compensation measures are accounted for significantly influences the assessment of any specific compensation measure. As shown in the Malawian case study, the planned irrigation system increases yields on the compensation area. The yield increase can be accounted for in terms of an increase in physical yield, lower heating value (LHV), monetary value, or cereal unit (CU). Depending on the indicator chosen, $ILUC_{GHG\_net}$ can range from a positive 17 g CO_{2eq} MJ^{-1} of ethanol (monetary value) to –19 g CO_{2eq} MJ^{-1} of ethanol (LHV). Methodological decisions thus strongly influence the assessment of compensation measures. To ensure that ILUC does not occur in Malawi, the sugar or ethanol company's compensatory share in the overall investment would have to be at least 1.3%, so that the whole range of results for $ILUC_{GHG\_net}$ would be negative.

Despite these methodological issues, the analyses of compensation measures clearly show that such measures significantly reduce ILUC-induced GHG emissions. The particularly strong positive influence of compensation measures on $ILUC_{GHG\_net}$ indicates that the possibility of including the effect of such measures is precisely the advantage offered by a regionalized case-study approach for ILUC quantification. Case-studies conducted with the described methodology allow for more precise assessments of the ILUC-induced GHG emissions of a specific biofuel investment than do existing models that are not able to consider compensation measures.

The case-study results furthermore make it possible to derive recommendations of how biofuel projects can be designed in order to save GHG emissions. ILUC factors as they are presently being discussed at the EU level do not offer incentives for investment in compensation measures. The agricultural sector is thoroughly dynamic, though, and several measures exist that could free up land, allowing bioenergy to expand to a limited degree while retaining food production at the same level. The results provided by studies conducted with the case-study approach enable feedstock producers, biofuel producers, and governments of biofuel-producing or importing countries to identify compensation measures for ILUC. Knowledge of such measures furthermore offers the opportunity to include additional criteria for avoiding ILUC or ILUC-induced GHG emissions in the certification of biofuels.

8.4 Allocation of LUC CO_2 emissions between indirect and direct drivers of the final LUC

Another topic that has been addressed in the dissertation is the allocation of the final LUC and the related CO_2 emissions between biofuel feedstock expansion (e.g. through pasture land conversion) and agricultural activities that directly displace the natural ecosystem (e.g. deforestation). In existing ILUC-quantification approaches, GHG emissions resulting from the final LUC are usually debited entirely to the expanding biofuel feedstock. This approach, however, can cause a free-rider effect as was shown in the case of sugarcane ethanol production in Brazil.

The expansion of sugarcane production in Minas Gerais mainly displaces pasture land, leading to deforestation in the Amazon region in order to produce new pasture land, with one hectare of sugarcane expansion resulting in the generation of 0.2 ha of new pasture land (according to best estimates). Debiting all CO_2 emissions from the final LUC to the expanding ethanol production has the disadvantage that it disburdens the cattle farming of any responsibility for LUC-induced CO_2 emissions, posing the risk of a free-rider effect. As soon as the scope of the CF is consistently applied to all agricultural products in the same manner that it is now applied to biofuels, ILUC disappears, as DLUC is completely charged to the agricultural activities directly displacing the natural ecosystem. ILUC, however, has been proven to be a serious concern with regard to biofuel feedstock expansion. Even so, consideration of ILUC as is currently done leads to the undesirable effect of double counting of the LUC-induced CO_2 emissions by burdening ethanol as well as meat, an approach that does not seem to be appropriate for handling LUC-induced CO_2 emissions.

An allocation approach that assigns the induced CO_2 emissions to both forms of agricultural activity – expansion of biofuel feedstock as well as agricultural activities directly displacing the natural ecosystem – was tested as an approach to avoid double counting and at the same time establish incentives for avoiding LUC. Depending on the allocation procedure chosen, ILUC-induced CO_2 emissions in the Brazilian example are reduced by up to 10%, as a portion is allocated to meat production.

Hypothesis 5 says that if CO_2 emissions from the final natural ecosystem conversion are allocated between the indirect and direct drivers to the final LUC, ILUC-induced CO_2 emissions will be significantly lower than in the usual case, in which CO_2 emissions are entirely debited to the indirect driver biofuel feedstock expansion. Hypothesis 5 can thus be confirmed – at least for the case study on Brazil.

The allocation approach offers the advantage all agricultural activities responsible for the final LUC – be it directly or indirectly – can be addressed while at the same time avoiding double counting. Nonetheless, it is often very difficult or may even be impossible to link a biofuel feedstock expansion to a specific LUC. As the German case study shows, the specific location of the final LUC can be difficult to foresee, especially when ILUC is likely to spill over the border. Thus, for such cases it is impossible to really say where and in what form LUC will occur or which agricultural activity will follow the natural ecosystem conversion. Thus, the allocation approach presented here must serve as a first approximation.

8.5 Optimizing the CF of ethanol production

The CF of ethanol produced at specific sites in the case-study countries was calculated in order to determine whether the biofuels fulfill the requirements of the RED 2009, to analyze measures by which the CF could be improved, and to estimate which effect $ILUC_{GHG\_net}$ would have on the overall GHG emissions.

In Malawi, sugarcane ethanol is produced from molasses, a by-product of sugar manufacturing. The case study on ethanol production in the Southern Region demonstrates that ethanol production there is accompanied by high GHG emissions that are largely the result of storing the vinasse in open ponds. Vinasse, the liquid residue from the fermentation of sugar juice or molasses, is characterized by high organic carbon content, resulting in substantial methane emissions when it is openly stored. A second reason for the overall high CF is the use of coal as a fuel in the ethanol plant, which also leads to high GHG emissions. Two measures were identified that could help to improve the CF: First, vinasse could be used for biogas production due to its high organic carbon content; second, switching to green harvesting would provide amounts of additional biomass (cane trash) that could be used as a fuel in the ethanol plant. With the help of these measures, the CF could be reduced from 115 g CO_{2eq} MJ^{-1} of ethanol to 20 g CO_{2eq} MJ^{-1} of ethanol (using energy allocation). Although sugarcane ethanol produced in the Southern Region in Malawi currently does not fulfill the requirements of the RED 2009, it could do so through investments in such optimization measures.

