THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Land and climate effects of bioenergy

– Brazilian sugarcane ethanol and combined biofuel-district heating in Europe

Andrea Egeskog

Division of Physical Resource Theory
Department of Energy and Environment
Chalmers University of Technology
Göteborg, Sweden 2016

Land and climate effects of bioenergy – Brazilian sugarcane ethanol and combined biofuel-district heating in Europe
Andrea Egeskog

ISBN 978-91-7597-350-0
Doktorsavhandlingar vid Chalmers tekniska högskola Ny serie 4031
ISSN 0346-718X

Division of Physical Resource Theory
Department of Energy and Environment
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000
Fax + 46 (0)31-772 3150
http://www.chalmers.se/ee

Author e-mail: egeskog.andrea@gmail.com

Cover photo: Sugarcane fields in the state of Goiás, Brazil, March 2013. To the left a recently harvested field and to the right standing sugarcane.
Picture by Andrea Egeskog

Printed by Chalmers Reproservice
Göteborg, Sweden 2016

Land and climate effects of bioenergy

Brazilian sugarcane ethanol and combined biofuel-district heating in Europe

Andrea Egeskog

Physical Resource Theory, Department of Energy and Environment

Chalmers University of Technology

Abstract

According to the Intergovernmental Panel on Climate Change, use of fossil fuels is the largest source of the increase in atmospheric CO_2. The second largest is land use change. To reach stringent climate targets, emissions from fossil fuel combustion and land use change will need to be reduced to near zero within a few decades. Biomass is a renewable energy source that can be used to replace fossil fuels. However, it is a limited resource, expected to become scarce relative to future demand, prompting interest in optimizing efficiency. Further, when biomass for biofuels expands into new land areas, the total biospheric carbon stock (the sum of soil and above-ground carbon) may increase or decrease, influencing the net effect on greenhouse gas balances. This thesis, which consists of five separate papers, analyzes several key aspects associated with two bioenergy systems: (i) combined biofuels and district heat production in the EU and (ii) sugarcane for ethanol production in Brazil, with special attention to integration with existing food and energy systems. The overall aim is to investigate specific options for improving management of land use and land use change, efficient use of resources, and greenhouse gas balances for specific bioenergy systems.

In **Paper I**, we study biomass gasification for the production of biofuels and heat for district heating systems in Europe. We find that each investigated country, except Italy, has a heat sink capacity in its district heating systems that is larger than the amount of heat that would be co-generated in plants producing biofuel volumes corresponding to national biofuel targets.

In **Papers II–V**, we study expansion of sugarcane ethanol production in Brazil at the regional, state, and national levels, including both conventional sugarcane ethanol systems and combined ethanol-milk production systems in which sugarcane residues are used as animal feed. We find that the harvest method influences greenhouse gas emissions from sugarcane-based ethanol production, as does the impact on soil carbon content. How the by-product bagasse is used also affects the results.

For **Paper V**, we interview Brazilian farmers and landholders regarding their actions connected to engaging with sugarcane production. We find that it is common among the interviewees to invest profits from sugarcane production to maintain and improve the prior beef and milk production systems. This likely affects indirect land use change associated with sugarcane expansion on former pasture land.

Keywords: bioenergy, biofuels for transport, sugarcane ethanol, district heating, Brazil, EU

List of papers

This thesis is based on the work contained in the following papers:

Paper I: **Co-generation of biofuels for transportation and heat for district heating systems – an assessment of the national possibilities in the EU**
A. Egeskog, J. Hansson, G. Berndes, S. Werner
Energy Policy, 2009, Volume 37, pp 5260–5272

AE and GB formulated the research question with contributions from SW; all contributed to model development; AE collected data and performed the modelling; AE, JH and GB analysed the results; JH wrote the paper with contributions from AE and GB.

Paper II: **Sugarcane ethanol production in Brazil: an expansion model sensitive to socioeconomic and environmental concerns**
G. Sparovek, G. Berndes, A. Egeskog, F. Freitas, S. Gustafsson, J. Hansson
Bio FPR, Volume 1, September 2007, Pages 270–282

GS and GB formulated the research question with contributions from all authors; AE and SG carried out the modeling for the case study with contributions from GS and FF; all authors helped analyze the results from the case study; GS and GB wrote the paper and AE and SG contributed with writing regarding the case study.

Paper III: **Integrating bioenergy and food production – A case study of combined ethanol and dairy production in Pontal, Brazil**
A. Egeskog, G. Berndes, F. Freitas, S. Gustafsson, G. Sparovek
Energy for Sustainable Development, Volume 15, Issue 1, March 2011, Pages 8–16

AE, GB, SG and GS formulated the research question; AE, GB and GS contributed to model development; AE collected data and carried out the greenhouse gas and integration modeling, FF and SG helped with collection of data for the integration model; AE and GB analyzed the results; AE wrote the paper with contributions from GB.

Paper IV: **Greenhouse gas balances and land use changes associated with the planned expansion (to 2020) of the sugarcane ethanol industry in Sao Paulo, Brazil**
A. Egeskog, F. Freitas, G. Berndes, G. Sparovek, S. Wirsenius
Biomass and Bioenergy, Volume 63, April 2014, Pages 280–290

AE and GB formulated the research question; AE, FF, GB and SW contributed to the model developments; AE collected data and carried out the greenhouse gas modeling, FF collected data and carried out the land modeling; AE, GB and SW analyzed the results; AE wrote the paper with contributions from GB and SW.

Paper V: **Actions and opinions of Brazilian farmers that shift to sugarcane – an interview based assessment with discussion of implications for land use change**
A. Egeskog, A. Baretto, G. Berndes, F. Freitas, M. Holmén, G. Sparovek, J. Torén
Submitted to Land Use Policy

AE formulated the research question; AE and MH carried out the method development with contributions from GB and JT; AE, AB, FF, MH and JT carried out the data collection; AE and MH analyzed the results with contributions from AB, GB, FF, GS and JT; AE wrote the paper with contributions from GB and MH.

Related publications in scientific journals not included in this thesis

Strategies for 2nd Generation Biofuels in EU – Co-firing to stimulate feedstock supply development and process integration to improve energy efficiency and economic competitiveness
G. Berndes, J. Hansson, A. Egeskog, F. Johnsson
Biomass and Bioenergy, Volume 34, 2010, Pages 227–236

The REFUEL EU road map for biofuels in transport: Application of the project's tools to some short-term policy issues
M. Londo, S. Lensink, A. Wakker, G. Fischer, S. Prieler, H. Velthuizen, M. Wit, A. Faaij, M. Junginger, G. Berndes, J. Hansson, A. Egeskog, H. Duer, J. Lundbaek, G. Wisniewski, A. Kupczyk, K. Könighofer
Biomass and Bioenergy, Volume 34, 2010, Pages 244–250

Errata

Page 274, Paper II: A reference to “Figure 4 shows an example …” should instead read “Figure 3 shows an example…”

Page 283, Figure 2, Paper IV: The axis should say “kha” not “ha”; the captions should read “160” and “220 kha” instead of “65” and “75” ha.

Acknowledgements

I would like to express my gratitude to all the lovely persons
who in one way or another contributed to this thesis:

My supervisors Göran and Stefan

My examiners Christian and Kristian

My co-authors

My colleagues and friends in Brazil

My colleagues and friends at Physical Resource Theory

My father Hans for editing my thesis

My friends and family and special thanks to Mattias, Alva and Stina, para sempre!

This work was financed by the AGS project Pathways to Sustainable European Energy Systems and the Swedish Energy Agency.

To Mattias, Alva and Stina, without you I'm nothing

– Varför blir du inte akademiker då, […]
– Du menar doktorera? Men det är ju en livsuppgift. […]
– Det är inte mer än högst en femårsplan nu för tiden, […]
epadoktor kallar de den, för att markera hur lättköpt den är.
[…]
– Epa dr – vilken titel för telefonkatalogen!

Ur Maken en förhållanderoman *av Gun-Britt Sundström s. 214*

Contents

Illustration by Alva Egeskog of my research in Brazil including growing sugarcane, cattle and machinery.

Chapter 1
Introduction

On Earth's surface, where we work, live and love, each of the last three decades has been warmer than any preceding decade since 1850. Our use of fossil fuels and land are extremely likely the dominant cause (IPCC, 2014). Use of fossil fuels currently emits about 32 Gton carbon dioxide (CO_2) per year (IPCC, 2014). Biofuels are used to replace fossil fuels in order to reduce greenhouse gas (GHG) emissions. However, producing biofuels results in GHG emissions from the associated land use (LU) and land use change (LUC) as well as the production process. Forestry and other land use emit about 5 Gton CO_2-equivalent (CO_2-eq) per year (IPCC, 2014).

The bioenergy resource base, e.g., forest roundwood, forestry and agricultural residues, energy crops, by-products in the food and forestry industry, and organic waste, is influenced by a range of factors such as population growth, diets, and productivity developments in agriculture and forestry. Many estimates of the global bioenergy potential diverge due to the inherent uncertainty of important factors, e.g., future diets and how access to biomass resources is influenced by sustainability considerations (Berndes et al., 2003; Smeets et al., 2007; Batidzirai et al., 2012). However, many studies conclude that several hundreds of EJ of bioenergy could be produced per year by 2050 under favorable conditions. The current annual global consumption of biomass for energy is almost 47 EJ (IEA, 2014a), more than 12% of the annual global primary energy consumption (IEA, 2014a). Most of today's consumption of biomass stems from traditional biomass use for heating and cooking in developing countries, 30 EJ (SRREN, 2011), and the use of residue streams (including organic waste) to produce refined fuels or to generate heat and/or electricity. Residue streams are limited by the amount of biomass used for production of food and various biomaterials; estimates of the residue supply potential in 2050 range from about 50 to 250 EJ (IEA Bioenergy, 2009). Dedicated biomass production systems are often assessed as having the greatest, but most uncertain, potential (Chum et al., 2011).

Interest in heat from production of, e.g., biomass-based biofuels has grown in recent years. When heating values are too low for electricity production, surplus heat can be used in district heating systems. Due to a number of European systems studies (e.g., Heat Roadmap Europe, 2013; Stratego, 2015) and an increasing number of scientific publications showing the energy efficiency potential of modern district heating and cooling systems, interest among EU policymakers has grown (see, e.g., EC, 2012).

Global biofuel production increased more than fivefold in the first decade of this century (EIA, 2015). The area dedicated to cultivating feedstocks for biofuel production was, in 2012, 25 million hectares (Mha) in the US (mostly corn for ethanol), and roughly 6 Mha of sugarcane for ethanol in Brazil (EIA, 2015), along with significant soy cultivation, primarily for animal feed but also providing oil used for various purposes including biodiesel production. Germany has the third-largest cropland area dedicated to biofuels with almost 3 Mha, mostly planted with rapeseed for biodiesel (EIA, 2015). In 2012, global biofuel production was 2.2 EJ (SCOPE, 2015). The US, Brazil, and the EU27 were the three largest producers and consumers of biofuels, with more than 85% of total production and consumption (EIA, 2015). Biofuels output, adjusted for energy content, accounted for 3.5% of global oil demand for road transport in 2013 (IEA, 2014b).

The US, Brazil, and the EU all have different standards and regulations regarding production and use of biofuels. In 2005, the US introduced a renewable fuel standard (RFS) stating that renewable fuels (with lower GHG emissions than the fuels they replace) must be blended into transportation fuels at an annually increased rate (AFDC, 2015). Today 95% of all US gasoline contains ethanol at typically 10% blend-in rates (i.e., E10). E15 has been approved for use in newer car models, and E85 is sold for flex fuel cars (AFDC, 2015). Brazil, which has the most mature market for fuel ethanol, increased the mandatory blending of anhydrous ethanol to 27% in March 2015 (GAIN, 2015). Pure ethanol is also sold for flex fuel cars. The EU promotes an increase in the use of bioenergy for transportation (EC, 2005). By 2020, the EU aims for each EU nation to derive 10% of its transport fuel from renewable sources such as biofuels (EC, 2009a). Fuel suppliers are also required to reduce the GHG intensity of the EU fuel mix by 6% by 2020 compared to 2010 (EC, 2015a). The EU has defined a set of sustainability criteria to ensure that the use of biofuels (for transport) is done in a way that guarantees real carbon savings and protects biodiversity. Only biofuels that comply with the criteria can receive government support and count towards national renewable energy targets (EC, 2015b). The criteria pertain to GHG emissions from cultivation, production, and transport of the biofuels compared to emissions associated with the relevant fossil fuels, along with restrictions on where the biofuels are grown and from what materials they are produced, in order to reduce the risk of biodiversity loss (EC, 2015b).

After a period of rapid growth, biofuel production and consumption in the US, the EU, and Brazil appear to be shifting gears. In the US, concerns about indirect LUC (iLUC) emissions connected to biofuel production have resulted in debate and policy reviews (in 2010 the US EPA incorporated emissions from iLUC in its renewable fuel standard), contributing to market uncertainty (LUC is discussed further in Section 2.2). In the EU, controversy over iLUC and wider sustainability issues has capped the contribution of conventional crop-based biofuels to the EU target at 7%. To reduce national GHG emissions and respond to the iLUC debate in the US and the EU, Brazil promotes (using economic incentives) pasture intensification, e.g. expansion of sugarcane on degraded pastures that can be intensified (Plano ABC, 2012). In Brazil, the ethanol industry's economic situation is worsening, partly due to inflation-targeted gasoline price regulations that undermine ethanol profitability. The increase in consumption of biofuels started to level off around 2010 in the EU, the US, and Brazil (EIA, 2015). In 2000, these nations consumed (and produced) 97% of all biofuels; in 2012, that number was down to 87% (EIA, 2015). However, biofuel consumption is still increasing in other regions (EIA, 2015). Policy support is growing in non-OECD countries, notably oil-importing economies in Southeast Asia and Africa that subsidize fuel consumption, where rising domestic biofuel production can help lower fuel imports (IEA, 2014b).

The focus in the US and the EU has somewhat shifted away from biofuels based on two main discussions: first, discussion about biofuels negatively impacting global food and feed prices and, second, discussion of the impact of GHG emissions from iLUC on net GHG emissions. Demand for biofuels has contributed to higher food and feed prices globally (see, e.g., OECD-FAO, 2008; Persson, 2014). The United States Department of Agriculture estimates that almost 80% of all corn produced in the US from September 2013 to August 2015 was used for bio-ethanol production (USDA ERS, 2015). However, this number does not include any information on the use of residues. Mumm et al. (2014) state that although 40.5% of US corn grain was channeled to ethanol processing in 2011, only 25% of the corn acreage was attributable to ethanol when accounting for feed co-product utilization. In Brazil, sugarcane covers 14% of all crop area (IBGE, 2013). Increased demand for food and feed, speculation on international food markets, and poor harvests due to extreme weather events, among other factors, have likely also had an impact on global food and feed prices (ELOBIO, 2010; Persson, 2014). Arable land is a finite resource, so an increased global demand for biofuels necessitates finding efficient solutions for biomass, biofuels, food, and feed production.

Bioenergy systems can contribute positively to climate change mitigation but concerns need to be addressed.

(i) Biomass is a limited resource and should be used efficiently; biofuel production often generates by-products that should not be wasted.
(ii) Land use effects need to be considered; both direct and indirect land use change are important.
(iii) Biofuels expansion may cause displacement of land users and cause negative social and economic impacts.
(iv) Measures addressing iLUC concerns need to reflect high quality information about local conditions; understanding farmers' actions and opinions in conjunction with shifting to bioenergy is important.

The overall aim of this thesis is to investigate specific options for improving the management of LU and LUC, the efficient use of resources, and the GHG balances for specific bioenergy systems. The focus is on options for producing biomass-based fuels for the transport sector (biofuels) that integrate with existing food and energy systems. The papers in the thesis study three main areas:

(i) Biomass gasification to produce biofuels and heat for district heating systems in Europe (Paper I).

(ii) Expansion of sugarcane ethanol production in Brazil on the regional (Paper III), state (Paper IV) and national (Paper II) level, where by-products from processing are used as feed or for heat and/or electricity generation to improve the overall efficiency of biomass use.

(iii) Expansion of sugarcane ethanol production in Brazil, where farmers' actions and opinions related to sugarcane (and the frequently connected cattle production) are examined (Paper V).

Chapter 2

Climate impacts of bioenergy

If managed sustainably, biomass is a renewable energy source that can be used as a substitute for fossil fuels to reduce GHG emissions. However, in practice, bioenergy is never fully climate neutral because production, e.g., cultivation, harvesting and transportation, often uses fossil resources and also causes emissions of non-CO_2 GHGs such as methane (CH_4) and nitrous oxide (N_2O) (Figure 1). Further, cultivation of bioenergy crops influences biospheric carbon stocks, the sum of organic carbon in soils and in above-ground biomass, and this may lead to either CO_2 sequestration or additional emissions. Still, as long as the total GHG emissions, including those associated with possible decreases in biospheric carbon stocks (both directly and indirectly), are smaller than the emissions reduction achieved from the fossil fuel displacement, the use of bioenergy leads to a net reduction in CO_2 emissions to the atmosphere.

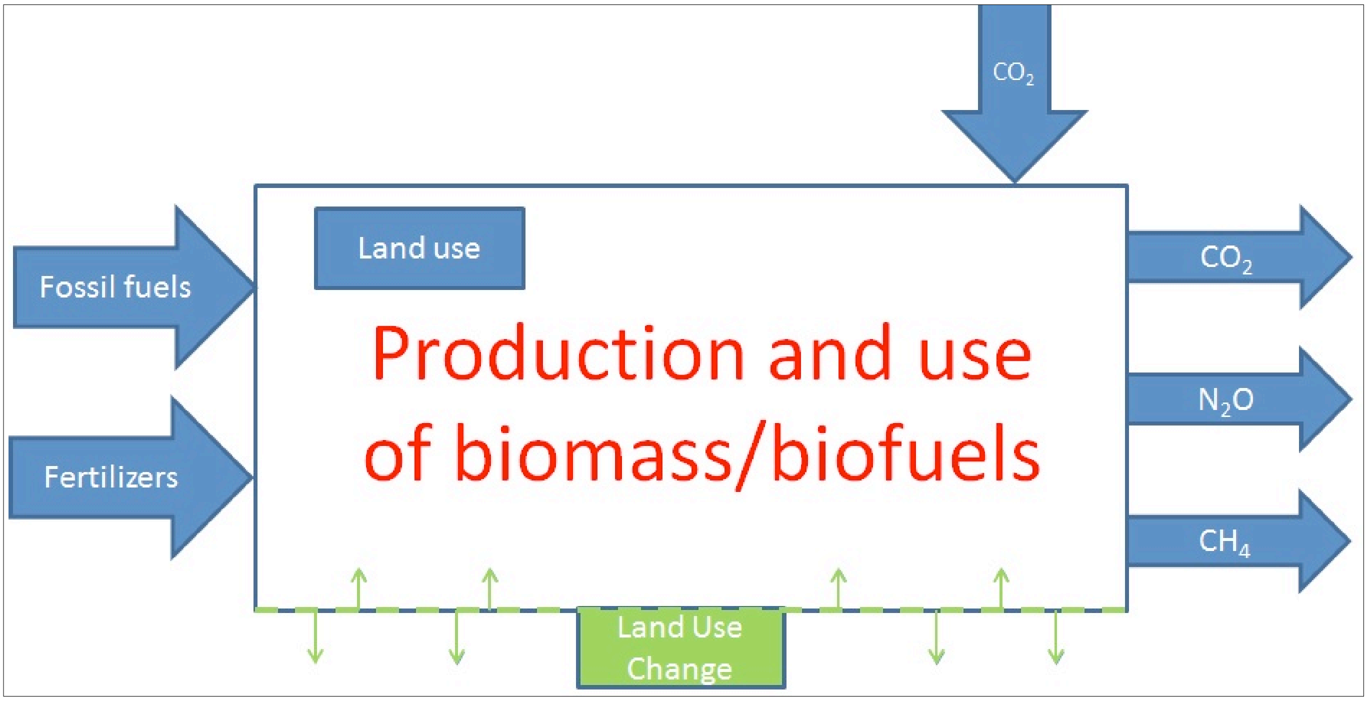

Figure 1 Important inputs and outputs from production of biomass for biofuels.

Strategies to maximize GHG savings from replacing fossil fuels with biofuels need to consider GHG emissions from both biomass cultivation and conversion to biofuels. In the last five years, evaluations of net GHG emissions connected to biofuels have improved. Improved models, e.g. life cycle assessment (LCA) models, and the effort to improve data regarding, e.g., use of by-products, N_2O emissions, biospheric carbon stocks, and iLUC, have changed some earlier results significantly (SCOPE, 2015). The complexity, involving different feedstocks, regions, soils, local land use contexts, and conversion processes, means more data and still better analyses to provide sound support for policies are needed. Default values do not correctly describe the situation for each individual biofuel/production site; more site-specific values are needed. In Papers III–V, we have focused on finding and describing site-specific parameters regarding sugarcane expansion in some regions in Brazil. Effects of bioenergy expansion on rural populations are considered in Papers II, III, and V.

Biomass plantations can lead to impacts other than GHG emissions. Attempts to avoid expansion over ecosystems storing large amounts of carbon (e.g., forests) may lead to other negative effects, e.g., biodiversity impacts or increased competition for water resources. These kinds of consequences are beyond the scope of this thesis.

2.1 Emissions from production of biomass for use as biofuels

Emissions from production of biomass for use as biofuels often include emissions from production of machinery and buildings; emissions from production of fertilizers, pesticides, herbicides, and insecticides; emissions from transports to and from fields and machine operations in fields; emissions from use of nitrogen fertilizers; emissions from production of biofuels; and emissions from transport of biofuels to markets. Avoided emissions from use of biofuels and avoided emissions from use of by-products (if relevant) are also often included when calculating total emissions from biofuel production.

Many studies of GHG emissions from the production of Brazilian sugarcane ethanol are based on the work by Macedo et al. (2004; 2008). However, improved data on the use of the by-product bagasse (see Chapter 3) and N_2O emissions are available (SCOPE, 2015).

Nitrogen fertilizers are applied to biomass plantations to supply plant nutrients essential for plant growth, causing large GHG emissions; in the systems study in Paper III and Paper IV, almost 20% and roughly 25%, respectively, of all GHG emissions from production, change in soil carbon and transport to EU (iLUC emissions not included) stem from nitrogen fertilizer use. The amount of nitrogen fertilizer needed and the resulting rate of N_2O formation in the soil depend on many factors, e.g., type of plant, soil composition (moisture, oxygen concentrations, available organic carbon and nitrogen, and the C/N ratio), harvesting management (which has an impact on, e.g., available carbon and nitrogen and the C/N ratio), and climate (affecting precipitation and temperature) (Signor and Cerri, 2013). Thus, N_2O emissions from nitrogen fertilizer use are variable and uncertain. However, factors related to soil could be altered by management practices. Therefore, understanding the processes of N_2O formation in soils and the factors influencing these emissions is fundamental to developing efficient strategies to reduce N_2O emissions in agricultural soils (Signor and Cerri, 2013). The nitrogen product and rate, time, and place of application have a large impact on N_2O emissions from nitrogen fertilizer use on sugarcane (Fertcare, 2015), and nitrification inhibitors have been shown to reduce N_2O emissions in sugarcane production in Brazil (Soareset al., 2015).

2.1.1 Methods commonly used to calculate production emissions

Studies of environmental effects, including those focused on energy balances and GHG emission balances, usually employ methodologies in line with the principles, framework, requirements, and guidelines in the ISO 14040:2006 and 14044:2006 standards for LCA. The EU Renewable Energy Directive specifies a method to calculate default values for GHG emissions from production of biofuels (EC, 2009a: *Annex V part C*). Emissions are summed and avoided emissions subtracted, but emissions from iLUC are not included. The US EPA performs lifecycle GHG emissions analyses (including direct and indirect LUC emissions) for different biofuels (US EPA, 2010). Even though default values are known not to correctly describe GHG emissions from all different biofuels (since, e.g., LUC and N_2O emissions may vary substantially for the same crop depending on the production site), such values are used in both the EU and the US to evaluate different biofuels. Default values are used because the alternative would require evaluating every producer at each production site.

Papers III and IV use the BIOenergy net GreenHouse Gas emissions (BIOGHG) model, a dynamic model describing an existing and expanding sugarcane ethanol production system in Brazil, to calculate recurring production GHG emissions. Paper II uses a previous, simpler, version of the model. From a given production scenario, cumulative and annual net GHG emissions are calculated. The BIOGHG model quantifies both GHG emissions and savings associated with sugarcane and ethanol production and net change of carbon in soils at the site of the sugarcane production. The ethanol is assumed to be transported by truck to the Brazilian coast and shipped to the EU, displacing conventional gasoline use in cars (with no consideration of possible gasoline market effects affecting displacement efficiency). Only transport emissions associated with the ethanol transport are considered; i.e., GHG emissions associated with return trips for trucks and tankers are not included. The results from the model regarding production emissions are consistent with EU default values (see Paper IV for a comparison). BIOGHG does not consider iLUC emissions.

2.2 Carbon stocks, land use and land use change

The establishment of biomass production systems to provide bioenergy feedstocks can influence biospheric carbon stocks. For example, if forests are converted to cropland, large CO_2 emissions occur. Conversely, if perennial plants are planted on marginal lands with carbon-poor soils, atmospheric CO_2

may become assimilated in the soils and aboveground biomass. Emissions (positive or negative) connected to LUC are typically called LUC emissions, which can be either direct or indirect, iLUC emissions.

For well-drained soils, the equilibrium content of soil organic carbon (C) depends mainly on biomass input, climate (particularly temperature and precipitation), and soil composition (particularly clay content and the C:N ratio). In agricultural soils, tillage also affects the equilibrium content of soil organic C. The absence of frequent tillage on pasture land is likely to explain part of the generally observed higher C levels in pastures relative to cropland in Brazil (see, e.g., Cerri et al., 2011; Franco et al., 2015; Galdos et al., 2009; Maia et al., 2009). Mello et al. (2014) studied 135 different sugarcane sites in Brazil and found that, on average, it takes two to three years to pay back the soil carbon loss after converting pastures to sugarcane fields. Regarding sugarcane production, management practices (e.g., amount of residues left after harvest) can help improve, e.g., the soil organic C content (Cherubin et al., 2015).

When biomass plantations expand on, e.g., pastures used for meat production, this also causes iLUC. To compensate for the drop in supply, meat production is established on new pasture areas and intensified on remaining pastures. Depending on where the new pastures are established, these iLUC emissions can vary a lot. If, e.g., dense forest with high carbon content is converted into pasture, this will lead to high LUC emissions, and replacing gasoline with biofuels may not lead to net GHG savings for many years. Similarly, if cropland previously used for food production is instead used for the cultivation of biofuel feedstock, the reduced food output will drive up food prices, which can lead to changes in both consumption and land use. Intensification on cropland often produces less of a gain in yield compared to pasture, because cropland typically starts from a higher baseline.

High net GHG savings from biofuels require both LU and LUC emissions to be kept sufficiently low (see, e.g., SRREN, 2011; SCOPE, 2015). Quantifying the iLUC associated with a given biofuel project is difficult, and whether biofuel production should be made responsible for effects that are directly caused by other activities, with only an indirect link to a certain biofuel project, is under debate.

2.2.1 Estimates of land use change

Even though the significance of LU and LUC was demonstrated in the 1990s when direct LUC effects were considered in LCA studies (e.g., Reinhardt, 1991; DeLuchi, 1993), it was rarely discussed outside the scientific community. However, in 2008 the study of iLUC emissions by Searchinger et al. (2008) received considerable attention. More recent iLUC estimates are lower as models have been updated to consider improved efficiencies in feedstock production, decreasing deforestation rates, and increasingly stringent regulation of agricultural practices (Figure 2), although large uncertainties remain (Verstegen et al., 2015).

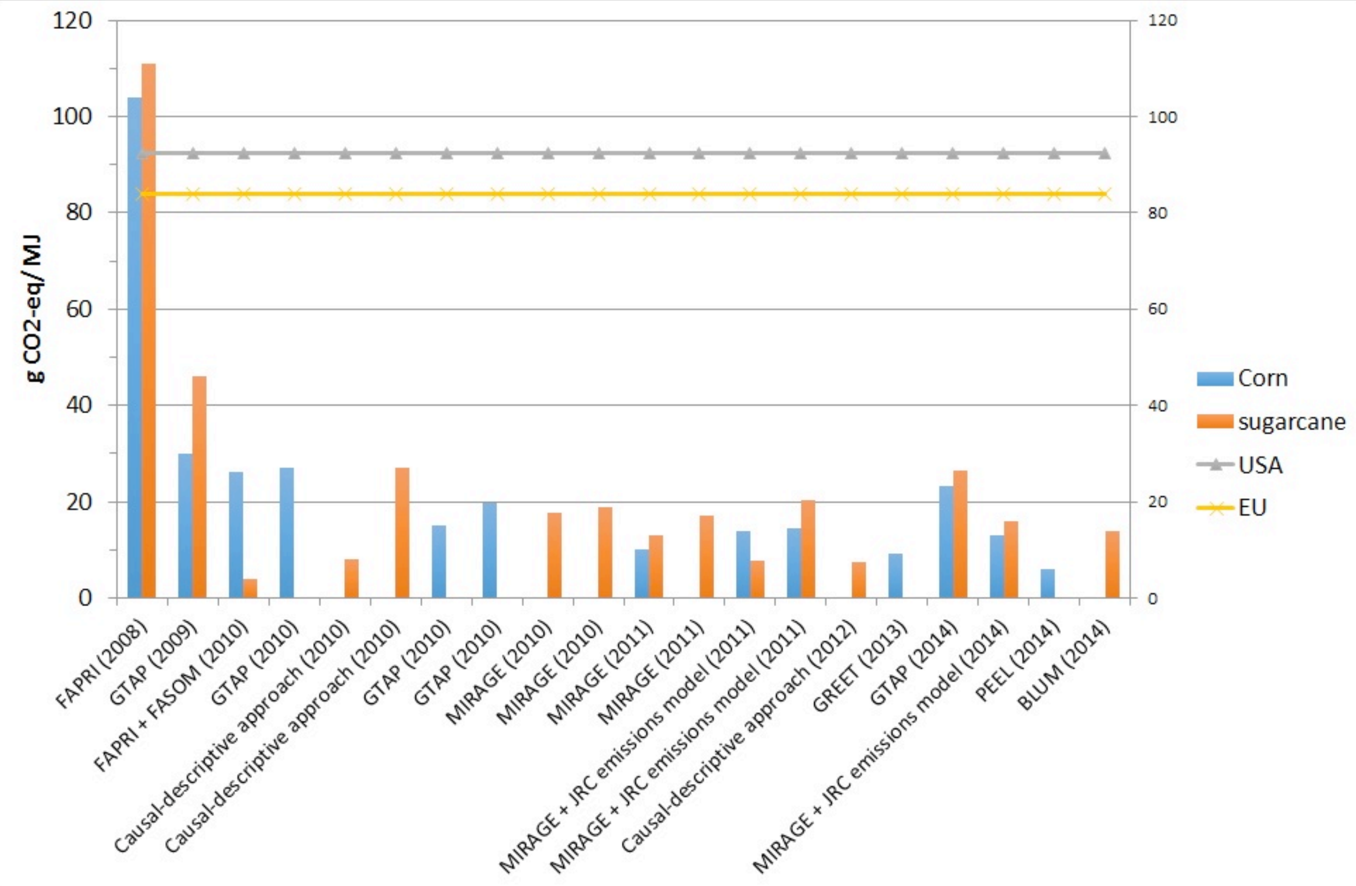

Figure 2 Modeled iLUC emissions for the two major ethanol feedstocks, corn and sugarcane, showing method/model used and publication year. FAPRI 2008 is equal to the results presented in Searchinger et al., 2008. When a study reports a range for iLUC emissions, two bars are shown in the figure. Reference emissions for petroleum fuels in the EU and the US are included in the diagram. Based on data from Macedo et al. (2014).