With 17 g CO_{2eq} MJ^{-1} of ethanol, the CF of sugarcane ethanol production at the site in Minas Gerais, Brazil, is significantly lower than that of ethanol produced in Malawi. With regard to GHG emissions, the Brazilian method of fertigation is a much better option for treating vinasse. Another advantage in Minas Gerais is the consolidated sugar and ethanol production in a single mill, where bagasse, a fibrous residue from sugarcane milling, is used to produce all process energy needed for sugar and ethanol manufacturing, thus resulting in no attributable GHG emissions for the fuel and only a minimal impact from the ethanol manufacturing itself on the overall CF. Thus, the ethanol easily fulfills the requirements of the RED 2009. Still, the CF could be further improved by switching completely to green harvesting and by using the cane trash for additional electricity production, which could then be fed into the grid.

Wheat ethanol production in Germany has a CF of 26 g CO_{2eq} MJ^{-1} of ethanol when natural gas is used in the ethanol plant to provide process energy; the product thus likewise easily fulfills the requirements of the RED; however, the CF increases to 58 g CO_{2eq} MJ^{-1} of ethanol if wheat is cultivated on former grassland; this is due to the CO_2 emissions that occur as a consequence of DLUC. Ploughing up grassland should thus be more stringently avoided because of its negative impact on climate. A promising measure for reducing the overall CF is using wheat straw as a substitute for natural gas in the ethanol plant, which would reduce the CF from 26 to 13 g CO_{2eq} MJ^{-1} of ethanol (taking into account that a portion of the straw must remain on the field in order to ensure a sustainable carbon balance in the soil).

The CF results prove that the relevance of ILUC-induced GHG emissions for the overall GHG emissions differs in the three case studies. In Malawi, ethanol does not fulfill the RED 2009 mandate, but considering $ILUC_{GHG\_net}$ when including the positive effect of the irrigation system could effectively reduce the overall GHG emissions. Sugarcane ethanol produced in Brazil, however, would fulfill the requirements of the RED, even if the best estimate for $ILUC_{GHG\_net}$ is taken into account; however, if the range of results for $ILUC_{GHG\_net}$ is considered, it is not clear whether the product will still save GHG emissions as compared to fossil fuels. Wheat ethanol produced in Germany also fulfills the RED mandate, but only if $ILUC_{GHG\_net}$ is disregarded (as is currently the case). The effect of $ILUC_{GHG\_net}$ on the overall GHG emissions due to biofuel production thus depends on both the CF and the amount of $ILUC_{GHG\_net}$.

8.6 Recommendations for further research

The dissertation shows that the bottom-up ILUC case-study approach offers several advantages in comparison to mostly applied economic models, which work as top-down approaches. Advantages of the case-study approach include, in particular, the possibility of including regional conditions (e.g. on feedstock cultivation and LUC) and the possibility of considering compensation measures. By doing so, it is possible to determine more realistic ILUC factors for specific biofuel feedstock expansion than is possible with an economic model that outputs average biofuel ILUC factors.

The case studies allow an assessment of the *applicability* of the ILUC case-study approach to specific types of feedstock. While it can be used very well with perennial crops, which allow one to actually observe a biofuel feedstock expansion (e.g. the case studies on Malawi and Brazil), the applicability to annual crops is rather limited, as it is only possible to estimate whether an overall expansion of a specific crop area will occur within a country or elsewhere (e.g. the case study on Germany). Further research is required in order to analyze how to best deal with annual crops.

One feasible approach could be to *combine the bottom-up ILUC case-study approach with top-down economic modeling,* as economic models and other top-down models in general also offer advantages that the ILUC case-study approach cannot achieve. CGE models, for instance, could help to determine where specific feedstocks are expected to come from if feedstock cultivation and biofuel production do not occur in the same country. CGE modeling could also identify countries from which the EU is likely to import biofuels. Based on these results, combined with those of bottom-up case studies in the countries identified, the EU could incentivize the implementation of compensation measures ascertained by means of the case-study approach. Furthermore, economic modeling could help to determine the location of the final LUC and to determine the extent to which diets and the total fuel demand change as market reactions due to biofuel feedstock expansion.

A limitation of the application of the ILUC case-study approach is that it has so far only been applied to ethanol case studies. An *application to biodiesel case studies* would offer further relevant information given that substitution is primarily known to occur in the case of biodiesel production, with the vegetable oils used in biodiesel production presumably being substituted by palm oil produced in Indonesia or Malaysia. In order to further analyze such relations and their effect on ILUC-induced GHG emissions, more research on biodiesel case studies is desirable.

The possibility of accounting for the GHG effect of compensation measures is a great advantage of the ILUC case-study approach. In this dissertation only a few compensation measures were identified and analyzed with regard to their GHG impact. The *investigation of further compensation measures* would help in deriving more general as well as more specific conclusions with regard to the impact of compensation measures. Furthermore, *impacts on other environmental impact categories* and environmental services should be analyzed before implementing such measures, as unintended effects, for instance, on water availability or biodiversity, could occur.

Including compensation measures in the certification of biofuels could establish an incentive that would encourage biofuel (feedstock) producers, governments, and local authorities to take advantage of the opportunity to reduce or even overcompensate ILUC. However, methodological decisions strongly influence $ILUC_{GHG\_net}$ – with or without consideration of compensation measures and assessment of specific compensation measures. An inclusion of compensation measures in biofuel certification must therefore not be undertaken without further research on the topic.

The allocation of the final LUC CO_2 emissions between the expanding biofuel feedstock and the agricultural activity directly displacing the natural ecosystem offers the advantage that indirect as well as direct drivers for LUC can be considered while at the same time avoiding double counting. The allocation approach presented here, however, only serves as a first approximation that highlights the relevance of this topic; further research is needed regarding the problem of avoiding double counting and on allocating LUC-induced GHG emissions between various drivers.