Many studies have found that, when excluding iLUC, production and use of Brazilian sugarcane ethanol cause considerably less GHG emissions than gasoline (Paper IV; Galdos et al., 2013; Macedo et al., 2008). Studies have also investigated whether deployment of sugarcane ethanol in Brazil causes any significant GHG emissions due to iLUC. The results of these studies vary (Figure 2), which is to be expected since different methods, models, and databases are used.

In 2015, new rules came into force in the EU, amending the current legislation on biofuels to reduce the risk of iLUC and to prepare the transition towards advanced biofuels (EC, 2015c). In the EU, iLUC emissions are not included in GHG emissions calculations of biofuels, but fuel providers, EU countries, and the European Commission must report on iLUC. The US EPA (US EPA RFS2, 2010) calculates GHG emissions from LUC (direct and indirect). In Brazil, regulations to avoid iLUC aim at directing expansion to pastures and banning illegal deforestation in the Amazon (Plano ABC 2012; BRAZIL iNDC, 2015). However, findings in Paper IV indicate that a future expansion of sugarcane plantations may to a significant degree take place on cropland, unless regulations/incentives prevent this. Also, Brazilian regulations permit vast amounts of additional deforestation (Smith et al., 2015).

2.2.2 Methods commonly used to calculate emissions from change in carbon stocks (stemming from land use and land use change)

Existing quantification methods regarding emissions from LU and LUC either employ approaches where global LUC is allocated to specific biofuels/feedstocks grown on specified land types (e.g., Garg et al., 2011; Lapola et al., 2010; PRB, 2008), or economic equilibrium modeling that integrates biophysical information and/or biophysical models (e.g., Gesch and Archer, 2013; Heggenstaller et al., 2008; Langeveldt et al., 2014; Berndes et al., 2008).

In the EU Renewable Energy Directive (EC, 2009a), emissions from land use and direct LUC are calculated by using IPCC guidelines (IPCC, 2006). In the US, the partial general equilibrium model FASOM is used to calculate direct and indirect LUC emissions from biofuels produced domestically (US EPA RFS2, 2010). The FAPRI model, a global agricultural sector economic model, is used to estimate the direct and indirect LUC impacts of biofuels feedstock production on international agricultural and livestock production (US EPA RFS2, 2010).

In Papers III and IV, we have used the BIOGHG model to calculate GHG emissions from direct LUC. In the BIOGHG model, feedstock (sugarcane), harvest type (manual or mechanical), and land type (cropland, degraded pasture or well managed pasture) are used to quantify GHG emissions (see Table 1 for assumptions on soil carbon levels).

Table 1. Soil carbon content in the top soil (0-30 cm) for different land use types before and after a change to sugarcane

	Paper III Degraded pasture (ton C/ha) [a]	Paper IV Well managed pasture (ton C/ha) [b]	Paper IV Degraded pasture (ton C/ha) [b]	Paper IV Crops (not sugarcane) (tonC/ha) [b]
Original carbon content in soil	40	60	40	30
New soil carbon equilibrium, burning before manual harvest	28	40	40	40
New soil carbon equilibrium, no burning before machine harvest	38	50	50	50

[a] The values are based on communication with Carlos Cerri, Department of soil science, ESALQ/USP, Piracicaba, Brazil. Personal communication, November 2006.
[b] The values are based on Maia et al, 2009; Galdos et al., 2009; Cerri et al., 2011 and IPCC, 2006.

2.3 Bioenergy, a part of the energy system

Currently, biofuels can be used to replace, e.g., gasoline in the transport sector. Biofuels could also limit further development of transport fuels based on coal or tar sands. However, by offering a means for reducing GHG emissions, biofuels could also slow down electrification of transport, including development and deployment of electric cars. Biofuels could also reduce the price for transport fuels and allow for transport to increase. In addition to potentially reducing GHG emissions, biofuels can be used to improve energy supply security and create employment opportunities.

Chapter 3
Efficient use of resources

Since biomass is a land-demanding resource and land is a finite resource, biomass should be used efficiently. Efficient biomass use for energy is expected to become a high priority as demand for bioenergy increases. Efficient conversion processes and the production of several products from the same feedstock are two important efficiency factors.

Co-generation of heat and power is promoted in the EU (EP&C, 2004), but heat can also be co-generated with biofuels. When the heating value of waste heat is too low to be used for electricity production, the heat can be used in district heating systems or as process heat in some applications instead of being wasted. Biomass gasification with subsequent synthesis to make liquid or gaseous biofuels is under development. Lignocellulosic crops, forest wood, residues, and organic waste can be used as feedstock for this type of biofuel. A number of development and demonstration projects are in progress and biomass gasification technology for small-to-medium scale power generation is close to commercialization (EC, 2016). In order to improve the overall energy efficiency (and economic viability) of the process, biofuel plants employing gasification can be designed and located so that some of the surplus heat can be used in district heating systems (see Paper I). Here, these plants are designated CBH (Combined Biofuel and Heat) plants. Excess heat from CBH plants can be used in other heat sinks, too, e.g., the fermentation process in ethanol production. These other heat sinks are beyond the scope of this thesis.

Biofuels produced from common agricultural food/feed crops, such as ethanol from sugarcane, sugar beet, wheat, or corn and biodiesel from, e.g., oil palm, soy, and rapeseed, have been available for many years. Residues from biofuel production can sometimes be used as animal feed or used for heat and/or electricity production. When residues are used to replace traditional feed, less traditional feed needs to be produced, reducing the demand for land. Residue-based feed can also be used to reduce demand for pasture land; in Brazil, vast areas of pasture are needed for cattle ranching during the dry season unless supplementary feeds are used. Residue-based feed as a means toward reducing pasture land is studied in Papers II and III.

Papers II–V investigate bioethanol from sugarcane. On a dry matter basis, the sugarcane plant consists of roughly equal shares of sugar (used for ethanol or sugar production), bagasse (the fibrous, non-sugar part of the stem), and tops and leaves (often left at the fields if not burned before harvest). In early 2000, the average mill in São Paulo consumed almost 95% of the bagasse to cover internal energy demands – best practice: 80% (Marcelo et al., 2004). The left-over bagasse was often sold to other industries (orange juice mills and pulp and paper mills) as process fuel (Macedo et al., 2004), and some mills used it to produce electricity to sell to the grid (SCOPE, 2015).

Until 1995, 120 mills (roughly half of all mills) had the equipment to produce animal feed from surplus bagasse (Paper II). However, with the deregulation of the power sector in 1999, the sugarcane industry was able to increase resource efficiency and afford the more efficient equipment required to generate electricity, an additional product with guaranteed revenue. Electricity production to the grid increased (Chum et al. 2015), and, in 2010, bagasse-based electricity became the third largest electricity source in Brazil (Silva et al., 2014). As the opportunity to produce electricity from bagasse grew more widespread, animal feed from bagasse became rare. In 2007, the number of mills with equipment for feed production was down to 30 (Paper II). Today, there are fewer still.

Since the practice of burning sugarcane fields before harvest is being phased out in Brazil, more biomass could become available for various purposes. Tops and leaves left unburned in the field may provide several benefits: increased soil organic matter, reduced soil erosion, recycling of nutrients, stable soil temperatures, reduced water loss by evapotranspiration, and reduced weed infestation (Cerri et al., 2011; Monquero et al., 2008; Gava et al., 2001; Oliveira et al., 1999).

On the other hand, these residues are a valuable raw material for the mills, for producing electricity or, in the future, additional volumes of ethanol. If large amounts of tops and leaves are left in the field, some negative aspects need to be considered, such as an increased risk of accidental fires, increased incidence of pests, and reduced sprouting, leading to lower sugarcane productivity (Magalhães et al., 2012; Rosetto et al., 2008; Cardoso et al., 2015). Dias et al. (2011) found that half the tops and leaves could be taken from the fields without negatively impacting the benefits of leaving it. Recovery of tops and leaves is being tried by several mills to increase surplus power generation, to extend power generation into the off-season, and to improve the capacity factor of existing facilities (Smith et al., 2015).

However, transportation of tops and leaves to the mill is not an industrial reality yet, due to costs and because the few mills that do use it for electricity production only use a fraction of the total available tops and leaves (personal communication, Marina Dias, National University of São Paulo (UNIFESP), September 2015).

Typically, every five years, the sugarcane fields in Brazil are renewed, the old stems are removed, and new stems are planted (see Section 4.5, “The sugarcane cycle”). In the interim[1], some months to a little less than one year, rather than leave the fields fallow, farmers have recently integrated other food crops (mainly soy and peanuts) (Smith et al., 2015). This production system is more efficient, reducing the demand for land.

[1] In the center-south of Brazil, where São Paulo state is located, sugarcane is often planted between May and October and harvested between April and November.

Chapter 4
The Brazilian context

Brazil is the world's fifth-largest country, with 200 million inhabitants and a total area of more than 850 Mha (consisting of more than 60% forest (528 Mha), 18% pasture (157 Mha), and 7% cropland (61 Mha)) (Lossaou et al., 2015). Sugarcane plantations cover less than 4% of the total agricultural area (cropland and pasture) (IBGE, 2015), and in 2012 the sugarcane industry accounted for almost 2% of Brazil's GDP (SugarCane Org., 2016). Roughly half the sugarcane is used for ethanol production, and Brazil is the world's second-largest ethanol producer.

4.1 Brazilian land rights over time

Starting in 1530, the Portuguese gave away Brazilian land to those willing to farm the land and pay one-sixth of the harvest in tax (INCRA, 2016). Violent land conflicts began in 1822, when Brazil became an independent state, the Empire of Brazil (INCRA, 2016). In 1850, the emperor tried to settle the conflicts, banning the practice of claiming land by occupying it, instead requiring cash payments for public land (INCRA, 2016). However, this made it difficult for small holders to acquire new land and illegal occupation continued. In 1934, Brazil joined an ongoing trend in Latin America towards adoption of the social function principle (i.e., the principle according to which the right of private ownership includes an obligation to use land in ways that benefit society as a whole) (Ondetti, 2016). According to the 1946 Constitution, private property could be expropriated by the state on the basis of "social interest" (Ondetti, 2016). The state had to compensate the owner in cash, making it difficult for the state to acquire land. In the 1950s and 60s, land reform became a hot topic, contributing to the military coup in 1964 (INCRA, 2016). In order to calm the land-reform debate, the military regime (1964-1985) made it possible for the state to compensate expropriated land-owners with bonds (Brazilian Law, 1964). However, not much happened until 1985, when the civilian regime instituted the National Plan for Agrarian Reform (Agrarian Act, 1985), aiming at settling 1.4 million families on 43 million ha by 1989.[2] In addition to the shift to less conservative presidents since then, the emergence of a well-organized grassroots movement for agrarian reform anchored by the Movement of Landless Rural Workers (Movimento dos

[2] By 1989 they had settled roughly 83,000 families on almost 4.5 million ha (INCRA, 2016).

Trabalhadores Rurais Sem Terra, MST) has been important (Ondetti, 2016). The settlers described in Paper II (the case study) and Paper III have received their land through this land reform and by help from MST. Recently, there has been considerable skepticism in Brazil regarding land-rights reform. President Rousseff, despite belonging to the historically pro–agrarian reform Workers' Party, has not made rural land redistribution a priority. Moreover, this policy has few vocal defenders among prominent political figures (possibly explained by the large number of large landowners and their supporters in Congress) and numerous critics in the news media and academia (Ondetti, 2016). Also, Brazil's good economy in the last decade, contributing to very low unemployment rates, has dampened the calls made by the poorest for enforcement of the land rights reforms. However, the issue is gaining prominence once more, with the new Brazilian depression, unemployment figures rising, inflation, etc. (personal communication, Alberto Barretto, ESALQ, Piracicaba, Brazil, February 2016).

4.2 Legislation of land use

About 65% (almost 570 Mha) of Brazil is covered by natural vegetation, roughly equally divided between private owners and public conservation areas (Freitas et al., 2015). Since 1965, the forest code states that private landowners have to keep a certain share of natural forest as legal reserves on their property (Brazilian law, 1965). In the 1990s, the law was updated to also require that sensitive areas (areas close to water and areas sensitive to soil erosion) be preserved and maintained (Soares-Filho et al., 2014). The forest code severely restricted deforestation on private property but proved challenging to enforce, particularly in the Amazon (Soares-Filho et al., 2014).

Due to the introduction of different conservation policies in Brazil in 2004, including, e.g., a remote-sensing-based monitoring and enforcement program (CPI, 2015), deforestation rates dropped in the Amazon in the beginning of the 2000s, and agribusiness lobbies took advantage of this by suggesting a revised forest code (Soares-Filho et al., 2014). In 2012, the Brazilian parliament passed the revised forest code (Brazilian law, 2012). During our interviews in Brazil in early 2013 (Paper V), all interviewed farmers in São Paulo said they were waiting for clarification of the new law. The new forest code still protects natural vegetation on geographically delimited areas regarded as the most environmentally sensitive, e.g., riparian floodplains, steep slopes, and high altitudes, and defines a variable percentage of the farmland to be preserved, ranging from 80% in the Amazonian Forest biome to 20% in most other parts of Brazil (Sparovek et al., 2012). However, the recent revision of the Brazilian forest code resulted in weaker protection of natural vegetation and less demanding requirements on restoration planting and promotion of natural regeneration on agricultural land (Sparovek et al., 2015). Interestingly, during the interviews performed for Paper V, we discovered that the sugarcane industry is enforcing the law on farmers delivering sugarcane to their mills. The two operating mills in Quirinópolis, Goiás, only buy sugarcane from farmers who have legal reserves and riparian areas. The industry also assists in planting riparian areas when the farmers need help. In the cases in which farmers in São Paulo said they were waiting for clarification of the law, post-interview analysis suggests that farmers were not waiting for clarification from federal or state authorities but from the relevant sugarcane mills. The clarification concerned requirements for legal reserves as well as permanent protection areas around water bodies on their properties.

4.3 Reducing national greenhouse gas emissions

In September 2015, Brazil pledged to reduce its GHG emissions by 37% below 2005 levels by 2025 and set a goal of reaching a 43% reduction by 2030 (BRAZIL iNDC, 2015), targets to be met by:

(i) Increasing the share of sustainable biofuels in the Brazilian energy mix by, e.g., expanding biofuel consumption and increasing ethanol supply;

(ii) Strengthening and enforcing the implementation of the Forest Code, at federal, state, and municipal levels, strengthening policies and measures with a view to achieve, in the Brazilian Amazonia, zero illegal deforestation, restoring and reforesting forests for multiple purposes, and restoring degraded pastures, directing sugarcane expansion to degraded pastures and promoting cropland-livestock-forestry systems by providing subsidized loans (Plano ABC, 2012);

(iii) Expanding the use and production of renewable energy sources for electricity other than hydropower, i.e., wind, biomass and solar, in the total energy mix.

4.4 Sugarcane and the proalcool program

Reputedly, the first sugarcane was planted in Brazil in 1516 in order to produce sugar for the European market (Johnston, 2015). The production of Brazilian bio-ethanol for blending in gasoline dates back to 1931, with the construction of the Institute for Sugar and Alcohol (Institution do Açúcar e do Álcool (IAA)) and legislation requiring engine additions that made ethanol blends possible. Since 1931, gasoline mixed with up to 40% anhydrous ethanol (gasohol) has been used as an automotive fuel (Geller, 1985). However ethanol was not used in any significant amounts until the 1970s (Goldemberg, 2008).

1975–1985

When the 1970s energy crisis began, Brazil was importing 80% of its oil supply (de Oliveira, 1991); in 1973, the oil price quadrupled (Geller, 1985). On top of this, global sugar prices dropped considerably in 1975 (Geller, 1985). Therefore, in November 1975, the Brazilian government launched two programs to reduce dependency on imported oil: i) *the oil program*, to search for oil domestically, and ii) *the pro alcohol (proalcool) program*, to increase ethanol production from sugarcane to substitute for gasoline (de Oliveira, 1991). At first, the proalcool program sought to get national sugar producers to diversify their production by adding distilleries to their sugar mills (de Oliveira, 1991). However, in order to reach the targets for 1985, new sugarcane producers producing ethanol in pure ethanol mills were needed (de Oliveira, 1991). By 1981, 70% of sugarcane mills approved by the government were stand-alone ethanol mills (Geller, 1985). The targets set for 1985 were met (de Oliveira, 1991).

In 2006, we interviewed settlers in Pontal do Paranapanema (Pontal), São Paulo state, about their opinions on ethanol production (Papers II and III). At that time, there were two or three small-scale stand-alone mills (only producing ethanol) operating in the region. Their poor performance likely influenced the settlers' negative opinions on sugarcane. During our interviews in Pontal in 2013, the settlers' opinions had shifted towards more positive attitudes. Six new plants had been built after 2006 (UDOP, 2016), and many of the settlers were working with the sugarcane industry. The new jobs led to increased salary levels in the region, and this in turn boosted local markets (Interviews for Paper V; personal communication, Flavio Freitas, KTH, Stockholm, Sweden, January 2016). Also, in 2006 large-scale farmers in Pontal had extensive beef production on degraded pasture land, which, by law, could be taken by the state for the agrarian reform (see Section 4.1, Brazilian land rights over time). Sugarcane has made this process more difficult since sugarcane is a productive land use with strong political support. This, too, has likely affected the settlers' opinions.

1986–1995

In 1990, ethanol replaced half of the Brazilian demand for gasoline (Moreira and Goldemberg, 1999). Meanwhile, world market sugar prices recovered and sugar exports increased, leading to significant shortage of hydrous ethanol (for fueling pure-ethanol cars) in the 1989/90-season (Moreira and Goldemberg, 1999). Anhydrous ethanol continued to be blended (often at a 22% rate) with gasoline (Rosillo-Calle and Cortez, 1998). The federal government promoted increased productivity among ethanol producers in order to cut production costs (Rosillo-Calle and Cortez, 1998) and increase production. Due to technical and institutional problems, surplus bagasse is not used as a substitute for fuel oil in other industries or for producing electricity to the grid (de Oliveira, 1991). However, 120 mills have the equipment to make feed out of bagasse (Paper II) to increase productivity and revenues.

1996–2005

In the period 1996 to 2005, the Brazilian inflation rate was brought back to normal[3], creating a more stable economy (den Wall Bake et al., 2009). The government could reduce its interest in the sugarcane sector and fulfill complete deregulation of anhydrous ethanol in March 1997 and hydrated ethanol in February 1999 (Goldemberg et al., 2004). Since then, the government has not directly determined the price of ethanol. At this point, the government only had the gasohol blend-ratio left as a policy tool for directly affecting market supply and demand of anhydrous ethanol (den Wall Bake et al., 2009). Production of hydrated ethanol was boosted by the introduction of the flex-fueled vehicle (FFV) in 2003 (den Wall Bake et al., 2009). As oil prices kept rising, FFV sales became a great success, with a market share of nearly 20% in the first year and nearly 80% in December 2005 (Joseph, 2005).

3 Between1980 and 1994 the Brazilian government financed its operation and its development projects not out of taxes or borrowing funds but simply by creating money. This lead to high inflation rates and hyperinflation.

2006–2015

During the 2008 financial crisis, the Brazilian sugarcane sector found itself highly indebted and unable to obtain money from the banks to finance operational costs. Consequently, mills had to cut expenses. They did so by reducing the application of fertilizers and herbicides, postponing sugarcane field renewals, and laying off personnel. These actions had an immediate and lasting impact on sugarcane yield and quality. Weather problems added to the problem (excess rain in 2009, drought in 2010, and frost and sugarcane flowering in 2011). In 2010, the 20-year-long trend of increasing yields (except for one low year in 2000) came to an end (IBGE, 2016). However, other production costs, including chemical inputs, labor, and land rents, increased sharply, mainly because of higher oil prices and a shortage of qualified labor in the agricultural sector. During our interviews for Paper V, farmers stated that the lack of qualified labor made it difficult for them to maintain or start activities that would have increased productivity but required qualified labor. Fortunately, the sector identified the problems associated with past actions and contexts, started correcting them by accelerating sugarcane field renewal, and took precautions to plant better quality seeds and reduce the negative impacts of mechanization (soil compaction and damage to ratoons (shoots)). The government also helped by making money available to finance sugarcane-planting activities. With this, yields increased in 2013 (IBGE, 2016). However, yields dropped again in 2014 due to weather events. In São Paulo state, yields were the lowest since 1990 (IBGE, 2016).

On the political side, the central issue is the government policy to maintain gasoline prices for the domestic market below international prices, thus reducing the competitiveness of ethanol at filling stations. To prevent inflation, the government kept gasoline prices constant at the pump between 2005 (Jank, 2013) and 2014, in spite of escalating international oil and gasoline prices (Smith et al., 2015). The sugarcane sector has seen some rough years, but sugarcane ethanol and bioelectricity produced from leftover fibers, stalks, and leaves make sugarcane the largest source of renewable energy in Brazil (SUGARCANE, 2015) and it bagasse is third largest electricity source (Silva et al., 2014). Sugarcane provides 16% of the country's total energy needs, second only to oil and ahead of hydropower. More than 40% of the country's demand for gasoline is met by sugarcane ethanol (SUGARCANE, 2015). In 2014, sugarcane mills supplied about 4% of Brazil's electricity requirements (SUGARCANE, 2015).

4.5 The sugarcane cycle

The complete sugarcane crop cycle in Brazil is variable, depending on local climate, varieties, and cultural practices. The cycle usually takes six years, with five harvests and four ratoon-cultivation treatments. The sugarcane yields decrease annually within each cycle. Unless otherwise indicated, the BIOGHG model (Papers III and IV) considers the sugarcane cycle described below. [4]

The sugarcane cycle begins with liming. Lime is applied before the soil is prepared to help distribute the lime evenly as it is not very mobile in soil. During the preparation of the soil, the topsoil and the subsoil

---

[4] This Section is based on Macedo et al., 2004 and Macedo et al., 2008, unless otherwise indicated.

(50 cm depth) are ploughed to destroy old root systems and to prepare the soil for better water drainage.[5] After plowing, rows are made, and fertilizers (nitrogen, phosphorous, and potassium) are added. Cut-up sugarcane stems (called stocks) from the previous harvest are put down in the rows. Preferably, 12 plants per meter should start to grow, but 12–18 stocks per meter are often planted. Putting down stocks can be done manually or mechanically. When sugarcane stocks are put in the ground to start the new production cycle, more stems are needed compared to when seedlings are produced beforehand from the stems and then planted at the site.[6] The stocks are covered with soil, but just before the soil is put down they are sprayed with insecticides, fungicides, beneficial nematodes, and a booster to stimulate good root systems.[7] When the stocks are covered, the soil is sprayed with herbicides. It takes 90–120 days until the sugarcane is high enough to cover the ground, so herbicides might be sprayed once more.
Two common insects need to be treated when the plant has started to grow: i) Broca-da-cana-de-açúcar (*Diatraea saccharalis*), which bores the plants and contaminate it leading to reduced sucrose yields. This insect is controlled by flies to 80%, but if that doesn't work insecticides are sprayed from aircraft; and ii) Cigarrinha-da-raiz – (*Mahanarva fimbriolata*), which eats the sap and also deposits toxic waste in the plant. This insect is always sprayed from aircraft; no natural predators exist. Sometimes sugarcane is affected by rust. Depending on the sugarcane variety, aerial spraying is done 0–3 times per year.

The first harvest takes place approximately one year after planting. Sugarcane is harvested either manually or by machine (mechanical harvest). Manual harvest is normally preceded by burning the fields, in order to scare away wild animals and make the harvest less time-consuming. Mechanical harvest is rarely preceded by burning, although it does happen. São Paulo State law (2008) stipulates that burning should be phased out by 2021, in large and flat areas suitable for mechanical harvest, and by 2031, in small and sloping areas not suitable for mechanical harvest. In 2008, the sugarcane industry union (UNICA, 2009) signed a protocol in which its associates (individually and voluntarily) decided to phase out field-burning before harvest by 2014, in areas suitable for mechanical harvest, and by 2017, in areas not suitable for mechanical harvest. In 2012 Piracicaba and some other regions in São Paulo state banned field-burning all together due to its negative health impacts (Ministerio Publico, 2012).

After each harvest, herbicides are sprayed once, and fertilizers (nitrogen and potassium) are added again. The stocks are left in the ground, and new shoots – ratoons – grow from them. This step is performed four times in four years. After the fifth harvest (the fourth ratoon crop), the field is left fallow for a little less than one year. Sometimes soy, peanuts, or other nitrogen-fixing plants are produced during the fallow period.[8]

---

5 CO_2 emissions from usage of machinery at the fields are taken from Macedo et al. (2004), excluding emissions from aircraft used for spraying, which are not included in BIOGHG as spraying from the air is a relatively new action.

6 Planting seedlings is not common practice yet and not modelled in BIOGHG.

7 Regarding insecticides, fungicides, beneficial nematodes and boosters, only emissions from production of insecticides are included based on that being the only available data from Macedo et al. (2004).

8 This use of land is not included in BIOGHG.

Chapter 5
Conclusions

The overall aim of this thesis was to investigate specific options for management of land and resources associated with two bioenergy systems, were resource use and GHG balances were the main concerns.

When biomass is gasified to produce biofuels, excess heat is generated. The heat that cannot be used for electricity generation, due to too low heating value, can be used is district heat systems or as process heat. In Paper I we found that – if biofuels corresponding to the EU 2020 biofuel target was produced – such excess heat could meet about 15% of the total heat demand in the existing district heat systems in the 20 EU countries that have substantial district heat systems. Roughly 80% of all heat in EUs district heat systems are today produced in heat-only boilers and combined heat and power (CHP) plants that use fossil fuels. Assuming that the CHP plants continue producing electricity, the use of excess heat from biomass gasification can improve the efficiency of biomass use by roughly 20%, but the contribution to reaching targets for CO_2 emissions reduction would be relatively small (the reductions correspond to about 0.1% of the total GHG emissions in the 20 EU countries in 1990).

Surplus bagasse can be used to produce electricity, replace fuel oil used for heat, and provide animal feed. In Paper III and IV we found that all three uses have advantages, including GHG emissions reduction and improved economy for farmers. Substituting heat from fuel oil burners is estimated to reduce net GHG emissions slightly more than substituting oil based electricity generation: 62 compared to 54 kg CO_2/ton sugarcane. If bagasse is used as animal feed, GHG emissions from displaced feed production is avoided. If the use as feed displaces grazing, the need for pasture land can be reduced 40–70% depending on circumstances (e.g. the productivity on the remaining pastures).

The localization of new sugarcane plantations obviously affects the land use where the sugarcane planting occurs (direct LUC), but may also influence the extent of indirect LUC. In Paper IV we found that if sugarcane mills would be built in the locations in São Paulo state where construction approvals exist, the associated sugarcane expansion will most likely mainly occur on cropland. Further, we found that soil carbon emissions associated with sugarcane planting and cultivation has a quite small effect on total GHG emissions when expansion takes place on cropland or pastures, and even smaller effect when mechanical harvesting is employed, i.e., when pre-harvest field burning is not taking place. Land productivity improvements in meat and dairy production can accommodate sugarcane expansion by reducing the need of pasture lands to meet food demand. The scope for land productivity improvements is generally smaller on croplands than on pastures in Brazil, i.e., there is less possibility to mitigate displacement of food production and iLUC. Expansion on cropland also conflicts with the federal government's policy of directing sugarcane expansion to degraded pastures.

Obviously, how land is used in a given location depends on what the landowners decide to do with it. Thus, land owner decisions are important to consider when land use change effects are studied. In paper V, we interviewed Brazilian landowners and farm managers who have shifted fully or partially from pasture-based beef or milk production to sugarcane production or to leasing land to sugarcane producers. We found that most of the interviewees consider it important to be "environmentally friendly", which they consider being equal to complying with environmental laws and regulations and following the rules set by the sugarcane industry. Illegal deforestation was objected to but the interviewees had no objections against legal deforestation for the purpose of creating new cropland or pastures. In Brazil, vast areas can still be deforested legally. Our interviews suggest that implementing strict regulations regarding, e.g., forest protection will be important to avoid unwanted LUC.

Chapter 6
Reflections on future research

Since the deregulation of the electricity market in 1999, more and more sugarcane mills use their excess bagasse to produce electricity for the grid. The Federal Government recently stated that Brazil will reduce GHG emissions through, among other things, increasing electricity production from biomass, e.g., bagasse (BRAZIL iNDC, 2015). Unless regulations or incentives promote the use of bagasse for animal feed (Papers II and III), this practice is likely to face increasing competition from the use of bagasse for electricity production.

Because surplus bagasse can be used for both feed, electricity and heat production, the GHG benefits of the options, taking into account both the energy and transport systems as well as LU and LUC (direct and indirect), should be investigated further. The usage of bagasse as animal feed may become supported by, e.g., schemes certifying low iLUC biofuels. This since integration of biofuel with food/feed production is considered an option for reducing the risk of causing iLUC. However, more research is warranted before systems for integrated production of biofuel and food/feed are included in schemes promoting low iLUC biofuels. For instance, alternative uses of residues and by-products should to be considered and the feasibility of integrated systems need to be clarified considering economic, social and environmental factors influencing their practical implementation. For instance, our interviews with land owners and land managers indicated that some farmers considered improving their beef and milk production by, e.g., introducing additional feed systems, but they faced challenges due to difficulties in finding skilled labor.

In early 2013, the largest supermarket chains in Brazil announced that they would only buy/sell beef from areas that had not been recently deforested. When we asked interviewees (Paper V) about this scheme, the general impression was that they did not believe that it would be effective in reducing de-forestation. We were told that beef producers would just move cattle around so that they could send animals to the slaughterhouse from an area not recently deforested (the chains would only control from where animals were sent to slaughterhouses). This expectation was also confirmed by Gibbs et al. (2015).

The outcome of the supermarket chains' initiative, highlights the importance of ex-ante analysis.[9] Governance of bioenergy and land use is challenging and one aspect warranting more research concerns behaviour of actors along bioenergy supply chains. Also, how they interact with and/or engage in supply chains for other products such as food should be further investigated. Research into actor behavior and organizational structures along supply chains can inform governance, including the development of policies, sustainability standards, codes of conduct, and legislation. In addition, governance need to balance a multitude of objectives and more research is needed to clarify how different bioenergy and land use options contribute to different objectives.

[9] Here we use the term ex-ante analysis to describe an analysis carried out to help give an idea of the future impact of a not yet implemented policy. In latin ex-ante means "before the event".

Chapter 7
Summary of appended papers

7.1 Paper I: Co-generation of biofuels for transportation and heat for district heating systems – an assessment of the national possibilities in the EU.

In the EU25, there are more than 5,000 district heating systems. Together they provide about 15% of the total annual heat demand (not including electricity for heating, due to lack of statistics). The importance of district heating varies among member states, reaching at most about 30–40% in the Baltic states and Denmark (estimates for 2003 based on IEA, 2005, and Werner, 2006). In 2003, about 80% of the district heating in the EU25 was generated with fossil fuels, either in combined heat and power (CHP) plants (about 75%) or heat-only boilers (HOB) (about 25%) (Werner, 2006). The EU promotes an increased use of bioenergy for heat and electricity production and for production of biofuels for transportation (EC, 2005). For example, each member state is supposed to achieve a minimum share of 10% renewable energy, primarily biofuels, in the transport sector by 2020 (EP&C, 2009).

Since the potential for biomass is limited, high efficiencies in biomass conversion processes are of interest. In order to improve the overall energy efficiency (and economic viability) of biofuels for transportation, biofuel plants can be designed and located so that part of the surplus heat can be used in district heating systems, substituting for heat from fossil fuels.

7.1.1 Objective and scope

(i) Estimate the heat sink capacity of district heating systems – the amount of heat these systems demand – in the EU member states.