9 References

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A Appendix

A.1 Background data for the case study on Malawi

Table A.1: Sugarcane area in Malawi in 2011
Source: Questionnaires

Year	Nchalo [ha]	Dwangwa [ha]	Total [ha]
Estate	13,799	6,808	**20,607**
Outgrowers	755	2,051	**2,806**
Total	**14,554**	**8,859**	**23,413**

Table A.2: Land uses in Malawi between 1990 and 2009
Source: (FAO 2012)

Year	Agricultural area [1000 ha]	Arable land [1000 ha]	Permanent crops [1000 ha]	Permanent meadows and pastures [1000 ha]	Forest area [1000 ha]	Other land [1000 ha]
1990	4,218	2,250	128	1,840	3,896	1,314
1991	4,320	2,350	130	1,840	3,863	1,245
1992	4,270	2,300	130	1,840	3,830	1,328
1993	4,270	2,300	130	1,840	3,797	1,361
1994	4,070	2,100	130	1,840	3,764	1,594
1995	4,280	2,300	130	1,850	3,732	1,417
1996	4,380	2,400	130	1,850	3,699	1,349
1997	4,430	2,450	130	1,850	3,666	1,332
1998	4,580	2,600	130	1,850	3,633	1,215
1999	4,675	2,700	125	1,850	3,600	1,153
2000	4,720	2,750	120	1,850	3,567	1,141
2001	4,820	2,850	120	1,850	3,534	1,074
2002	4,820	2,850	120	1,850	3,501	1,107
2003	4,970	3,000	120	1,850	3,468	990
2004	4,970	3,000	120	1,850	3,435	1,023
2005	5,170	3,200	120	1,850	3,402	856
2006	5,275	3,300	125	1,850	3,369	784
2007	4,975	3,000	125	1,850	3,336	1,117
2008	5,375	3,400	125	1,850	3,303	750
2009	5,480	3,500	130	1,850	3,270	678
2010	5,580	3,600	130	1,850	3,237	611

Table A.3: Export, import quantities and food supply in Malawi between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Export quantity [1000 t]	215	319	271	435	333	302	336	896	383	504	450
Import quantity [1000 t]	96	135	582	238	193	307	260	224	362	320	320
Food supply (crops) [1000 t]	6,170	6,370	6,267	6,371	6,530	678	7,463	7,792	7,761	7,952	
Food supply (livestock/fish) [1000 t]	219	226	199	218	244	281	248	283	321	354	
Food supply (total) [1000 t]	6,389	6,596	6,467	6,590	6,774	7,159	7,712	8,075	8,082	8,306	
Share of export in food supply [%]	3.4	4.8	4.2	6.6	4.9	4.2	4.4	11.1	4.7	6.1	
Share of import in food supply [%]	1.5	2.1	9.0	3.6	2.9	4.3	3.4	2.8	4.5	3.9	
Trade balance [1000 t]	119	184	–311	198	140	–6	77	672	21	184	129

Table A.4: Meat and milk consumption in Malawi and in the World between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Meat										
Malawi (kg capita^{-1} yr^{-1})	5.5	5.6	5.3	5.4	5.5	5.5	5.4	6.1	7.3	8.3
World (kg capita^{-1} yr^{-1})	38.2	38.2	38.8	39.2	39.4	39.9	40.5	41	41.7	41.9
Ratio between Malawi and World	0.14	0.15	0.14	0.14	0.14	0.14	0.13	0.15	0.18	0.20
Milk										
Malawi (kg capita^{-1} yr^{-1})	3.7	4.2	3.1	3.1	3.7	5.8	2.9	3.7	4.4	5
World (kg capita^{-1} yr^{-1})	78.3	78.7	79.8	80.6	81.8	83.5	84.5	86.6	86.4	87.3
Ratio between Malawi and World	0.05	0.05	0.04	0.04	0.05	0.07	0.03	0.04	0.05	0.06

Table A.5: Average maize yields in Malawi and in the World between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Malawi [t ha^{-1}]	1.7	1.2	1.0	1.2	1.0	0.8	1.5	2.7	1.6	2.2	2.0
World [t ha^{-1}]	4.3	4.5	4.4	4.5	4.9	4.8	4.8	5.0	5.1	5.2	5.2
Ratio between Malawi and World	0.40	0.26	0.24	0.27	0.21	0.17	0.31	0.53	0.32	0.43	0.39

Table A.6: Average yields of different crops in Malawi between 2000 and 2010 [t ha^{-1}]
Source: (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Anise; badian; fennel	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6
Bananas	19.4	20.0	20.0	20.7	20.0	19.5	19.5	19.5	19.5	19.5	18.3
Beans, dry	0.4	0.5	0.4	0.5	0.4	0.4	0.5	0.5	0.5	0.6	0.7
Cabbages	11.4	12.5	14.3	15.0	16.7	16.7	16.6	16.7	16.7	14.0	16.6
Cassava	15.5	16.9	15.0	15.7	16.2	14.3	17.3	18.8	19.1	20.3	20.4
Chick peas	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5
Chilies and peppers	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.1	1.4
Citrus fruit; nes	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	7.3	4.5	2.5
Cloves	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coffee, green	1.3	1.0	0.9	1.0	0.7	0.8	1.0	0.9	0.9	1.4	0.9
Cow peas, dry	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.2
Fruit, fresh nes	6.2	6.3	6.3	6.5	6.5	6.6	6.6	6.6	6.6	4.5	4.0
Fruit; tropical fresh nes	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.4	3.1
Groundnuts, with shell	0.7	0.9	0.8	0.8	0.7	0.6	0.8	1.0	0.9	1.0	1.0
Lentils	0.9	0.8	0.9	0.9	1.0	1.0	0.9	0.9	0.9	1.2	1.0
Maize	1.7	1.2	1.0	1.2	1.0	0.8	1.5	2.7	1.6	2.2	2.0

Mangoes; mango-steens	6.1	6.6	8.2	9.8	10.7	10.7	10.8	11.0	11.0	13.4	15.5
Millet	0.6	0.6	0.6	0.6	0.5	0.4	0.7	0.7	0.7	0.6	0.5
Nutmeg; mace	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.8	0.6
Nuts; nes	1.0	1.0	1.0	0.9	1.0	0.9	1.0	1.0	1.0	1.0	1.0
Onions, dry	13.0	14.9	16.8	18.8	20.0	20.0	20.0	20.0	20.0	21.1	24.5
Peas, dry	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.5	0.5
Pepper (Piper spp.)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.7	0.9
Pigeon peas	0.7	0.8	0.8	0.8	0.7	0.4	0.9	1.0	0.9	1.0	1.0
Plantains	5.8	6.6	7.5	9.0	10.0	9.7	9.4	9.4	9.4	10.0	9.6
Potatoes	11.5	13.5	12.7	13.1	12.1	9.0	13.3	15.2	14.6	16.2	16.1
Rice, paddy	1.6	1.9	1.6	1.6	1.2	0.8	1.8	1.9	1.8	2.1	1.9
Seed cotton	0.9	0.8	0.9	0.9	0.8	0.6	0.9	1.0	1.1	0.9	0.6
Sorghum	0.7	0.7	0.7	0.8	0.6	0.3	0.8	0.9	0.8	0.8	0.6
Spices; nes	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8
Sugar cane	105.0	107.3	108.3	102.4	105.0	109.1	108.9	108.7	108.7	108.7	108.7
Sunflower seed	0.6	0.6	0.7	0.6	0.6	0.4	0.7	0.8	0.8	0.8	0.8
Tea	2.3	2.0	2.1	2.2	2.7	2.1	2.4	2.5	2.5	2.5	2.3
Tobacco, unman.	0.8	0.7	0.7	0.7	0.8	0.7	0.9	1.0	1.0	1.1	1.1
Tomatoes	8.8	8.8	8.8	8.8	8.8	8.8	8.9	8.9	8.9	8.8	8.9
Tung Nuts	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1.0	0.9
Vanilla	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.3
Vegetables; fresh nes	8.4	8.5	8.5	8.6	8.7	8.7	8.8	8.8	8.8	2.3	2.6
Wheat	0.8	0.9	0.6	0.8	0.8	0.9	1.2	2.3	1.6	1.5	1.5