(ii) Investigate whether district heating systems in the EU are large enough to accommodate the heat from biomass-gasification-based co-generation of synthetic biofuels for transportation corresponding to the EU 2020 target (10% renewable fuels in the transport sector).

7.1.2 Method

The techno-economical potential for CBH is assessed based on a model characterization of the existing and potential district heating systems in Europe in 2020. The existing (2003) district heating systems in the EU25 are inventoried and characterized. The existing district heating systems are characterized at the national aggregated level, including the size of the heat sink and relevant characteristics such as present heat supply and fuel use. The CBH unit is here assumed to be second-generation biofuel production, where 50% of the energy input (biomass) is converted to biofuel and 10% ends up as usable surplus heat, corresponding to performance of CBH plants based on Thunman et al. (2008). This characterization, along with the estimate of the sizes of the district heating systems in 2020, forms the basis for investigating the possibilities for CBH in the EU25 countries. The Euroheatspot model (based on the Heatspot model, see, e.g., ÖPwC, 2005) is used to analyze changes in district heating systems when heat from CBH is introduced.

In the Euroheatspot model, the national district heating systems are described by a heat load duration diagram, in which the heat supply options in the system are placed in the specified merit order and are ranked by size. The installed capacity (in MW) for each included heat supply option, corresponding to the compiled production levels in each country, is estimated by using an analytical expression representing the annual load curve. Based on the estimated installed capacity, the annual district heating production from the different heat supply options is recalculated after the CBH has been introduced (see Figure 3).

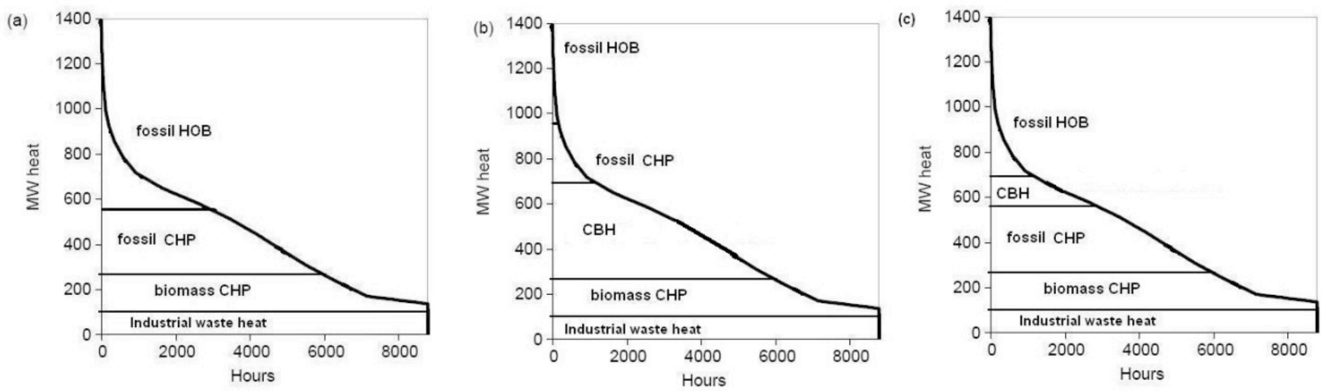

Figure 3 Description of the Euroheatspot model. Heat load charts for every European country's aggregate heating system and changes in heat source when CBH is introduced. (a) An existing district heating system, (b) a system with heat from CBH placed ahead of fossil CHP, and (c) a system with biomass heat placed after CHP.

7.1.3 Main findings and conclusions

(i) Heat sinks represented by the existing national aggregated district heating systems are in general large compared to the amount of surplus heat that would be generated from CBH plants with a combined biofuel production capacity corresponding to the 2020 renewable transportation target.

(ii) Most countries' district heating systems can easily absorb the excess heat from the biofuel production (assuming that heat from CBH can successfully compete with fossil CHP as in Figure 3b). In Figure 4, the heat from CBH plants (producing biofuel to meet the EU's

2020 target) is presented in relation to heat production in different countries, assuming that CBH heat is less expensive than heat from fossil CHP (case b in Figure 3). Each investigated country, except Italy, has district heating systems with the capacity to absorb more heat from CBH production than the heat corresponding to the relevant national target for biofuels.

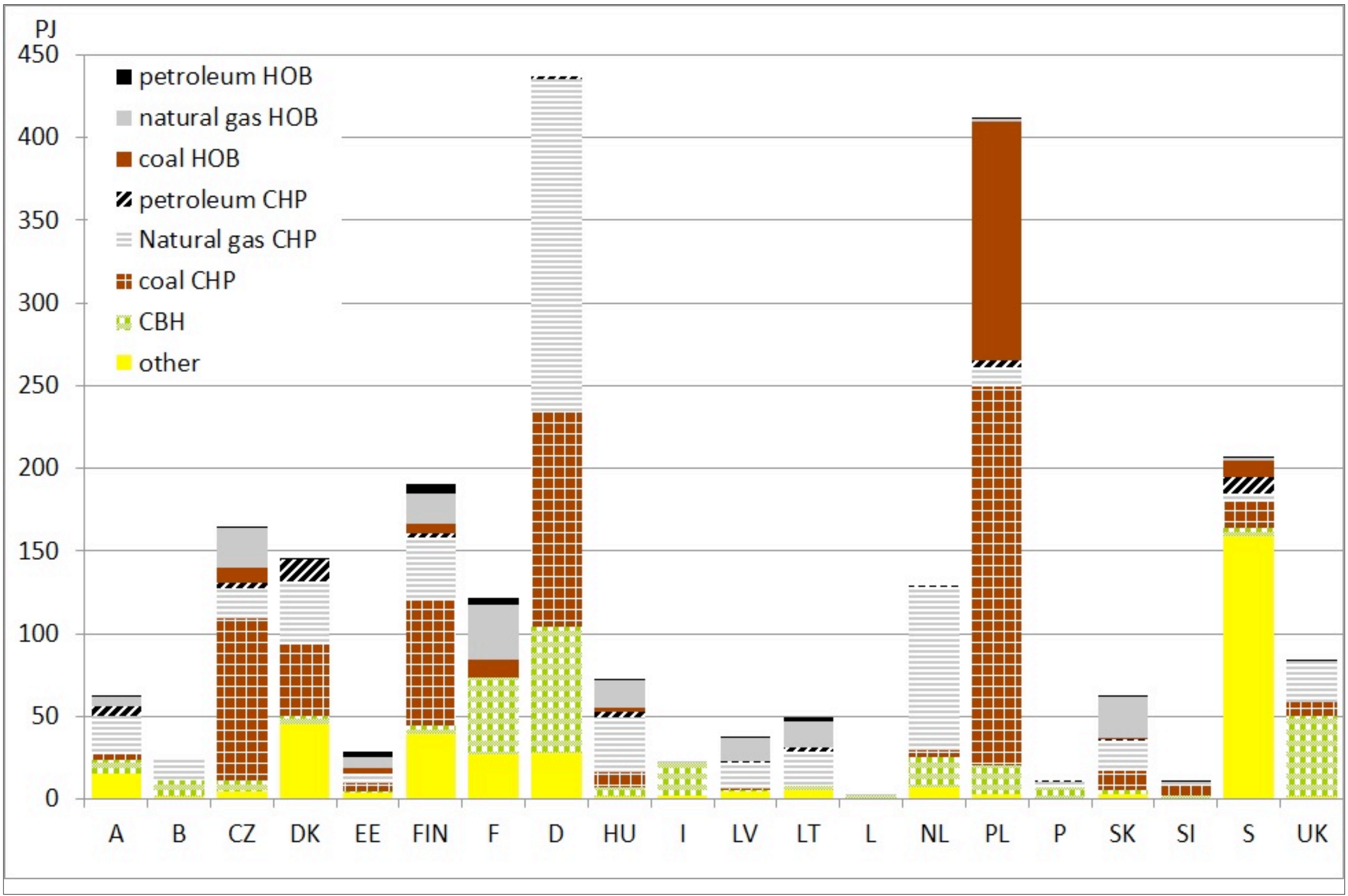

Figure 4 Distribution of heat sources in aggregated national district heating, where heat from CBH corresponds to the 2020 EU biofuel target for 2020 (assuming that this heat is cheaper than heat from fossil CHP). "Other" includes industrial waste heat, heat from waste incineration, waste heat from nuclear power plants, biomass CHP, geothermal heating, and solar energy.

7.2 Paper II: Sugarcane ethanol production in Brazil: an expansion model sensitive to socioeconomic and environmental concerns

Because of increasing demand, Brazil is expected to expand its sugarcane-based ethanol production. Addressing concerns about social and environmental impacts of expanding sugarcane ethanol production requires careful consideration of Brazilian agriculture in general and specific local conditions in particular. In this paper we present a model for increased ethanol production that integrates with beef/dairy production systems in Brazil. Through integration with the prevailing land use, the expansion model aims to avoid displacement of extensive livestock production and the associated risk of causing indirect land use change (iLUC). It also promotes milk and beef cattle intensification and provides investment opportunities at the local level. The expansion model is judged to be feasible under the market conditions that existed when the study was made. A case study, developed in the Pontal do Paranapanema region (state of São Paulo, Brazil), illustrates the model in agrarian reform settlements.

At the time of the study, conservative estimates suggested that the area for sugarcane production in Brazil could double in the next ten years. However, the Federal Government still had not defined a specific policy for this coming expansion scenario. Considering that ethanol use for transport is motivated by, among other things, the desire to reduce GHG emissions, it is important to investigate whether the common understanding – that use of Brazilian ethanol for transport (in Brazil or importing nations) leads to substantial reductions in GHGs – holds in the context of a substantially expanding sugarcane ethanol production.

7.2.1 Objective and scope

(i) Present an overview of Brazilian agriculture – with special attention to sugarcane ethanol production – and against this background discuss challenges for agricultural development in Brazil, especially sugarcane expansion. Describe the integrated ethanol-beef/dairy production model is subsequently and discuss prospects for realizing this model, considering benefits and barriers from varying stakeholder perspectives.

(ii) Present a theoretical strategy (the integration model) aiming to reduce the risk for iLUC connected to sugarcane expansion in Brazil by describing an expansion model for sugarcane ethanol production that addresses socioeconomic and environmental – especially climate – concerns. The model integrates sugarcane ethanol production with the existing local agriculture and stimulates increased livestock production productivity.

(iii) Present and discuss the integration model (which is not a new innovation) in the new context of international biofuel markets and the associated debate about sustainability impacts, in particular related to direct and indirect LUC.

(iv) Evaluate the feasibility of the model in a specific context in Brazil, an agrarian reform settlement in Pontal do Paranapanema, a relatively poor region in São Paulo State, where sugarcane was expected to expand in the near future.

7.2.2 Method

A literature review is performed to gather data and gain a better understanding of Brazilian agriculture in general and sugarcane production in particular. Based on this, we propose a strategy for sugarcane expansion that may avoid displacement of beef/dairy production and thus reduce the risk of iLUC. We conduct interviews in an agrarian reform settlement in Pontal do Paranapanema (São Paulo state) and based on these present a first model-based assessment and comparison of the integrated ethanol-beef/dairy system with the conventional sugarcane ethanol system, for an expansion scenario in this region.

7.2.3 Main findings and conclusions

Based on the literature study and the case study we hypothesize that the expansion model can reduce displacement of livestock production and thus the risk of iLUC caused by new establishment of extensive cattle production in remote regions. A number of actors could benefit from this integration model, e.g.:

(i) *Farmers*

Sugarcane is often grown in regions with dry winters. In these regions livestock production is restricted due to the low pasture productivity during the winter. If ranchers get additional feed during the winter, they can increase productivity and reduce the winter area to the size needed during the summer.

(ii) *The local economy*

Native farmers are judged likely to use their increased incomes on local investments, thereby stimulating other local sectors. Also, in addition to the labor demand from the sugarcane sector, intensified livestock production will increase the demand for labor.

7.3 Paper III: Integrating bioenergy and food production – a case study of combined sugarcane ethanol and dairy production in Pontal, Brazil

Sugarcane is expanding rapidly in the state of São Paulo, Brazil. The region of Pontal do Paranapanema (Pontal) (Figure 5) in the western part of São Paulo state is one region where sugarcane is likely to expand further (Freitas and Sparovek, 2008). This expansion could negatively affect the relatively poor small-scale milk-producing family farmers living in the area. Freitas and Sparovek (2008) report that the small-scale farmers in the region who had already switched to sugarcane production experience economic stagnation. The farmers lack investment capital, making it impossible for them to manage all stages of the sugarcane production. Having to buy services from the sugarcane industry leads to reduced net incomes from sugarcane production. Relatively small-sized farms also limit the possible net income (Egeskog and Gustafsson, 2007).

One way for small-scale family farmers in Pontal to economically benefit from sugarcane expansion is to improve milk production systems in combination with planting sugarcane. If settlers allow sugarcane on part of their property and in exchange for this can buy feed from sugarcane residues (which is readily produced in the ethanol plant), they can change to a more productive cattle breed, double the amount of milk-producing animals, and keep them on a smaller area than needed for their present cattle production.

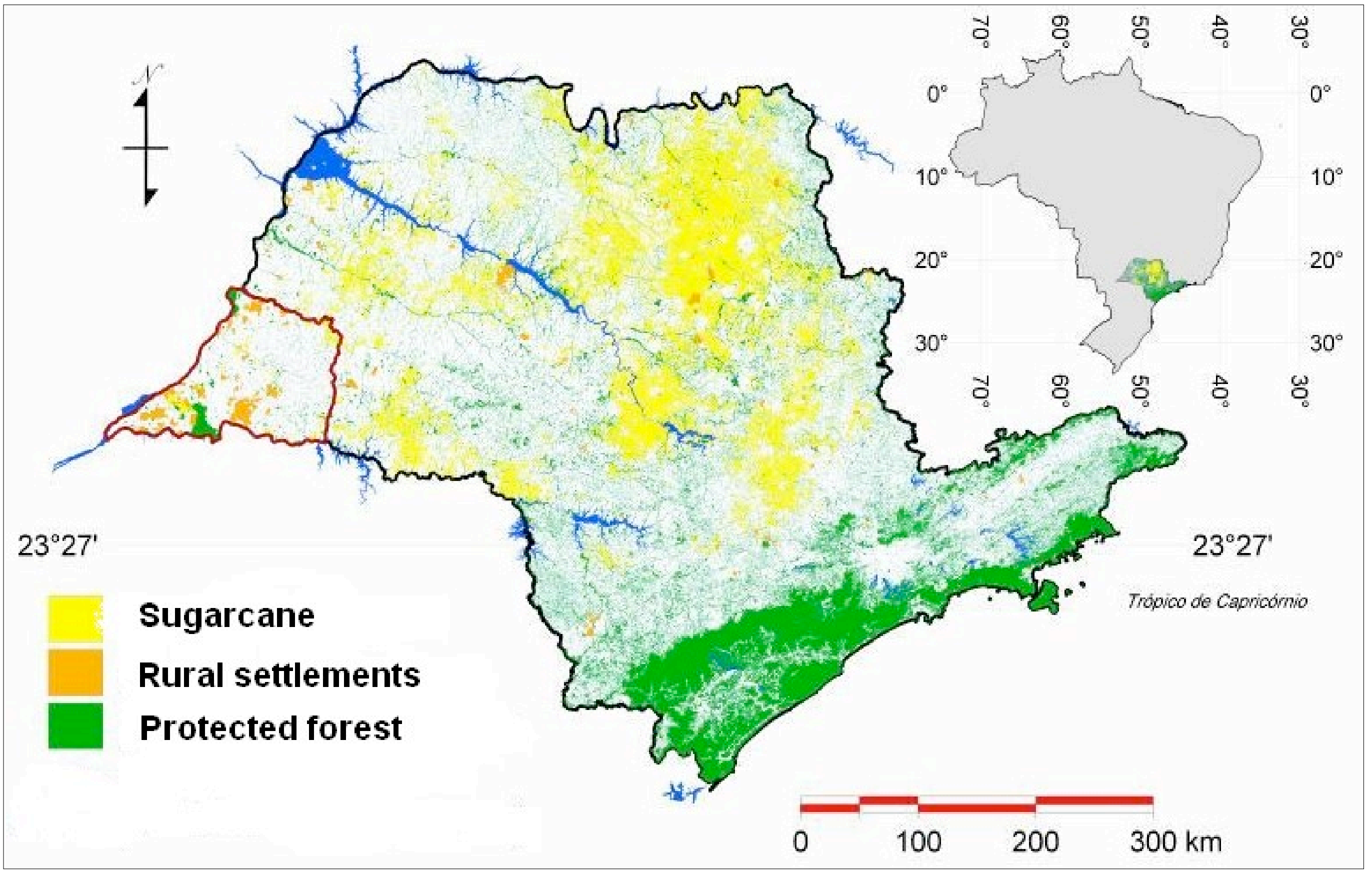

Figure 5 Sugarcane, protected forests, and agrarian reform settlements in the state of São Paulo; Pontal do Paranapanema is marked with a red line.

7.3.1 Objective and scope

(i) Investigate how the integration of milk and ethanol production affects small-scale family farmers' profits.

(ii) Investigate whether the integrated milk/ethanol system is attractive from a climate change mitigation perspective.

7.3.2 Method

Two different models are developed to analyze selected effects of implementing the integrated ethanol/dairy system in Pontal: one model for quantifying the net revenues from milk production in the settlements (the Change of Cattle (CoC) model) and one model for quantifying the associated GHG emissions (the BIOGHG model). The CoC model is constructed to represent the transition from low-productive to medium-productive dairy cattle. It describes the settlers' incomes and expenses connected to their dairy cattle production system. The annual net income for the settlers is quantified for the time period when they make the transition from the current milk production systems with low-productive dairy cattle to the integrated ethanol/dairy system with medium-productive dairy cattle. The model is partly based on information from a questionnaire survey conducted in Pontal in 2006 (Egeskog and Gustafsson, 2007). The BIOGHG model is constructed to quantify emissions connected to a scenario for sugarcane expansion in Pontal where small-scale family farmers shift to the combined ethanol/dairy system and large scale farmers shift to sugarcane.

7.3.3 Main findings and conclusions

(i) The integration of milk and ethanol production can help small-scale family farmers increase their income ten-fold. However, two crucial factors for income development are (a) the price for the necessary additional feed and (b) price levels for milk.

(ii) A sugarcane expansion for ethanol in Pontal will, based on our assumptions, lead to reduced GHG emissions from the European transport sector when Brazilian ethanol is used to replace gasoline in Europe (Figure 6). The average avoided emissions for the 20-year period are roughly 60 g CO_2-eq/MJ ethanol. Compare with Figure 2 showing that iLUC emissions might be around or below 20 g CO_2-eq/MJ ethanol.

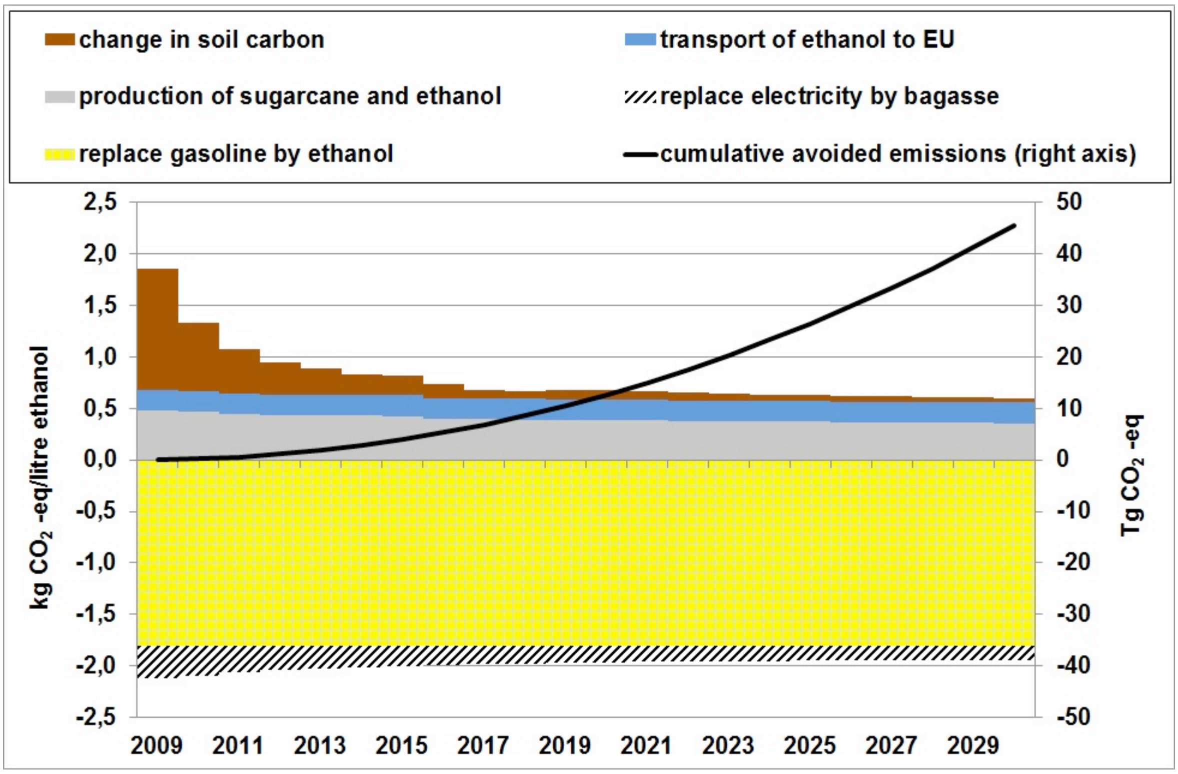

Figure 6 Emissions per liter ethanol and cumulative avoided emissions in conjunction with an expansion of sugarcane for ethanol in the Pontal region. Manual harvest is assumed to be phased out completely by 2017. Emissions increase in the first two years. Possible deforestation through iLUC is not included.

Including settlers in the sugarcane expansion will help them increase their net annual income but will not improve the direct GHG savings because bagasse used for producing animal feed results in reduced electricity production from bagasse (or reduced replacement of fuel oil in other industries). However, the medium-productive dairy cattle need a smaller area per liter of milk produced, and this can be important with respect to reducing the risk that ethanol expansion on pastures leads to GHG emissions connected to iLUC. If demand for milk is constant, the increased milk production in Pontal, rising from an average of 7,000 to 80,000 liters/farmer annually, could displace other milk production and hence reduce total land requirements for milk production. This may reduce the pressure for expanding agriculture into forested areas and thereby indirectly reduce GHG emissions (i.e., have a positive iLUC effect).

While the transition to the integrated ethanol/dairy system does not necessarily lead to reduced GHG emissions per liter milk produced, possible GHG emissions reduction from making the transition can follow from the improved land-use efficiency. The reduced land conversion pressure may be important for realizing the GHG savings potential of the system, since iLUC emissions can drastically reduce net GHG savings. Incentives may be needed to make settlers consider the transition an attractive option. Investigations of the feasibility of implementing integrated ethanol/dairy systems that also include landowners with large landholdings are warranted.

7.4 Paper IV: Greenhouse gas balances and land use changes associated with the planned expansion (to 2020) of the sugarcane ethanol industry in Sao Paulo, Brazil

Brazil is one of the world's largest ethanol producers. The state of São Paulo, where roughly one-third of the agricultural area is used for sugarcane, accounted for almost 60% of Brazil's sugarcane production in 2012 (IBGE, 2013). The sugarcane area in São Paulo almost doubled from 2002 to 2010 (SPIEA, 2012). At the end of 2008, 21 new mills had been granted construction approval (UDOP, 2008); see Figure 7 for a map of existing and approved mills. The sugarcane area is projected to increase further (MAPA, 2012), driven by increased demand for both ethanol and sugar (UNICA, 2011). In 2012, the number of

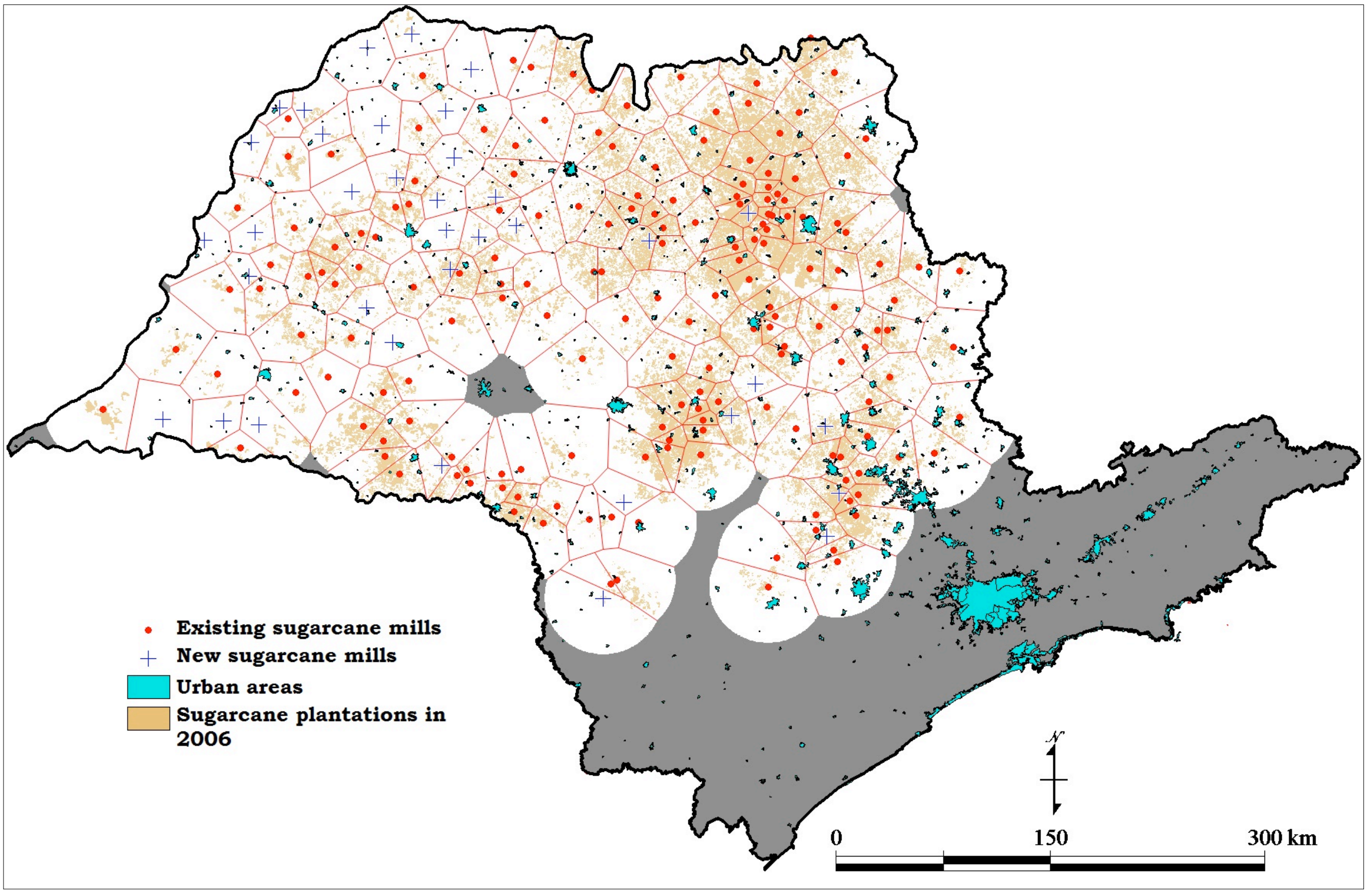

Figure 7 Existing and approved mills in the state of São Paulo. The dots represent mills built before 2008; the crosses represent the 21 approved mills. The orange areas represent existing sugarcane; the blue/gray indicates areas that are either more than 40 km away from a mill or protected (e.g., Atlantic rainforest).

operating mills had not changed since the end of 2008 (UDOP, 2012). However, ethanol markets can change rapidly depending on ethanol and petroleum prices and policy developments (e.g., tax exemptions and import tariffs). If growth in ethanol demand and attractive ethanol prices are considered likely, already-approved sugarcane mill projects may be implemented relatively rapidly.

Sugarcane expansion in Brazil is commonly believed to avoid direct competition for prime cropland/food production, in general, since sugarcane is and will mostly be planted on extensively used pasture lands. Expansion on extensively used pastures is also assumed to reduce the risk for iLUC. However, the claim that expansion is mostly taking place on extensively used pastures has little support in the literature. In fact, Rudorff et al. (2010) and Freitas (2010) show that, from 2004 to 2008, expansion of sugarcane in São Paulo has taken place on roughly equal shares of pastureland and cropland.

7.4.1 Objective and scope

(i) Describe what type of land use is likely to be directly replaced by sugarcane if large-scale sugarcane expansion is to take place again in São Paulo state.

(ii) Estimate GHG balances (including soil carbon stock changes) associated with a sugarcane ethanol production expansion scenario in São Paulo state.

7.4.2 Method

A sugarcane expansion scenario for São Paulo state is developed, based on combining:

(i) an assessment of approved licenses to build sugarcane mills.

(ii) an inventory of relevant policies and laws.

(iii) a mapping of historic LUC associated with the construction and start-up of sugarcane mills.

A multitude of factors (biophysical, technical, socioeconomic, and legal conditions, biofuel and food markets, company strategies, etc.) influence real-world development plans. Many of these factors may be difficult to capture in the techno-economic models commonly used to produce biofuel expansion scenarios. Our ambition is to produce a scenario that corresponds to the development judged "most likely", so geographic information about the location of existing and planned sugarcane mills and existing land use in these locations is included.

First, a land allocation method is used to calculate where the expansion of sugarcane will take place around each of the 21 approved mills. The fraction of agricultural land planted with sugarcane is highly correlated with the distance from the existing mills (Freitas and Sparovek, 2008; Sparovek et al., 2010). We assume that the distribution of sugarcane plantations around approved mills is similar to around existing mills. Quantifying the associated GHG emissions from the planned expansion is done using the BIOGHG model. We assume that the sugarcane plantation area associated with each of the existing mills is constant during the 20-year modeling period (ethanol output from these mills increases due to increased sugarcane yields and improved ethanol output per unit of sugarcane). We also assume that the 21 approved mill projects are implemented in the first three years of the modeling period. This would imply an average expansion rate similar to the period 2002–2010. The direct LUC associated with planting sugarcane to provide feedstock for each of the 21 approved mills is estimated based on information about land use surrounding existing operating mills and the 21 approved mills (INPE, 2008; PROBIO, 2002; UDOP, 2008) and a methodology for modeling land allocation surrounding the mills.

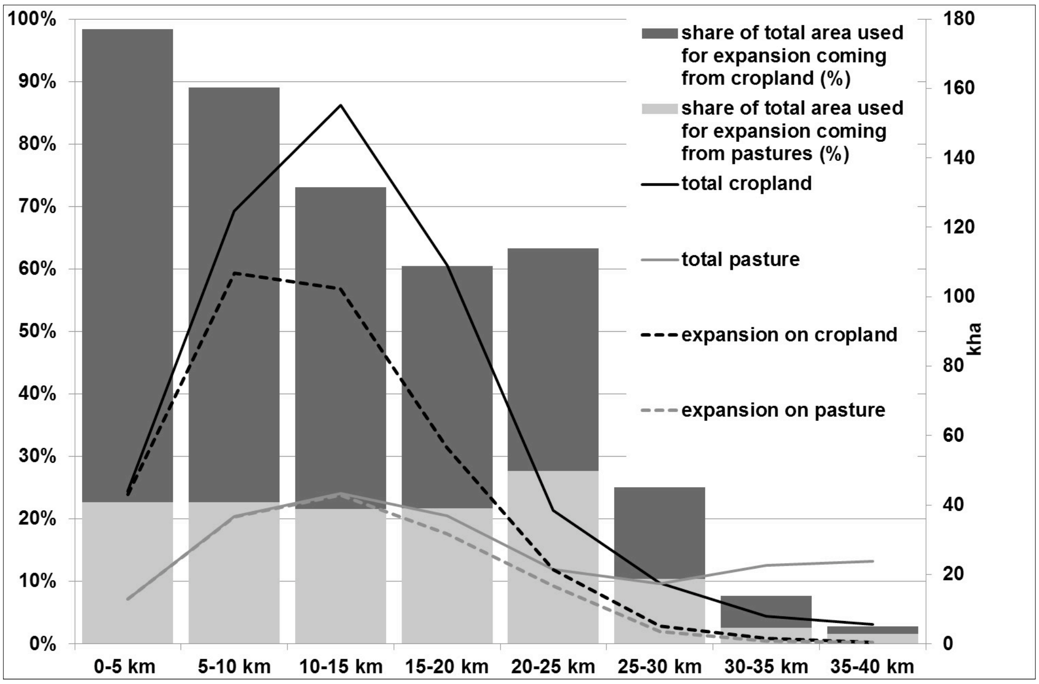

Figure 8 Estimated average land allocation to sugarcane plantations surrounding approved mills (%), total land available (kha), and land used for sugarcane (kha).