Table A.7: CF due to sugarcane ethanol production in the Southern Region of Malawi (energy allocation, SC 1.1)

Items	CF [kg CO_{2eq} t^{-1} of sugarcane]	Share in total CF [%]
Irrigation	10.2	22
Fertilization	15.5	33
Pesticides	1.6	3
Fuel use	4.6	10
Pre-harvest burning	14.5	31
Total	46.3	100

Table A.8: Travel report (Malawi)

Date (M/D/YR)	**Action**	**Interviewee**	**Institution**	**Place**
2/7/2011	Interview	David Mkanbisi	University of Malawi, Bunda College of Agriculture	Lilongwe
2/7/2011	Interview	Charles Jumbe	University of Malawi, Bunda College of Agriculture	Lilongwe
2/8/2011	Interview	Pieter Waalewijn, Hardwick Tchale	World Bank Group	Lilongwe
2/8/2011	Interview	Patson Nalivata	University of Malawi, Bunda College of Agriculture	Lilongwe
2/8/2011	Interview	Ilona Grünewald	Rural Development, Agriculture, Natural Resources at European Commission	Lilongwe
2/9/2011	Interview	Antje Ilberg	GIZ Planning Adviser of the Ministry of Lands, Housing and Urban Development of the republic of Malawi	Lilongwe
2/9/2011	Interview	Aloysius Mphatso Kamperewera	Ministry of Lands and Natural Resources, Environmental Affairs Department	Lilongwe
2/10/2011	Interview	Kenneth Wiyo	University of Malawi, Bunda College of Agriculture	Lilongwe
2/14/2011	Interview	Victor Kasuzweri	District Environmental Officer	Nkhotakota
2/14/2011	Interview	Peter Mwangupili	District Forestry Officer	Nkhotakota

2/14/2011	Interview	M.L. Chilimmadzi	District Water Officer	Nkhotakota
2/14/2011	Interview	Llewellyn Mwalwanda	Total LandCare	Nkhotakota
2/16/2011	Interview	Aaron Kisebe	Dwangwa Cane Growers Limited	Dwangwa
2/16/2011	Interview	Andy Stewart	Illovo Sugar Limited	Dwangwa
2/16/2011	Interview	Ed Halse	Illovo Sugar Limited	Dwangwa
2/17/2011	Interview	Henry Chakaniza	Illovo Sugar Limited	Dwangwa
2/18/2011	Interview	Lusubilo Chakaniza	Ethanol Company Limited	Dwangwa
2/22/2011	Interview	John Ngalande	Ministry of Energy and Mining, Department of Forestry	Lilongwe
2/23/2011	Interview	Joel Godwin Munthali	Ministry of Agriculture and Food Security, Department of Land Resources Conservation	Lilongwe
2/23/2011	Interview	Geoffrey Mwepa	Ministry of Irrigation and Water Development, Department of Irrigation Services	Lilongwe
2/25/2011	Interview	Migthy Felemu	District Forestry Officer	Chikwawa
2/25/2011	Interview	Peter Magombo	District Environmental Officer	Chikwawa
2/28/2011	Interview	Etienne Rousseau	Illovo Sugar Limited	Nchalo
2/28/2011	Interview	Keith Domleo	Illovo Sugar Limited	Nchalo
3/1/2011	Interview	Shire Valley Cane Growers Trust	Humphrey Savieri	Chikwawa
3/1/2011	Interview	Shire Valley Cane Growers Trust	K. Kasitomu	Chikwawa

Table A.9: Current and planned land uses in the SVIP, physical yields, and monetary values before and after SVIP implementation (LY scenario)

Source: Project description; expected yields from Fandika et al. (2008); producer prices taken from FAO (2012)

	Assumed utilization [ha]	Current yield [t ha^{-1}]	Monetary value [USD]	Planned utilization [ha]	Expected yield [t ha^{-1}]	Expected monetary value [USD]
Maize	91	0.53	15,660	91	5.0	149,037
Sorghum	7	0.59	2,268	7	5.0	19,100
Rice	36	1.1	42,203	36	3.0	115,148
Total	134		60,131	134		283,284

* Producer prices: 327 USD t^{-1} of maize, 548 USD t^{-1} of sorghum, 1,067 USD t^{-1} of rice

Table A.10: Current and planned land uses in the SVIP, physical yields, and lower heating values before and after SVIP implementation (LY scenario)

Source: Current yields from project description; expected yields from Fandika et al. (2008); LHV taken from Fehrenbach et al. (2007), Woods (2000), Akgün et al. (2011)

	Assumed utilization [ha]	Current yield [t ha^{-1}]	LHV [MJ]	Planned utilization [ha]	Expected yield [t ha^{-1}]	Expected LHV [MJ]
Maize	91	0.53	728	91	5.0	6,929
Sorghum	7	0.59	57	7	5.0	482
Rice	36	1.1	447	36	3.0	1,219
Total	134		1,232	134		8,631

* LHV: 16.5 MJ kg^{-1} of maize, 15.9 MJ kg^{-1} of sorghum, 13 MJ kg^{-1} of rice; water content: 15%

A.2 Background data for the case study on Brazil

Table A.11: Amount of sugarcane and ethanol production in Brazil in 2010
Source: Data on sugarcane production: (FAO 2012); data on ethanol production (eia 2011).

	Sugarcane production [1000 t]	Ethanol production [1000 barrel d^{-1}]
Brazil	717,464	486
World	1,694,505	1,520
Brazilian share in overall production [%]	42	32

Table A.12: Land uses in Brazil between 1990 and 2010
Source: (FAO 2012)

Year	Agricultural area [1000 ha]	Arable land [1000 ha]	Permanent crops [1000 ha]	Permanent meadows and pastures [1000 ha]	Forest area [1000 ha]	Other land [1000 ha]
1990	241,608	50,681	6,727	184,200	574,839	29,495
1991	244,941	51,998	6,989	185,954	571,949	29,052
1992	246,709	51,803	7,197	187,709	569,060	30,173
1993	249,463	52,264	7,736	189,463	566,170	30,309
1994	251,418	52,745	7,455	191,218	563,281	31,243
1995	258,472	58,059	7,441	192,972	560,391	27,079
1996	259,019	57,858	7,542	193,619	557,501	29,422
1997	259,566	57,788	7,512	194,266	554,612	31,764
1998	260,112	57,717	7,483	194,912	551,722	34,108
1999	260,759	57,747	7,453	195,559	548,833	36,350
2000	261,406	57,776	7,424	196,206	545,943	38,593
2001	263,465	59,071	7,394	197,000	542,853	39,624
2002	265,868	61,504	7,364	197,000	539,763	40,311
2003	268,477	64,642	7,335	196,500	536,674	40,791
2004	271,011	67,206	7,305	196,500	533,584	41,347
2005	271,299	68,023	7,276	196,000	530,494	44,149
2006	270,681	67,435	7,246	196,000	528,300	46,962
2007	271,082	67,832	7,250	196,000	526,105	48,755
2008	273,489	70,239	7,250	196,000	523,911	48,542
2009	273,520	70,420	7,100	196,000	521,716	50,706
2010	273,421	70,321	7,100	196,000	519,522	52,999

Table A.13: Deforestation in the states of the Amazônia Legal between 1990 and 2011 [1000 ha]
Source: (INPE 2011a)

Year	Acre	Ama-zonas	Amapá	Mara-nhão	Mato Gros-so	Pará	Ron-dônia	Rorai-ma	Tocan-tins
1990	620	1,510	60	2,450	5,140	6,990	2,340	290	1,650
1991	540	1,180	130	1,420	5,960	5,750	1,430	630	730
1992	550	520	250	1,100	4,020	4,890	1,670	150	580
1993	380	980	410	670	2,840	3,780	1,110	420	440
1994	400	799	36	1,135	4,674	3,787	2,265	281	409
1995	482	370		372	6,220	4,284	2,595	240	333
1996	482	370		372	6,220	4,284	2,595	240	333
1997	1,208	2,114	9	1,745	10,391	7,845	4,730	220	797
1998	433	1,023		1,061	6,543	6,135	2,432	214	320
1999	358	589	18	409	5,271	4,139	1,986	184	273
2000	536	670	30	1,012	6,466	5,829	2,041	223	576
2001	441	720		1,230	6,963	5,111	2,358	220	216
2002	547	612		1,065	6,369	6,671	2,465	253	244
2003	419	634	7	958	7,703	5,237	2,673	345	189
2004	883	885	0	1,085	7,892	7,510	3,099	84	212
2005	1,078	1,558	25	993	10,405	7,145	3,597	439	156
2006	728	1,232	46	755	11,814	8,870	3,858	311	158
2007	592	775	33	922	7,145	5,899	3,244	133	271
2008	398	788	30	674	4,333	5,659	2,049	231	124
2009	184	610	39	631	2,678	5,526	1,611	309	63
2010	259	595	53	712	871	3,770	435	256	49
2011	271	526	51	365	1126	2870	869	120	40

Table A.14: Increase in harvested area for various crops in Brazil between 1990 and 2010
Source: Based on (FAO 2012)

	Increase in harvested area [1000 ha]	Share of total increase [%]
Soybeans	11,840	60.5
Sugarcane	4,804	24.6
Maize	1,285	6.6
Sorghum	523	2.7
Cashew	176	0.9
Tobacco	176	0.9
Oil palm fruit	73	0.4

	Increase in harvested area [1000 ha]	**Share of total increase [%]**
Coconut	61	0.3
Natural rubber	66	0.3
Mate	60	0.3
Others	492	2.5
Total	**19,556**	**100.0**

Table A.15: Area harvested for various crops in Brazil between 2000 and 2010 [1000 ha]
Source: (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Apples	30	31	32	32	33	35	36	38	38	38	39
Avocados	13	12	12	10	12	12	10	10	9	8	11
Bananas	525	510	503	510	491	491	505	515	513	480	487
Barley	144	143	147	119	142	145	82	100	79	77	84
Beans, dry	4,332	3,450	4,141	4,091	3,979	3,749	4,034	3,788	3,782	4,100	3,424
Broad beans	41	25	32	35	36	34	37	35	42	45	28
Buckwheat	41	43	45	50	51	46	47	48	51	50	46
Cashew nuts	651	639	665	683	691	700	710	731	747	758	759
Cashew apple	538	590	595	598	600	595	610	621	622	591	617
Cassava	1,722	1,667	1,675	1,634	1,755	1,902	1,897	1,894	1,889	1,761	1,787
Castor oil seed	195	172	136	134	173	231	151	163	158	159	152
Cocoa beans	706	666	582	591	639	625	647	629	641	636	661
Coconuts	264	273	277	280	285	291	290	283	287	284	275
Coffee, green	2,268	2,336	2,371	2,396	2,368	2,326	2,312	2,264	2,222	2,136	2,159
Figs	3	3	3	3	3	3	3	3	3	3	3
Fruit, tropical	47	33	36	35	37	36	44	47	49	51	62
Garlic	13	14	16	15	11	10	10	11	10	10	10
Grapefruit	4	3	4	4	4	4	4	4	4	4	4
Grapes	60	63	66	68	72	73	75	78	80	81	81
Groundnuts	103	105	97	89	105	136	111	114	121	94	94
Jute	1	1	1	1	2	4	4	5	1	1	1
Lemons; limes	50	49	50	51	49	50	47	45	44	41	43