7.4.3 Main findings and conclusions

(i) The results indicate that sugarcane expansion in the state of São Paulo may to a significant degree take place on cropland (Figure 8).

(ii) This study confirms that the Brazilian sugarcane ethanol system can deliver substantial GHG emissions savings when displacing fossil-based fuels, even if expansion mainly takes place on cropland. The GHG outcome is sensitive to how the sugarcane ethanol system is designed, and there is scope for further enhancement of GHG emissions reductions, especially in association with the use of bagasse and harvest residues that are available in mechanically harvested systems. However, unless associated with significant iLUC emissions and/or a shift from bagasse to coal as process fuel (due to bagasse being used for other purposes), it seems likely that sugarcane ethanol expansion in the state of São Paulo will result in substantial GHG savings. The average avoided emissions for the 20-year period are roughly 80 g CO_2-eq/MJ ethanol.[10] Compare with Figure 2 showing that iLUC emissions might be around or below 20 g CO_2-eq/MJ ethanol.

[10] In Paper III the result was instead 60 g CO_2-eq/MJ ethanol. The difference can be explained by 1) higher avoided emissions in Paper IV since more bagasse is used to replace fossil fuel based electricity and heat (instead of, as in Paper III, be used as feed); and 2) higher emissions from soil carbon change in Paper III due to different assumptions compared to Paper IV (see Table 1) and in Paper III emissions from burning of sugarcane are included, in Paper IV we assume no burning before harvest.

7.5 Paper V: Actions and opinions of Brazilian farmers that shift to sugarcane – an interview based assessment with discussion of implications for land use change

Many studies have found that – excluding iLUC emissions – production and use of Brazilian sugarcane ethanol cause less GHG emissions than for gasoline. However, including iLUC emissions can make a great difference to total emissions. To avoid promotion of biofuels that cause large GHG emissions, US estimates include a fixed number for iLUC emissions for, e.g., sugarcane production in Brazil. The EU has instead decided to keep emissions from iLUC connected to different biofuels separate from the total emissions figures, while requiring the assumed iLUC to be reported. To avoid causing iLUC when expanding, e.g., sugarcane plantations, schemes have been proposed to identify and promote production types (e.g., integration with food production or planting on degraded pastures) judged to have low risk of causing iLUC (Plano ABC; RSB, 2015). The design of the schemes tends to reflect the mainstream narrative on iLUC, i.e., farmers influence land use outside the project boundary through their influence on food prices: lower production for the food markets (due to farmers' shift to biofuel crops) induces an increase in food commodity prices, which in turn stimulates other farmers to increase their food commodity production, possibly causing LUC, which would then be assigned as iLUC to the biofuel.

Creating schemes to encourage farmers to produce biofuels in a way that causes no or little iLUC emissions requires sufficient knowledge of all aspects connected with iLUC stemming from biofuel production. We find that knowledge regarding farmers' actions in connection with a shift to sugarcane in Brazil is missing.

7.5.1 Objective and scope

(i) Analyze actions and opinions among Brazilian landowners and farm managers who have shifted fully or partially from pasture-based beef or milk production to sugarcane production or to leasing land to sugarcane producers.
The focus is on events that take place *after* sugarcane ethanol factories have been established in the relevant regions. Special attention is placed on decisions and actions pertaining to intensification of remaining land use once the land has been dedicated to sugarcane production.

(ii) Hypothesize that farmers' decisions can influence LU and LUC directly and/or indirectly in association with the shift to sugarcane and that schemes promoting iLUC-free biofuels may fail to recognize some of the decision-making processes that determine whether biofuels are free from iLUC.

(iii) Contribute to the understanding of the Brazilian agricultural sector as a complex system with multiple inter-linkages between actors as well as product markets.

7.5.2 Method

In March and April 2013, 28 semi-structured open-ended interviews are conducted in the Brazilian States of São Paulo and Goiás. The interviews focus on actions before, during, and after a change to sugarcane (see Appendix II for the questions). If the interviewee has taken over a sugarcane farm (relevant in the traditional sugarcane region Piracicaba, São Paulo), the focus is on actions associated with sugarcane production and other agricultural activities. Most interviews cover the following topics: farm history; changes in land use and farming activities; reasons for investments or disinvestments; environmental and economic concerns; opportunities; and farmers' networks. Interviews with other actors, such as agricultural consultants and sugarcane mill owners/representatives, complement the farmer perspectives.

7.5.3 Main findings and conclusions

(i) All interviewed farmers who started sugarcane operations planted their sugarcane on former pastures. Crop farmers in the region had also shifted (often from soy to sugarcane) but we could not get in contact with any crop producers. Most of the farmers who started sugarcane production also continued pasture production, either in the same region as the sugarcane plantations or elsewhere.

Farmers in the expansion regions commonly state that they wanted to buy more land but that land prices were too high at the moment. Instead, almost all who had pastures made investments to enhance land-use intensity on their remaining pastures. Income from sugarcane made it possible for the farmers to invest in this type of intensification. Most of the farmers who started intensified beef production after engaging with sugarcane have their beef production in a different region than sugarcane. The increasing land prices in sugarcane regions affect farmers' decisions on whether to intensify existing pasture production or instead expand their properties. The increased land price also makes some of the farmers buy additional land in the frontier regions where land prices are more competitive for beef production.

Both lessors and producers in the expansion regions consider sugarcane more risky economically than beef or milk production, but it is still preferred due to the much higher profitability.

(ii) We find three examples of behavior among the farmers that can be challenging to capture in models. The profits from sugarcane are used by the interviewees to buy land or to intensify other production at the farms located in other regions. This example of money transfer between sectors can be challenging to capture in general equilibrium models. According to the interviews, perceived risk and managerial difficulties lead most farmers to not exclusively prioritize the most profitable grain/pasture use at any point in time. At traditionally run farms, production sometimes does not change until a new generation takes over, even though change would have been economically rational before that. In such cases, a shift to sugarcane may be delayed compared to if the decision to switch is based solely on a straightforward cost-benefit analysis.

(iii) If certified production is more profitable than non-certified production, such schemes might even cause increased deforestation since the higher profits can be invested in new agricultural land in frontier regions (almost half of the farmers in this study who had both sugarcane and beef had beef production in a region other than their sugarcane region). However, it need not be a drawback from a global GHG balance point of view that farmers who cultivate feedstocks for iLUC-free biofuels also engage in other land use activities that cause LUC. If this land use displaces other land uses that are less area-efficient, the outcome will be a net reduction in LUC.

All farmers stated that it was important for them to be environmentally friendly, but none of them considered legal deforestation as an action leading to negative environmental impacts. Based on the interviews, (i) incentives and regulations covering activities that today count as legal deforestation are judged as likely needed for deforestation to stop, and (ii) if mills impose other laws or certificates (e.g., certified ethanol programs) this will probably also lead to full compliance among the farmers.

Reference list

AFDC, 2015. Alternative Fuels Data Center, U.S. department of energy. http://www.afdc.energy.gov (accessed 2015-11-19)

Agrarian Act, 1985. Decreto No. 97766 of October 10, 1985

Batidzirai B., Smeets E., Faaij A., 2012. Harmonizing bioenergy resource potentials – Methodological lessons from review of state of the art bioenergy potentials assessments. *Renewable Sustainable Energy Reviews. 16*, 6598–6630

Berndes, G., Hoogwijk, M., van den Broeck, R., 2003. The contribution of biomass in the future global energy supply; a reviw of 17 studies. *Biomass and Bioenergy* 25 (1), 1–28

Berndes, G., Börjesson, P., Ostwald, M. and Palm, M., 2008. Multifunctional biomass production systems – an introduction with presentation of specific applications in India and Sweden. *Biofuels, Bioproducts and Biorefining 2:* 16–25

Brazilian law, 1964. Lei nº 4.504, de 1964

Brazilian law, 1965. Lei nº 4.771, de 15 de setembro de 1965

Brazilian law, 2012. The Forest code. Federal Law # 12,651. 12 May 2012. http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12651compilado.htm (in Portuguese) (accessed 2015-08-01).

BRAZIL iNDC, 2015. Intended nationally determined contribution, towards achieving the objective of the United Nations framework convention on climate change. The Federative republic of Brazil

Cardoso, T. F., Chagas, M. F., Rivera, E. C., Cavalett, O., Morais, E. R., Geraldo, V. C., et al., 2015. A vertical integration simplified model for straw recovery as feedstock in sugarcane biorefineries. *Biomass and Bioenergy*, 81, 216–223. doi:10.1016/j.biombioe.2015.07.003

Casinge E., 2015. Lawmakers agree to limit food-based biofuels. http://www.euractiv.com/sections/sustainable-dev/meps-agree-limit-food-based-biofuels-313760 (accessed 2015-11-19)

Cerri CC, Galdos M, Maia S, Bernoux M, Feigl B, Powlson D, et al. 2011. Effects of sugarcane harvesting systems on soil carbon stocks in Brazil: an examination of existing data. *Eur J Soil Sci;* 62: 23–28.

Cherubin M., Francoa A., Cerri C.E.P., Oliveira D., Davies C., Cerri C.C., 2015. Sugarcane expansion in Brazilian tropical soils – Effects of land use change on soil chemical attributes. *Agriculture, Ecosystems and Environment*, 211, 173–184

Chum H., Nigro F., McCormick R., et al., 2015. Conversion technologies for biofuels and their use. In: Souza G., Victoria R., Joly C., Verdade L. (Eds). Bioenergy and sustainability: bridging the gaps. *SCOPE* (2015). Chapter 12, pp. 374–467.

CPI, 2015. Strengthening Brazil's Forest Protection in a Changing Landscape.Juliano Assunção and Clarissa Gandour. Climate Policy Initiative (CPI) and the Pontifical Catholic University of Rio de Janeiro (PUC-Rio). Published: August 2015. Available at: http://climatepolicyinitiative.org/wp-content/uploads/2015/08/POLICY-BRIEF-%E2%80%93-Strengthening-Brazil%E2%80%99s-Forest-Protection-in-a-Changing-Landscape.pdf

de Luchi, M.A.1993. Greenhouse-gas emissions from the use of new fuels for transportation and electricity. *Transportation Research Part A*, 27A, 187–191

de Oliveira A., 1991. Reassessing the Brazilian alcohol programme. *Energy Policy*, January/February, 47–55

den Wall Bake J., Jungingera M., Faaij A., Poot T., Walter A., 2009. Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. *Biomass and bioenergy*, 33, 644–658

Dias M., Cunha M., Jesus C., Rocha G., Pradella J., Rossell C., Filho R., Bonomi A., 2011. Second generation ethanol in Brazil: Can it compete with electricity production? *Bioresource Technology*, 102, 8964–8971

EC (European Commission), 2005. Biomass Action Plan, COM(2005) 628, SEC(2005) 1573, Brussels, Belgium

EC (Europena Commission), 2009a. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

EC (Europena Commission), 2009b. Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC

EC (European Commission), 2012. Directive 2012/27/EU of the European parliament and of the council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC

EC (European Commission), 2015a. Biofuels overview. http://ec.europa.eu/energy/en/topics/renewable-energy/biofuels (accessed 2015-11-19)

EC (European Commission), 2015b. Communication from the Commission on the practical implementation of the EU biofuels and bioliquids sustainability scheme and on counting rules for biofuels 2010/C 160/02

EC (European Commission), 2015c. Land use change. http://ec.europa.eu/energy/node/75 accessed 2016-01-26

EC (European Commission), 2016. Guideline for Safe and Eco-friendly Biomass Gasification. https://ec.europa.eu/energy/intelligent/projects/en/projects/gasification-guide accessed 2016-01-14

Egeskog, A., Gustafsson, S., 2007. Socioeconomic and environmental effects from sugarcane expansion into the Pontal do Paranapanema region (state of São Paulo, Brazil), a model-based analysis, Master Thesis, Chalmers, Gothenburg, Sweden.

EIA, 2015. US Energy Information and Administration, International Energy Statistics, Biofuels production 2000 to 2012. http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=79&pid=79&aid=1&cid=ww,&syid=2000&eyid=2012&unit=TBPD (accessed 2015-11-09)

ELOBIO, 2010. Reconciling biofuels, sustainability and commodities demand, pitfalls and policy options. Uslu, A., Bole, T., Londo, M., Pelkmans, L., Berndes, G., Prieler, S., Fischer, G., Cueste Cabal, H. Available at: www.elobio.eu

EMBRAPA, 2015. Low Carbon Agriculture, ABC Sector Plan – Sector Plan on Climate Change Mitigation and Adaptation to Consolidate a Low-Carbon Economy in Agriculture https://www.embrapa.br/en/tema-agricultura-de-baixo-carbono/nota-tecnica (accessed 2015-10-28)

EP&C (European Parliament and Council), 2004. Directive 2004/8/EC of the European Parliament and of the Council on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC. Brussels Belgium.

EP&C (European Parliament and Council), 2009. Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. Brussels Belgium.

FAO, 2016. http://faostat3.fao.org/download/R/RL/E, (accessed 2016-02-08)

Fertcare, 2015. Carbon Farming Extension Project Best Management Practices to reduce nitrous oxide emissions from sugarcane production. http://www.fertilizer.org.au/files/pdf/fertcare/BMP%20Sugarcane.pdf (accessed 2016-01-24)

Franco A., Cherubin M., Pavinato P., Cerri C.E.P., Six J., Davies C., Cerri C.C., 2015. Soil carbon, nitrogen and phosphorus changes under sugarcane expansion in Brazil. *Science of the Total Environment* 515–516, 30–38

Freitas, F., Sparovek, G., 2008. Sugarcane expansion near agrarian reform settlements: a case study of Pontal, Brazil. Conference proceeding at ISPRS, Beijing. Available at: http://www.isprs.org/congresses/beijing2008/proceedings/8_pdf/1_WG-VIII-1/17.pdf

Freitas F. Sugarcane expansion: land use changes and social impacts in São Paulo state. Brazil [master thesis]. Stockholm (Sweden): KTH; 2010.