Linseed	5	5	5	6	11	22	19	16	12	13	17
Maize	11,615	12,330	11,751	12,966	12,411	11,549	12,613	13,767	14,445	13,655	12,683
Mangoes	68	67	67	68	70	68	75	76	74	75	75
Mate	69	84	80	84	75	76	79	75	71	71	67
Natural rubber	94	95	102	104	106	112	107	115	125	129	124
Nuts; nes	3	3	3	3	4	4	4	4	4	4	4
Oats	193	257	255	297	347	368	324	137	117	134	173
Oil palm fruit	45	46	45	52	55	56	97	102	103	104	106
Olives	0	0	0	0	0	0	0	0	0	0	0
Onions, dry	66	64	69	69	58	58	63	64	65	66	70
Oranges	856	825	829	836	823	806	806	821	837	787	776
Other bast fibres	4	5	6	6	7	12	13	12	9	9	10
Other melons	11	12	13	16	15	16	21	22	16	18	19
Papayas	40	35	36	36	34	33	37	35	37	34	34
Peaches	22	23	24	25	24	24	22	22	21	19	20
Pears	2	2	2	2	2	2	2	2	2	1	2
Peas, dry	1	2	3	2	4	2	2	2	2	3	3
Pepper	16	21	23	26	27	32	33	33	30	27	23
Persimmons	6	7	7	7	8	8	9	8	9	9	9
Pineapples	60	63	61	58	59	62	67	72	66	60	59
Potatoes	150	154	161	152	143	142	141	148	145	139	137
Quinces	2	2	0	0	0	0	0	0	0	0	0
Ramie	0	0	0	1	1	1	0	0	0	0	0
Rapeseed	24	24	32	34	34	30	31	32	33	31	31
Rice, paddy	3,655	3,143	3,146	3,181	3,733	3,916	2,971	2,891	2,851	2,872	2,722

Rye	7	7	5	3	3	5	3	4	5	4	2
Seed cotton	802	875	768	718	1,150	1,263	899	1,126	1,064	812	830
Sesame seed	24	24	24	24	24	25	25	25	25	25	25
Sisal	195	204	203	222	233	240	280	278	282	273	264
Sorghum	524	486	424	754	931	788	722	663	831	793	661
Soybeans	13,640	13,974	16,365	18,525	21,539	22,949	22,047	20,565	21,246	21,751	23,327
Strawberries	0	0	0	0	0	0	0	0	0	0	0
Sugar cane	4,846	4,958	5,100	5,371	5,632	5,806	6,356	7,081	8,140	8,618	9,077
Sunflower seed	58	53	43	52	42	69	68	73	114	81	76
Sweet potatoes	44	43	44	46	47	45	44	44	46	42	42
Tangerines	62	63	65	65	63	61	61	60	54	55	58
Tea	4	4	4	3	3	3	3	0	3	3	2
Tobacco	310	303	344	393	462	494	496	459	432	442	450
Tomatoes	56	57	63	63	60	61	59	58	61	68	68
Triticale	0	0	0	0	0	135	101	80	76	66	51
Tung nuts	0	0	0	0	0	0	0	0	0	0	0
Vegetables	185	183	195	201	184	200	205	210	201	213	205
Walnuts	2	2	2	2	1	1	2	2	2	2	2
Watermelons	81	77	75	82	81	85	93	97	88	94	95
Wheat	1,066	1,727	2,105	2,560	2,807	2,361	1,560	1,853	2,364	2,430	2,182
Yams	27	26	25	24	26	28	26	27	27	25	25

Table A.16: Export, import quantities and food supply in Brazil between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Export quantity [1000 t]	34,745	53,982	55,921	63,190	70.545	72,083	76,202	83,750	80,599	89,844	95,853
Import quantity [1000 t]	14,652	12,490	11,898	13,008	9.636	9,956	11,974	12,730	11.962	11,941	12,886
Food supply (crops) [1000 t]	107,451	104,422	110,753	113,152	118.163	120,011	122,441	123,807	128,434	128,948	
Food supply (livestock/fish) [1000 t]	55,048	54,479	58,069	58,104	60.380	61,499	63,922	64,072	67,366	72,484	
Food supply (total) [1000 t]	162,499	158,901	168,823	171,256	178.543	181,510	186,362	187,878	195,800	201,432	
Share of export in food supply [%]	21	34	33	37	40	40	41	47	41	45	
Share of import in food supply [%]	9	8	7	7	5	6	6	7	6	6	
Trade balance [1000 t]	20,093	41,492	44,024	50,182	60.909	62,127	64,228	71,020	68,637	77,903	82,967

Table A.17: Meat and milk consumption in Brazil and in the World between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Meat										
Brazil (kg capita^{-1} yr^{-1})	79.0	76.4	78.7	79.7	81.3	74.6	78	80.6	86.3	85.3
World (kg capita^{-1} yr^{-1})	38.2	38.2	38.8	39.2	39.4	39.9	40.5	41.0	41.7	41.9
Ratio between Brazil and World	2.07	2.00	2.03	2.03	2.06	1.87	1.93	1.97	2.07	2.04
Milk										
Brazil (kg capita^{-1} yr^{-1})	112.5	109.3	116.3	113.5	116.6	121.1	123.8	121.0	125.0	136.9
World (kg capita^{-1} yr^{-1})	78.3	78.7	79.8	80.6	81.8	83.5	84.5	86.6	86.4	87.3
Ratio between Brazil and World	1.44	1.39	1.46	1.41	1.43	1.45	1.47	1.40	1.45	1.57

Table A.18: Average maize yields in Brazil and in the World between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Brazil [t ha^{-1}]	2.7	3.4	3.1	3.7	3.4	3.0	3.4	3.8	4.1	3.7	4.4
World [t ha^{-1}]	4.3	4.5	4.4	4.5	4.9	4.8	4.8	5.0	5.1	5.2	5.2
Ratio between Brazil and World	0.63	0.76	0.69	0.84	0.68	0.63	0.70	0.76	0.80	0.72	0.84

Table A.19: Sugarcane area, ethanol production, and sugar production in Brazil between 1980 and 2010

Source: Data on sugarcane area and sugar production taken from (FAO 2012); data on ethanol production taken from (eia 2011)

Year	Sugarcane area [1000 ha]	Ethanol production [Million L]	Sugar production [1000 t]
1980	2,608	3,708	8,521
1981	2,826	4,161	8,423
1982	3,084	5,826	9,312
1983	3,479	7,863	9,576
1984	3,656	11,252	9,332
1985	3,912	11,821	8,274
1986	3,945	10,503	8,650
1987	4,309	11,455	8,458
1988	4,113	11,705	8,683
1989	4,068	11,896	7,793
1990	4,273	11,780	7,935
1991	4,211	12,750	9,348
1992	4,203	11,734	9,986
1993	3,864	11,315	10,038
1994	4,345	12,513	12,618
1995	4,559	12,746	13,594
1996	4,750	14,095	14,775
1997	4,814	15,493	15,975
1998	4,986	14,122	19,232
1999	4,899	12,982	20,955
2000	4,846	10,671	17,100
2001	4,958	11,466	20,400
2002	5,100	12,589	23,810
2003	5,371	14,470	26,400
2004	5,632	14,607	28,150
2005	5,806	16,040	29,500
2006	6,356	17,764	32,166
2007	7,081	22,557	31,280
2008	8,140	27,059	32,085
2009	8,514	26,103	34,637
2010	9,077	28,203	39,872

Table A.20: Sugarcane area and ethanol production in São Paulo and Brazil between 2003 and 2010
Source: Data on sugarcane area from (INPE 2011b); data on ethanol production taken from (UNICA and MAPA 2010)

Year	São Paulo (SP)	Brazil (BR)	Share of SP in BR	SP	BR	Share of SP in BR
	[ha]	[ha]	[%]	[Million L]	[Million L]	[%]
2003/2004	3,002,676	5,371,020	56	8,828	14,809	60
2004/2005	3,165,387	5,631,740	56	9,107	15,417	59
2005/2006	3,364,704	5,805,520	58	9,963	15,924	63
2006/2007	3,661,155	6,355,500	58	10,910	17,710	62
2007/2008	4,249,922	7,080,920	60	13,325	22,422	59
2008/2009	4,873,940	8,140,090	60	16,722	27,513	61
2009/2010	5,242,488	8,617,560	61	14,912	25,694	58
2010/2011	5,303,342	9,076,710	58	15,354	27,376	56

Table A.21: Sugarcane area in the South-Central Region of Brazil between 2003 and 2010
Source: Based on (INPE 2011b)

Year	Goiás	Espírito Santo	Minas Gerais	Mato Grosso do Sul	Mato Grosso	Paraná	Rio de Janeiro	São Paulo
	[1000 ha]	[1000 ha]	[1000 ha]	[1000 ha]	[1000 ha]	[1000 ha]	[1000 ha]	[1000 ha]
2003/2004								3,003
2004/2005								3,165
2005/2006	216		309	160	205	378		3,365
2006/2007	251		368	182	214	438		3,661
2007/2008	328		483	227	238	540		4,250
2008/2009	458		615	311	264	634		4,874
2009/2010	586		706	426	282	665		5,242
2010/2011	655	77	764	502	279	668	100	5,303

Table A.22: Size of pasture land, number of cattle, and stocking rate of cattle in the states of Brazil in 1996 and 2006
Source: IBGE (2010) and IBGE (2006); stocking rate calculated by author

Year	Pasture land [1000 ha]		Number of cattle [1000]		Stocking rate of cattle [head per ha]	
	1996	2006	1996	2006	1996	2006
Distrito Federal	96	82	86	78	0.89	0.96
Mato Grosso	21,452	22,809	14,438	19,583	0.67	0.86
Mato Grosso do Sul	21,811	18,421	19,754	17,405	0.91	0.94
Goiás	19,405	15,525	16,488	16,684	0.85	1.07
Rio Grande do Sul	11,680	8,955	13,221	11,148	1.13	1.24
Santa Catarina	2,339	3,455	3,097	3,586	1.32	1.04

Paraná	6,677	5,735	9,901	9,154	1.48	1.60
São Paulo	9,062	8,594	12,307	10,209	1.36	1.19
Rio de Janeiro	1,545	1,606	1,814	2,004	1.17	1.25
Espírito Santo	1,821	1,316	1,789	1,790	0.98	1.36
Minas Gerais	25,349	20,555	20,045	20,992	0.79	1.02
Bahia	14,490	12,902	8,730	10,441	0.60	0.81
Sergipe	1,154	1,164	941	956	0.82	0.82
Alagoas	862	874	968	914	1.12	1.05
Pernambuco	2,131	2,507	1,931	2,080	0.91	0.83
Paraíba	1,852	1,998	1,328	1,303	0.72	0.65
Rio Grande do Norte	1,246	1,334	954	974	0.77	0.73
Ceará	2,632	2,925	2,382	2,125	0.91	0.73
Piauí	2,398	2,783	1,704	1,595	0.71	0.57
Maranhão	5,311	6,163	3,903	5,646	0.73	0.92
Tocantins	11,078	10,291	5,218	6,093	0.47	0.59
Amapá	245	432	60	60	0.24	0.14
Pará	7456	13,168	6,080	12,808	0.82	0.97
Roarima	1,543	807	400	573	0.26	0.71
Amazonas	529	1,837	734	1,266	1.39	0.69
Acre	614	1,032	847	1,784	1.38	1.73
Rondônia	2,887	5,064	3,884	8,650	1.35	1.71
Brazil	177,665	172,333	153,005	169,900	0.86	0.99
South-Central Region	100,541	88,908	86,720	88,745	0.86	1.00

Table A.23: Travel report (Brazil)

Date (M/D/YR)	**Action**	**Interviewee**	**Institution**	**Place**
9/12/2011	Interview	Suani Teixeira Coelho	Centro Nacional de Referência em Biomassa at the University of São Paulo	City of São Paulo
9/12/2011	Interview	Patricia Guarda-bassi	Centro Nacional de Referência em Biomassa at the University of São Paulo	City of São Paulo
9/14/2011	Interview	Beatriz Stuart Secaf	União da Indústria de Cana-de-Açúcar	City of São Paulo
9/14/2011	Interview	Luana Maia	União da Indústria de Cana-de-Açúcar	City of São Paulo
9/14/2011	Interview	Verena Glass	Repórter Brasil	City of São Paulo
9/15/2011	Interview	Vinicius Ambrogi	GEOKLOCK	City of São Paulo