Freitas F., Sparovek G., Matsumoto M., 2015. The additionality of the legal reserve compensation mechanism presented in the Forest law (12,651 / 2012): An analysis of the supply and demand of Environmental Reserve Quota (In Portuguese, A adicionalidade do mecanismo de compensação de Reserva Legal da Lei 12.651/2012: Uma análise da oferta e demanda de Cotas de Reserva Ambiental). Book chapter, to be published by IPEA (Institute de Pesquisa Econômica Aplicada) – Research Institute of Applied Economy, early 2016

GAIN, 2015. Global Agricultural Information Network, USDA Foreign Agricultural Service, Biofuels-Brazil Raises Federal Taxes and Blend Mandate, 2015-04-16. GAIN report number: BR 15001

Galdos. M., Cerri, C.C., Cerri, C.E., 2009. Soil carbon stocks under burned and unburned sugarcane in Brazil, Geoderma. 153, 347–352

Galdos M, Cavalett O, Seabra J, Norgueira L, Bonomi A., 2013. Trends in global warming and human health impacts related to Brazilian sugarcane ethanol production considering black carbon emissions. Applied Energy 104: 576–582

Garg, K., Karlberg, L., Wani, S., Berndes, G., 2011. Biofuel production on wastelands in India: opportunities and trade-offs for soil and water management at the watershed scale. *Biofuels, Bioproducts and Biorefining 5*: 410–430

Gava G., Trivelin P., Oliveira M., Penatti C., 2001. Growth and accumulation of nitrogen by sugarcane cultivated in soil covered with cane trash (in Portuguese, with abstract in English), *Pesquisa Agropecuaria Brasil*. 36 1347–1354

Geller, H., 1985. Ethanol fuel from sugar cane in Brazil, *Annual Revision of Energy*. 10, 135–164

Gesch, R.W. and D.W. Archer., 2013. Double-cropping with winter camelina in the northern Corn Belt to produce fuel and food. *Industrial Crops and Products* 44: 718–725

Gibbs, H. K., Munger, J., L'Roe, J., Barreto, P., Pereira, R., Christie, M., Amaral, T. and Walker, N. F., 2015. Did Ranchers and Slaughterhouses Respond to Zero-Deforestation Agreements in the Brazilian Amazon? Conservation Letters. doi: 10.1111/conl.12175

Goldemberg J., Coelho S.T., Nastari P.M., Lucon O., 2004. Ethanol learning curve – the Brazilian experience. *Biomass and Bioenergy* 26 (2004) 301–304

Goldemberg J., 2008. The Brazilian biofuel industry. *Biotechnology for Biofuels*, doi:10.1186/1754-6834-1-6

Heat roadmap Europe, 2013. Heat roadmap Europe 2015, second pre-study for the EU27. By Aalborg university, Halmstad university, Ecofys and PlanEnergy. For Euroheat and Power. Available at: http://www.euroheat.org/Heat-Roadmap-Europe-165.aspx

Heggenstaller A., Anex R., Liebman M., Sundberg D., Gibson L., 2008. Productivity and Nutrient Dynamics in Bioenergy Double-Cropping Systems. *Agronomy Journal* 100: 1740–1748

IBGE 2015: Open database http://www.sidra.ibge.gov.br, in Portuguese

IBGE 2016: Open database http://www.sidra.ibge.gov.br, in Portuguese

IEA (International Energy Agency), 2005. IEA Statistics, Energy balances for OECD countries/ Non-OECD countries, Data 2003, Available on CD-ROM or at www.iea.org

IEA (International Energy Agency) Bioenergy, 2009, Bioenergy – a sustainable and reliable energy source, a review of status and prospects, *IEA BIOENERGY*: ExCo: 2009:06

IEA (International Energy Agency), 2014a. Key world energy statistics

IEA (International Energy Agency), 2014b. Renewable energy, medium term market report 2014, market analysis and forcasts to 2020. Excecutive summary

INCRA, 2016. History of the agrarian reform. http://www.incra.gov.br/reformaagraria_historia, (accessed 2015-10-30)

INPE, 2008. National Institute for Space Research – INPE. Sugarcane crop mapping in Brazil, 2008 [map]. Available from: http://www.dsr.inpe.br [2009, Nov].

IPCC, 2006. Guidelines for national Greenhouse gas inventories, Volume 4, Agriculture, Forestry and Other land Use, Chapter 2, 2006.

IPCC, 2014. Climate Change 2014, synthesis report, summary for policymakers.

Jank M., 2013. Desafios Institucionais e Tecnológicos para um Novo Ciclo de Expansão do Setor Sucroenergético. Unicamp Workshop Bioenergia, Campinas, SP, August 26, 2013.

Johnston, M., 2015. The Sugar Trade in the West Indies and Brazil Between 1492 and 1700. James Ford Bell Library, https://www.lib.umn.edu/bell/tradeproducts/sugar (accessed 2015-10-21)

Joseph H., 2005. Usage of ethanol in passenger cars, Anfavea, presented at the workshop and Business forum on Sustainable biomass production for the world market, November 30–December 3, 2005, Campinas, Brazil. Available from: www.bioenergytrade.org; 2005

Langeveld A., Dixon J., van Keulen H., Quist-Wessel F., 2014. Analyzing the effect of biofuel expansion on land use in major producing countries: evidence of increased multiple cropping. *Biofuels, Bioproducts and Biorefining* 8: 49–58

Lapola, D.M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., Priess, J.A., 2010. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceeding of the National Academy of Science*. USA. (doi/10.1073/pnas.0907318107)

Lossaou S., Fischer G., Tramberend S., van Velthuizen H., Kleinschmit B., Schomchacker R., 2015. Brazil's current and future land balances: Is there residual land for bioenergy production? *Biomass and Bioenergy*, 81, 452–461

Macedo, I., Leal, M., Silva, J., 2004. Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil. São Paulo State Environment Secretariat. Available at: www.unica.com.br/i_pages/files/pdf_ingles.pdf

Macedo, I., Seabra E., Silva, J., 2008. Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: The 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy*. 32, 582–595

Macedo et al., 2014 Greenhouse gas emissions from bioenergy. In: Souza, G., et al. (eds.) “Bioenergy and sustainability: bridging the gaps”. Report commissioned by SCOPE – Scientific Committee on Problems of the Environment

Magalhães P., Nogueira L., Canatarella H., Rossetto R., Franco H., Braunbeck O., 2012. Agro-industrial technological paths, in: M.K. Poppe, L.A.B. Cortez (Eds.), *Sustainability of Sugarcane Bioenergy* by Center of Strategic Studies and Management (CGEE). Brasília, Brazil. Pages 27–69.

Maia S, Ogle S, Cerri CEP, Cerri CC., 2009. Effects of grassland management on soil carbon sequestration in Rondônia and Mato Grosso states, Brazil. *Geoderma* 149: 84–91.

MAPA, 2012. Ministério da agricultura Pecuária e Abastecimento – MAPA. Brasil projeções do agronegócio 2011/2012 a 2021/2022. Brasília: The ministry; 2012. Portuguese

Mello F., Cerri CEP., Davies C., Holbrook M., Paustian K., Maia S., Galdos M., Bernoux M., Cerri CC., 2014. Payback time for soil carbon and sugar-cane ethanol. *Nature climate change*, 4, 605–609

Ministerio Público, 2012. A juíza federal daniela paulovich de lima, da 2ª vara em piracicaba/sp ministério público federal procuradoria da república no município de piracicaba

Monquero P., Amaral R., Binha D., Silva P., Silva A., Martins F., 2008. Weed infestation maps under dif ferent sugarcane harvest systems (in Portuguese, with abstract in English), *Planta Daninha*, 26 47–55

Moreira J., Goldemberg J., 1999. The alcohol program. *Energy Policy*, 27, 229–245

Mumm R., Goldsmith P., Raush K., Stein H., 2014. Land usage attributed to corn ethanol production in the United States: sensitivity to technological advances in corn grain yield, ethanol conversion, and co-product utilization. *Biotechnology for Biofuels*. DOI: 10.1186/1754-6834-7-61

OECD-FAO, 2008. Agricultural Outlook 2008–2017. Available at: http://www.fao.org/es/esc/common/ecg/550/en/AgOut2017E.pdf

Oliveira M., Trivelin P., Penatti C., Piccollo M., 1999. Field decomposition and release of sugar cane trash nutrients (in Portuguese, with abstract in English), *Pesquisa Agropecuaria Brasil*. 34, 2359–2362

Ondetti G., 2016. The social function of property, land rights and social welfare in Brazil. *Land Use Policy*, 50, 29–37

Persson M., 2014. The impact of biofuel demand on agricultural commodity prices: a systematic review. *Energy and Environment*. 4, 410–428

Persson U., 2015. District heating systems in future Europe: Modelling expansion potentials and mapping heat synergy regions. Thesis for degree of doctor of philosophy. Department of energy and environment, division of energy technology, Chalmers University, Gothenburg, Sweden. Available at: http://publications.lib.chalmers.se/records/fulltext/207521/207521.pdf

Plano ABC, 2012. Sector Plan for Mitigation and Adaptation to Climate Change for the Consolidation of Economy of Low Carbon in Agriculture, in Portuguese

PRB (President of the Republic of Brazil), 2008. National plan on climate change, Brazil. Brasília, LUIZ INÁCIO LULA DA SILVA President of the Federative Republic of Brazil, 2008. 28 pp.

PROBIO, 2002. Issued by Brazil’s ministry of environment: Paul Elliott Little. PROBIO, Project for the Conservation and Sustainable Use of Brazilian Biodiversity, activity report 1996–2002. Brasília; 2002 Aug: 73 p. Additional data available from authors, on request.

Reinhardt, G., 1991. Biofuels: Energy and GHG balances: Methodology and Case Study Rape Seed Biodiesel. Institut für Energie- und Umweltforschung Heidelberg, Heidelberg, Germany.

Rossetto R., Cantarella H., Dias F., Landell M., Vitti A., 2008. Conservation management and nutrient recycling in sugarcane with a view to mechanical harvesting, *Informações Agronômicas*, 8–13

Rosillo-Calle F. and Cortez L., 1998. Towards proalcool II – a review of the Brazilian bioethanol programme. *Biomass and Bioenergy* 14 (2), 115–124

RSB, 2015; Round table on Sustainable Biomaterials. New RSB standard for low iLUC biofuels. http://biofuels-news.com/display_news/9190/new_rsb_standard_for_low_iluc_biofuels/ (accessed 2015-05-20)

Rudorff B., de Aguiar D., da Silva W., Sugawara L., Adami M., Moreira M., 2010. Studies on the rapid expansion of sugarcane for ethanol production in São Paulo State (Brazil) using landsat data. *Remote Sensing*, 2 1057–1076

São Paulo State law, 2008. Law No. 11, 241

SCOPE, 2015. Bioenergy & Sustainability: bridging the gaps. Souza G., Victoria R., Joly C., Verdade L.

Searchinger T., Heimlich R., Houghton R., Dong F., Elobeid A., Fabiosa J., Tokgoz S., Hayes D., Yu T. 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change. *Science*, 319, 1238–1240

Signor D. and Cerri CEP., 2013. Nitrous oxide emissions in agricultural soils: a review. Pesquisa Agropecuária Tropical (Agricultural research in the tropics). 43, 322–338. Available at www.agro.ufg.br/pat

Silva A., Delai I., Delgado Montes M., Ometto A., 2014. Life cycle assessment of the sugarcane bagasse electricity generation in Brazil. *Renewable and Sustaianble Energy Reviewes*. 32, 532–547

Smeets E., Faaij A., Lewandowski., Turkenburg W., 2007. A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*. 33, 56–106

Smith, C.T., B. Lattimore, G. Berndes, N.S. Bentsen, I. Dimitriou, J.W.A. Langeveld, E. Thiffault (Eds.). 2015. Mobilizing Sustainable Bioenergy Supply Chains – Inter-Task Project Synthesis Report. IEA Bioenergy ExCo: 2015:04. ISBN 978-1-910154-19-9

Soares J.R., Cantarella H., Vargas V.P., Carmo J.B., Martins A.A., Sousa R.M., Andrade C.A., 2015. Enhanced-efficiency fertilizers in nitrous oxide emissions from urea applied to sugarcane. *Journal of Environmental Quality*. 44, 423–430

Soares-Filho B., Rajão R., Macedo M., Carneiro A., Costa W., Coe M., Rodrigues H., Alencar A., 2014. Cracking Brazil's Forest Code. *Science*, 344, 363–364

Sparovek G., Berndes G., Klug I., Barretto A., 2010. Brazilian agriculture and environmental legislation: status and future challenges. *Environmental Science and Technology*, 44, 6046–6053

Sparovek G, Berndes G, Barretto A. Klug I., 2012. The revision of the Brazilian forest act: increased deforestation or a historic step towards balancing agricultural development and nature conservation? *Environmental Science and Policy*; 16: 65–72.

Sparovek G., Barretto A., Matsumoto M., Berndes G., 2015a. Effects of Governance on Availability of Land for Agriculture and Conservation in Brazil. *Environmental Science and Technology*. 49, 10285–10293

SPIEA, 2012. São Paulo Instituto de Economia Agrícola – SPIEA [Internet]. Estatísticas da Produção Paulista [cited 2012 Sep 5]. Available from: http://www.iea.sp.gov.br, Portuguese

SRREN, 2011. Chum, H., A. Faaij, J. Moreira, G. Berndes, P. Dhamija, H. Dong, B. Gabrielle, A. Goss Eng, W. Lucht, M. Mapako, O. Masera Cerutti, T. McIntyre, T. Minowa, K. Pingoud, 2011: Bioenergy. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stratego, 2015. Heat Roadmap Europe 3 (STRATEGO): Translating the Heat Roadmap Europe Methodology to Member State Level. Connolly, David; Hansen, Kenneth; Drysdale, David; Lund, Henrik; Mathiesen, Brian Vad; Werner, Sven; Persson, Urban; Møller, Bernd; Wilke, Ole Garcia; Bettgenhäuser, Kjell; Pouwels, Willemijn; Boermans, Thomas; Novosel, Tomislav; Krajaãiç, Goran; Duiç, Neven; Trier, Daniel; Møller, Jacob Daniel; Odgaard, Anders Michael; Jensen, Linn Laurberg. Department of Development and Planning, Aalborg University, 2015. 550 s.

SUGARCANE, 2015. http://sugarcane.org/sugarcane-products/bioelectricity, (accessed 2015-09-14)

SugarCane Org., 2016. http://sugarcane.org/the-brazilian-experience/impact-on-brazils-economy, (accessed 2016-01-16)

Thunman, H., Lind, F., Johnsson, F., 2008. Combined energy production (In Swedish, Delstudie Energikombinat). Elforsk rapport

UDOP, 2008. União dos Produtores de Bioenergia – UDOP. Location of existing and planned sugarcane mills in the state of São Paulo, 2008 [map]. Available from: http://www.udop.com.br/ [2008, Nov].

UDOP, 2012. União dos Produtores de Bioenergia – UDOP. Location of existing and planned sugarcane mills in the state of São Paulo, 2012 [map]. Available from: http://www.udop.com.br/ [2012, May].

UDOP, 2016. União dos Produtores de Bioenergia – UDOP. Location of existing and planned sugarcane mills in the state of São Paulo, 2016 [map]. Available from: http://www.udop.com.br/ [2016, January].

UNICA, 2009. Phase out of burning before harvest [accessed 2010 June 5]. Available from: http://www.unica.com.br.

UNICA, 2011. UNICA [Internet]. Scientific data supports GHG reduction of sugarcane ethanol, even considering ILUC. Available from: http://www.english.unica.com.br (cited 2011-04-22)

USDA ERS, 2015. United states department of agriculture, economic research service Feed outlook: October 2015. http://www.ers.usda.gov/publications/fds-feed-outlook/fds-15j.aspx (accessed 2015-11-13)

US EPA, 2010. United States Environmental Protection Agency. EPA Lifecycle Analysis of Greenhouse Gas emissions from Renewable Fuels. Regulatory Announcement. Office of Transportation and Air Quality, EPA-420-F-10-006, February 2010.
Available at http://www3.epa.gov/otaq/renewablefuels/420f10006.pdf

US ERA RFS2, 2010. Regulatory impact analysis, Assessment and Standards Division Office of Transportation and Air Quality U.S. Environmental Protection Agency, EPA-420-R-10-006, February 2010

Verstegen J., Hilst F., Wolther G., Karssenberg D., de Jong S., Faaij A., 2015. What can and can't we say about indirect land use change in Brazil using an integrated economic – land use change model? doi:10.1111/gcbb.12270

Werner, S., 2006. Ecoheatcool 2005-2006, Work package 1 (The European heat market) and 4 (Possibilities with more district heating in Europe), Euroheat and Power, Brussels Belgium.

World Bank, 2016. http://data.worldbank.org/indicator/NV.AGR.TOTL.ZS (acessed 2016-01-16)

ÖPwC (Öhrlings PricewaterhouseCoopers), 2005. Bedömning av potential för högeffektiv kraftvärme i Sverige (Assessment of potential for highly efficient CHP in Sweden), Report for investigation regarding district heating, Stockholm, Sweden. In Swedish.