9/15/2011	Interview	Carolina Carvalho	Federal university of Rio de Janeiro	City of São Paulo
9/19/2011 – 9/20/2011	Participation and presentation at the IEA-Workshop “Quantifying and managing land use effects of bioenergy”			Campinas
9/20/2011	Interview	Simone Pereira de Souza	Brazilian Bioethanol Science and Technology Laboratory (CTBE)	Campinas
9/21/2011	Visit to the Cresciumal Sugar/Ethanol Mill			Leme
9/22/2011	Interview	Joaquim Eugênio Abel Seabra	Universidade Estadual de Campinas, UNICAMP	Campinas
9/28/2011	Interview	Eduardo Romeiro Filho	Universidade Federal de Minas Gerais, UFMG	Belo Horizonte
9/28/2011	Interview	Juan Carlos Claros Garcia	Universidade Federal de Minas Gerais, UFMG	Belo Horizonte
9/29/2011	Data ex-change	Juan Carlos Claros Garcia	Universidade Federal de Minas Gerais, UFMG	Belo Horizonte
9/30/2011	Visit to the Agropeu Sugar/Ethanol Mill			Pompeu
9/30/2011	Interview	Geraldo Magela Valadares	Agropeu	Pompeu
10/3/2011	Interview	Jane Silva	Comissão Pastoral da Terra	Belém
10/4/2011	Interview	Alfredo Kingo Oyama Homma	Empresa Brasileira de Pesquisa Agropecuária, Embrapa	Belém
10/4/2011	Interview	Marcos Ene Chaves Oliveira	Empresa Brasileira de Pesquisa Agropecuária, Embrapa	Belém
10/5/2011	Interview	Luis Barbosa	Conservation International	Belém
10/5/2011	Interview	Tercio Pompeu de Mello	SEMA – Secretaria de Estado de Meio Ambiente	Belém
10/10/2011	Interview	Túlio Dias	Agropalma	Tailândia
10/11/2011	Visit to the Agropalma palm oil mill			Tailândia

A.3 Background data for the case study on Germany

Table A.24: Size of various types of permanent grassland between 1993 and 2010 in Germany
Source: (BMELV 2012b)

Year	Permanent grassland [1000 ha]			
	Meadows	Pasture land	Mountain pastures	Total
1993	2,413	1,598	1,092	5,251
1994	2,291	1,771	1,061	5,271
1995	2,233	1,874	1,030	5,282
1996	1,130	1,909	993	5,273
1997	2,196	1,945	984	5,268
1998	2,177	2,007	930	5,265
1999	2,110	2,007	858	5,114
2000	2,000	2,082	831	5,048
2001	1,961	2,104	817	5,013
2002	1,931	2,124	781	4,970
2003	1,898	2,158	777	4,968
2004	1,870	2,210	700	4,913
2005	1,862	2,260	650	4,929
2006	1,848	2,250	641	4,882
2007	1,846	2,251	627	4,875
2008	1,756	2,297	587	4,789
2009	1,773	2,226	585	4,741
2010	1,899	2,545		4,655

Table A.25: Export and import quantities and food supply in Germany between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Export quantity [1000 t]	45,808	45,846	44,237	46,272	45,875	48,497	47,523	45,294	48,041	50,856	54,698
Import quantity [1000 t]	41,535	42,565	44,815	45,942	45,934	47,434	50,910	54,709	56,047	57,027	58,316
Food supply (crops) [1000 t]	58,898	58,958	58,870	56,864	57,469	57,233	56,250	56,033	55,667	56,193	
Food supply (livestock/fish) [1000 t]	36,479	37,502	38,982	40,211	39,187	39,786	40,065	40,858	41,103	41,527	
Food supply (total) [1000 t]	95,378	96,461	97,852	97,075	96,656	97,018	96,315	96,890	96,771	97,720	
Share of export in food supply [%]	48.0	47.5	45.2	47.7	47.5	50.0	49.3	46.7	49.6	52.0	
Share of import in food supply [%]	43.5	44.1	45.8	47.3	47.5	48.9	52.9	56.5	57.9	58.4	
Trade balance [1000 t]	4,272	3,281	–578	331	–59	1,063	–3,387	–9,415	–8,006	–6,171	–3,618

Table A.26: Export and import quantities of wheat, rapeseed, soybean, and maize in Germany between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Wheat											
Export quantity [1000 t]	4,569	5,710	5,872	4,473	3,927	4,627	6,106	4,646	7,038	9,688	8,915
Import quantity [1000 t]	1,291	968	1,393	1,541	966	1,441	1,664	2,055	2,583	4,068	3,992
Trade balance [1000 t]	3,278	4,743	4,479	2,932	2,961	3,187	4,442	2,591	4,455	5,619	4,923
Rapeseed											
Export quantity [1000 t]	622	683	775	389	538	255	310	405	430	237	279
Import quantity [1000 t]	1,363	1,258	1,221	1,211	1,410	1,461	1,628	2,199	2,747	3,294	2,314
Trade balance [1000 t]	–741	–575	–446	–821	–872	–1,206	–1,318	–1,794	–2,317	–3,057	–2,035
Soybean											
Export quantity [1000 t]	8	11	26	26	26	29	28	34	47	35	40
Import quantity [1000 t]	3,840	4,574	4,346	4,516	3,719	3,884	3,516	3,693	3,485	3,165	3,383

Trade balance [1000 t]	–3,832	–4,563	–4,320	–4,490	–3,693	–3,855	–3,488	–3,659	–3,438	–3,130	–3,343
Maize											
Export quantity [1000 t]	553	596	665	857	947	879	888	712	685	687	647
Import quantity [1000 t]	976	705	888	1,060	1,380	1,718	1,692	2,444	1,893	1,964	1,881
Trade balance [1000 t]	–422	–110	–224	–203	–433	–839	–804	–1,732	–1,207	–1,276	–1,234

Table A.27: Meat and milk consumption in Germany and in the World between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Meat										
Germany (kg capita^{-1} yr^{-1})	84.0	82.7	82.2	84.3	84.2	83.8	84.3	88.1	87.8	88.1
World (kg capita^{-1} yr^{-1})	38.2	38.2	38.8	39.2	39.4	39.9	40.5	41.0	41.7	41.9
Ratio between Germany and World	2.20	2.16	2.12	2.15	2.14	2.10	2.08	2.15	2.11	2.10
Milk										
Germany (kg capita^{-1} yr^{-1})	228.9	237.4	250.9	254.8	245.6	252.9	258.4	262.8	266.4	264.0
World (kg capita^{-1} yr^{-1})	78.3	78.7	79.8	80.6	81.8	83.5	84.5	86.6	86.4	87.3
Ratio between Germany and World	2.92	3.02	3.14	3.16	3.00	3.03	3.06	3.03	3.08	3.02

Table A.28: Average maize yields in Germany and in the World between 2000 and 2010
Source: Based on (FAO 2012)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Germany [t ha^{-1}]	9.2	8.8	9.4	7.4	9.1	9.2	8.0	9.4	9.8	9.8	8.8
World [t ha^{-1}]	4.3	4.5	4.4	4.5	4.9	4.8	4.8	5.0	5.1	5.2	5.2
Ratio between Germany and World	2.1	2.0	2.1	1.7	1.8	1.9	1.7	1.9	1.9	1.9	1.7